Effects of introducing low-cost high-speed rail on air-rail competition

Wang, Yixiao; Sun, Luoyi; Teunter, Ruud H.; Wu, Jianhong; Hua, Guowei

Published in:
Transport Policy

DOI:
10.1016/j.tranpol.2020.08.006

Transport Policy 99 (2020) 145–162

Contents lists available at ScienceDirect

Transport Policy

journal homepage: http://www.elsevier.com/locate/tranpol

Invited Research Paper

Effects of introducing low-cost high-speed rail on air-rail competition: Modelling and numerical analysis for Paris-Marseille

Yixiao Wang [a], Luoyi Sun [a], Ruud H. Teunter [b], Jianhong Wu [a,*], Guowei Hua [a]

[a] School of Economics and Management, Beijing Jiaotong University, No.3 Shangyuancun, Haidian District, Beijing, China
[b] Department of Operations, University of Groningen, PO Box 72, 9700, AB, Groningen, the Netherlands

ARTICLE INFO

Keywords:
High-speed rail policy
Introducing low-cost high-speed rail
Competition between rail and air

ABSTRACT

Given the trend of railway liberalization in Europe and Asia, we explore the effects of introducing low-cost high-speed rail as an answer to the railway reform on air-rail competition. In particular, by proposing a vertically differentiated model, we first derive the optimal pricing policies as well as the corresponding profits and market shares for low-cost high-speed rail (LCR), full-service high-speed rail (FSR) and air transport (Air). We do so for two types of LCR entrants, namely the incumbent owned entrant (to the FSR company) and the independently owned entrants. For both situations, we prove analytically that introducing LCR leads to reduced FSR and Air fares as well as to reduced Air traffic. The fare and traffic reductions increase with the passenger's time value and with the LCR travel time, while they decrease with the Air unit seat cost. Moreover, all LCR effects are stronger for an independently operated LCR. We apply our model to the Paris-Marseille route, based on data collected from publicly available sources. It is found that introducing an independently owned (incumbent owned) LCR on this route leads to 39% (33%) less air traffic, 20% (14%) less FSR traffic and a 37% (29%) increase in total rail traffic. Furthermore, this comes with increases of 2% (8%) in combined railway profit and 6% (5%) in total social welfare. These results support the decision of French policy makers to have LCR and FSR operated by the same company, as it comes with much higher combined railway profits and almost the same welfare increase as independently owned LCR. Further sensitivity analyses suggest that most LCR passengers would otherwise have traveled by FSR or Air, although LCR also attracts new passengers. In addition, offering a low-cost alternative is more effective if passengers value time more highly. Implications in terms of methodology and industry are provided.

1. Introduction

There is intense competition between low-cost and full-service airlines on many routes. In many countries, high-speed rail has also been introduced as an alternative to air transport. However, interestingly, besides offering 1st and 2nd class tickets, the service differentiation on high-speed rail tends to be limited. Indeed, to the best of our knowledge, the only large-scale introduction of low-cost high-speed rail has been by the operator "Ouigo" in France, which is owned by the same state-owned company (SNCF) that also operates the inOui/TGV full-service high-speed rail service. We remark that the earlier introduction of low-cost high-speed rail by iDTGV in France failed and TrenOK in Italy was also not successful. Very recently, on April 6th, 2020, "Avlo" was launched as the Spanish low-cost high-speed rail operator attached to Spain's national operator RENFE (Railway Gazette International, 2019).

Launched in 2013, Ouigo started with servicing the trunk routes and peripheral stations. Since then, it has expanded to cover almost all the high-speed lines in France, operating also from the station Gare de Lyon at the heart of Paris as of December 9th, 2018. Ouigo has established a firm foothold on the high-speed train market in France. The parent company SNCF recently declared that by "2020, Ouigo will represent 25% of high-speed rail service in France, with 30 destinations, 26 million passengers, 70 daily departures, 34 trainsets".

Offering low-cost service as an alternative to full-service allows high-speed rail to increase its market share and be more competitive compared to long-distance buses and private cars (Chiambaretto and Fernandez, 2014) and in particular to the potential competition from low-cost air transport (Sauter-Servaes and Nash, 2007). As we will

* Corresponding author. School of Economics and Management, Beijing Jiaotong University, No.3 Shangyuancun, Haidian District, Beijing, China.
E-mail addresses: yixiaowang@bjtu.edu.cn (Y. Wang), luoyisun@bjtu.edu.cn (L. Sun), r.h.teunter@rug.nl (R.H. Teunter), wujh@bjtu.edu.cn (J. Wu), gwhua@bjtu.edu.cn (G. Hua).

https://doi.org/10.1016/j.tranpol.2020.08.006
Received 12 May 2020; Accepted 8 August 2020
Available online 30 August 2020

highlight in the next section, research so far on the competitive advantages of introducing low-cost high-speed rail has been very scarce and purely of a strategic nature; tactical decisions on how to set ticket fares and how that effects market shares and profits have not been considered. This paper is the first to explore those issues.

Over 30 years have passed since the launching of the European railway reform, introducing intra-model competition. However, compared to the aviation liberalization from 1987 to 1997, the European railway industry has reformed at a relatively slow pace and scale, especially in the high-speed railway market (Delaplace and Dobruszkes, 2015; Chiambaretto and Fernandez, 2014). Besides the very recently launched Spanish operator Avlo, the only intra-model competition within high-speed rail operators are the independently owned Italian Italo and the French state-owned Ouigo. Different from aviation, rail operators in many countries are monopolists or oligopolists, who dominate the resources and are often reluctant to introduce (more) competition (Delaplace and Dobruszkes, 2015), even though this may benefit the society as a whole.

Given these circumstances, the introduction of Ouigo and Avlo, which are affiliated with their national railway companies, seems to be a feasible compromise. However, with the inevitable further liberalization and because of the increasing competition from the aviation industry, more independently owned operators are expected to enter the market (Delaplace and Dobruszkes, 2015; Chiambaretto and Fernandez, 2014). Thus, it is interesting to determine what the comparative effects of independently vs incumbent owned low-cost high-speed rail operators on profits, traffic and social welfare are. This is the focus of our study.

As mentioned, liberalization in aviation has moved at a faster pace. Particularly, in aviation, an often strategy observed has been for an incumbent full-service airline to acquire and operate a low-cost airline, also referred to as an “airlines within airlines” (AinA) strategy. The main motivation of AinA of a private full-service airline is to compete with other low-cost airlines (Homsombat et al., 2014; Kawamori and Lin, 2013; Hazledine, 2011; Graf, 2005; Morrell, 2005). In some respects, the introduction of Ouigo and Avlo can be seen as a comparable “railway within railway” strategy. However, the circumstances are rather different. The parent companies are state-owned and rather than protecting against low-cost rail competitors, the introduction of a low-cost operator is in response to the liberalization of the domestic passenger market under the EU’s Fourth Railway Package.

Furthermore, being (partly) state-owned, sustainability and welfare could also play more important roles in the rail sector (Delaplace and Dobruszkes, 2015). Research so far does suggest that government subsidies may still be needed though, as rail operators are mostly profit-driven (Delaplace and Dobruszkes, 2015; Jarach et al., 2009). In our study, we therefore consider welfare next to profit.

To keep the analysis insightful and tractable, we consider the effects of introducing low-cost high-speed rail next to full-service high-speed rail on the competition with air transport in general. So, we do not differentiate between the low-cost airline and full-service airline in our modelling. In real life, many routes exist where only one type of air transport is available, although this obviously does not apply to all cases. In our literature review and analyses in the next sections, we do make the distinction between low-cost and full-service air transport. Furthermore, we use the abbreviations LCR, FSR, LCA and FSA for the low-cost (high-speed) rail, full-service (high-speed) rail, low-cost air transport and full-service air transport. So, we consider the competition between LCR, FSR and air transport and do so for two situations: the new entrant LCR operator is incumbent owned by the FSR operator (as is the case for Ouigo), or it is completely independent operator (in line with the ongoing liberalization of railway in Europe).

Considering both situations allows us to address five fundamental questions: (1) What is the optimal pricing strategy for operators in the LCR-FSR-Air competition scenario? (2) How does the LCR entry affect equilibrium fares, traffic, profits and welfare? (3) Under what circumstances is it profitable and/or socially desirable to introduce LCR? (4) How do the situations with an incumbent owned and an independently owned LCR compare and, related, what should policy makers strive for? (5) What should aviation pay attention to when a LCR operator enters the market? We answer these questions through an analytical study, where we determine the profit-maximizing fares and related market shares.

By proposing a vertical differentiated model, where three types of transport modes compete against each other in the same time, we derived the optimal fares and corresponding traffic, profits and welfares in equilibrium in LCR-FSR-Air competition for the two types of new LCR entrants, namely incumbent owned (to the FSR company) and independently operated. Some key factors affecting the equilibrium results, as well as analytical observations in terms of the effects of introducing LCR on railway and aviation (fares, traffic, profits and consumer surplus) are determined for both situations and implications for both the railway and the aviation industry are discussed.

Using publicly available sources, we further collected data from the French transport market, for the Paris-Marseille route. Applying these in our model, we find that having an incumbent owned LCR operator, as is the case, is the most attractive alternative overall. It retains most of the benefits of introducing an independently owned LCR in terms of reduced fares, less Air traffic and increased total welfare, while allowing for a much higher total rail profit. A further numerical sensitivity study suggests that a higher LCR service quality improves railway profit and social welfare. Also, the introduction of LCR is most effective on routes where a large fraction of the passengers travel for leisure purposes.

The remainder of this paper is organized as follows. In Section 2, we review the related literature. In Section 3, we present the LCR-FSR-Air competition model with an incumbent owned LCR. In Section 4, we analyse the effects of introducing LCR and compare the effects of incumbent and independently owned LCR. A numerical analysis based on the case of Paris - Marseille is conducted in Section 5 and we further provide the management and policy insights for introducing LCR to the railway industry. Finally, Section 6 provides the conclusions.

2. Literature review

Quite a few authors have studied the competition between high-speed rail, low-cost air transport and full-service air transport. Although most of these studies implicitly consider ‘regular’ full-service high-speed rail, this is often referred to simply as “high-speed rail (HSR)”, because the low-cost alternative is not considered. As discussed in Section 1, however, we do consider both alternatives and use the abbreviations LCR for low-cost (high-speed) rail and FSR for full-service (high-speed) rail, besides the LCA for low-cost air transport and FSA for conventional full-service air transport.

2.1. Market effects of competition between FSR, LCA and FSA

Whereas we consider the introduction of the LCR, some existing studies have looked at the introduction of the LCA. These studies are still relevant for ours, as we also consider the intramodal effects of introducing a low-cost alternative, albeit for a different mode of transport. Delaplace and Dobruszkes (2015) showed that different market settings and hypotheses lead to different findings regarding the LCAs impacts on the competition between the FSR and FSA. A report by the consultancy firm Steer Davies Gleave (2006) showed that the emergence of the LCAs services can help reduce the competition between air and FSR. Albalate et al. (2015) argued that the introduction of LCA operators is indeed a way for Air industry to combat the threat of high-speed rail. Specifically, in Japan, the total airline market started to grow following the development of the LCAs (Albalate and Bel, 2012). In Europe, providing LCA next to FSA can also expand the total air traffic through market segmentation, as was shown using a linear regression model by Clewlow et al. (2014). Similar results were found for the Chinese market by Zhang et al. (2019).

At the same time, introducing LCA can have a negative effect on the market share of an incumbent FSA provider, as was shown by Friebel and Niffka (2009) in a case study for the German passenger transportation market (Lufthansa). Behrens and Pels (2012) came to similar findings for the London–Paris passenger market, where several conventional airlines quit after the introduction of the LCAs.

Next, we highlight the insights from studies on FSR, LCA and FSA competing for market share. Both Li et al. (2019) and Zhang and Zhang (2016) found for the Chinese case that FSR competes in particular with LCA for passengers. Bukovac and Douglas (2019) also observed for an Australian case that the introduction of the FSR could force the LCA providers to quit, while also leading to fewer FSA flights on the FSR routes. By considering the development history of the LCAs, Jiang and Li (2016) concluded that the wider geographical route coverage and higher degree of liberalization in the aviation sector makes LCA transport relatively more competitive vs. FSR in Europe, as compared to Japan. As pointed out by Xia et al. (2018), FSR competes mainly with LCA for passengers.

Some authors have studied the effect of market density on the level of competition between LCA and FSR, with mixed findings. Behrens and Pels (2012) applied logit models to show that the LCA-FSR competition is more intense on markets with a higher density. To the contrary, both Hu et al. (2019) and Wang et al. (2017) suggested that the presence of the LCAs may leave the FSR with less survival room in the low-density corridors in central and western China, based on the real options valuation and propensity score matching respectively.

2.2. Social welfare and competition

Some authors have studied the welfare effect of the competition between FSR and air transport. Considering a specific route, a Hotelling model was adopted by Yang and Zhang (2012) to yield analytical results on how Air-FSR competition affects fares, traffic and welfare. They found that if a (state-owned) FSR operator is more focused on welfare, then this leads to lower FSR fares and, through competition, also to lower Air fares. A further comparison of the social welfare with and without price discrimination in the airline industry showed that implementing a low-cost strategy in airlines can benefit the social welfare of FSR.

Tsunoda (2018) built on the research of Yang and Zhang (2012) and proposed a two-stage model, where the welfare-maximizing government determines the optimal weight on the welfare relative to the FSR's profit (referred to as the degree of regulation in their study) for the FSR operator in the first stage, while the FSA and FSR operators determine their fares in the second stage. They found that the passenger benefits play a crucial role. If the difference between FSR and FSA benefits to passengers is small, then the government should strengthen the degree of regulation on FSR. However, if the difference is large, then it is better to relax regulations as FSA is more beneficial for passengers, which is intuitive. Related, D' Alfonso et al. (2015) showed that when the emissions are also considered, the introduction of FSR is not necessarily good for welfare. For a market without LCA, they showed that introducing FSR as an alternative to FSA leads to a considerable increase in the total traffic, resulting in increased emissions and lower social welfare.

Some authors considered multiple routes, allowing them to explore network effects as well as interactions and externalities between the different routes. Adler et al. (2010) analysed the effect of the FSR infrastructure investments on the network social welfare. They modelled the passengers' choice using a random utility approach and used the data from 27 EU countries (Zhang et al., 2019) to show that expanding the FSR network can benefit social welfare. Jiang and Zhang (2016) showed that FSA is best moved to the fringe routes, whereas FSR remains dominant for the trunk routes. Capacity also plays an important role in network configuration. Studies by Jiang and Zhang (2014) and Xia and Zhang (2017) indicated that to maximize the overall welfare of the entire network and airlines should only offer both LCA and FSA connections from hubs with sufficient capacity.

2.3. Research on LCR's operations and its effect

As discussed in Section 1, very few authors have considered LCR. As our focus is on the introduction of LCR, we next review in detail the studies that do exist. These are all based on the case study of OUIGO, the French (SNCF) state-owned LCR that was launched in 2013 and also discussed in Section 1. Based on the interviews and secondary data, Chiambaretto and Fernandez (2014) went over the operational and marketing characteristics of OUIGO, such as the pricing policy, adding more seats per carriage, using secondary train stations and booking online. They concluded that commercial features (e.g. pricing policy and distribution channels) can be adapted/implemented more easily than technical features (e.g. network structure and staff), because of constraints related to the railway legal framework. The authors argued that LCR could help rail operators compete with short-distance LCAs as well as long-distance buses and cars.

Delaplace and Dobruszkes (2015) arrived at a similar conclusion. They considered LCR as a combination of the traditional FSR and LCA, rather than directly imitating LCA, by comparing OUIGO with the TGV and LCAs in terms of its marketing strategy, such as booking procedure, network geography, service quality and fares. They observed that the LCA operators were currently restricted to relatively long routes, where high-speed rail was typically not considered as an alternative by passengers. However, they suggested that if LCA would expand their operations to shorter routes, then this could help a FSR operator to combat the increasing competition from LCA.

2.4. LCA entry effects on local market

Since few studies exist on the effects of LCR entering a market, we review evidences from the entry of LCA. Many empirical studies have found that this has negative effects on the incumbent airlines' fares and traffic in different markets, e.g. the European market (Alderighi et al., 2012), US market (Asahi and Murakami, 2017; Abda et al., 2012; Daraban and Fournier, 2008), Indian market (Wang et al., 2018) and Brazilian market (Oliveira and Huse, 2009). However, not all research points in this direction. For instance, Homsombat et al. (2014) found for the Australian market that the fare of the incumbent FSA was increased after the LCA, owned by the incumbent, was introduced. For the Chinese market, Wang et al. (2018) and Fu et al. (2015) found that LCA's entry did not have a significant effect on fares through econometric analysis. Also, Detzen et al. (2012) found that there were positive effects of LCAs' entry on traffic, revenue and stock prices of the full-service airlines based on the US market. Apparently, the effects of introducing LCAs vary in different market conditions.

Few analytical studies have been conducted in this field. Through analytical modelling, Kawamori and Lin (2013) found that if the full-service carrier's operating cost and via-hub cost is neither too small nor too large, then quitting from the route competing with the hub carrier is optimal for the merged LCA. Using a similar method, Li et al. (2019) found that if the full-service airline adopts AinA, then maintaining a mixed one-stop and nonstop network is optimal. Alderighi et al. (2012) modelled the competition between the two FSAs and one LCA in a fixed market. They found that the incumbents' fares where lowered by the presence of LCA. However, they didn't analytically study the profits and welfare and some critical factors were ignored, such as passengers time value and AinA situation.

2.5. Contribution

Our review has shown that although many authors have studied the competition between high-speed rail and air transport, very few have considered low-cost high-speed rail. Moreover, those who did looked only at strategic aspects. To our best knowledge, this study is the first to derive both analytical and numerical results on the effect of introducing LCR, in a market with FSR and air transport, on fares, market shares, profits and social welfare. Moreover, by considering both an incumbent owned (by FSR) and independently owned LCR operator, we derive the policy insights in what provides best benefits for operators, passengers and society as a whole.

3. LCR-FSR-Air competition model with a new entrant LCR operator

Our interest is in the effects of introducing low-cost high-speed rail on a route where full-service high-speed rail is already competing with air transport, as has happened in France. We use the abbreviations LCR for low-cost (high-speed) rail and FSR for full-service (high-speed) rail, besides the conventional LCA for low-cost air and FSA for full-service air transport. We consider two possible situations, namely that LCR either has the same state-owned operator as FSR or that LCR is independently operated. We will analyse both situations, also in comparison to the benchmark situation without an LCR option. Indeed, we will start by analysing that benchmark situation in Section 3.1, before considering LCR-FSR-Air competition in Section 3.2.

Next, however, we introduce the general setting and notations. The three transport options are indexed by $i = L, F, A$, where L represents LCR, F represents FSR and A represents air transport. These differ in the service provided, such as the on-board services including Wi-Fi, comfort and cleanliness, leg room, responsiveness of crew, handling of customer complaints, safety, etc. Specifically, we assume that the level of the service quality of each mode, denoted by Q_L, Q_F and Q_A, respectively, satisfy $Q_L < Q_F < Q_A$. It is natural to assume that $Q_L < Q_F$, as LCR provides a lower service level than FSR. Besides, since air transport is usually considered superior to high-speed rail in terms of service quality (Xia and Zhang, 2017; Wan et al., 2016; Bilotkach et al., 2010; Morrell, 2005; Gonzalezsavignat et al., 2004), we assume that $Q_F < Q_A$.

We consider a vertically differentiated model where passengers are heterogeneous in their sensitivity to the service quality as shown in Fig. 1, in which we model using a sensitivity parameter, θ, is uniformly distribution from zero to one. We model the utility function of the passengers opting for mode i, $i = L, F, A$, as

$$U_i = b + \theta Q_i - vT_i - p_i$$

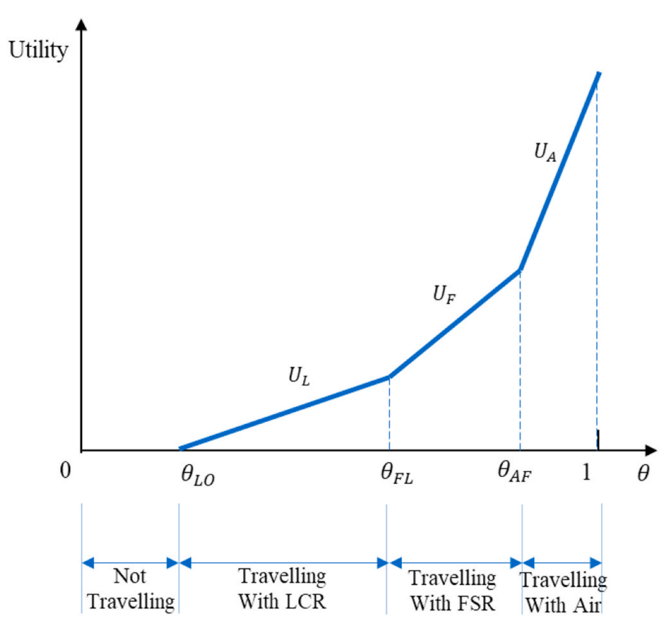

Fig. 1. Market division with LCR, FSR and air transport.

where $b > 0$ is the basic benefit gained from the trip, Q_i refers to the satisfaction of the passenger gained through the service tangible and intangible in mode i, v refers to the passenger's value of time, T_i is the total travel time if the passenger selects mode i and p_i is the ticket fare in mode i. Each passenger selects the transport mode that provides the highest utility, or decides not to travel if none of the available modes brings a positive utility. Let q_i denote the resulting passenger traffic of mode i.

We consider the high-speed train and air operators to be vertically separated from the railway and airport infrastructure, as is common in Europe and partially applies in Asia. Related, although we will compare competition outcomes in terms of welfare, we assume that the operators do not consider welfare but are profit-driven, as the transport service operating is seen as commercial rather than public behaviour (Nash, 2008). For each of the travel mode i, the revenue p_i is earned, but the unit seat cost c_i is incurred. The profit function for the travel mode i can therefore be written as

$$\pi_i = q_i(p_i - c_i) \tag{1}$$

Each operator aims to maximize its total profits (from all the modes operated). The capacities of the infrastructure (high-speed rail line and airport), high-speed rail trainsets and aircrafts are assumed to be abundant and so there is no limitation on the demand that an operator can handle. Table 1 lists the notations used in this paper.

3.1. Benchmark model: FSR-Air competition (no LCR)

A passenger is indifferent between FSR and Air if

$$b + \theta Q_A - vT_A - p_A = b + \theta Q_F - vT_F - p_F,$$

i.e. for θ equal to

$$\theta_{AF} = \frac{p_A - p_F + vT_A - vT_F}{Q_A - Q_F}$$

A passenger is indifferent between not traveling and FSR if

$$b + \theta Q_F - vT_F - p_F = 0$$

i.e. for θ equal to

$$\theta_{FO} = \frac{p_F - b + vT_F}{Q_F}$$

Thus, passenger traffic of Air and FSR, respectively, amount to

$$q_A = 1 - \theta_{AF} = 1 - \frac{p_A - p_F + vT_A - vT_F}{Q_A - Q_F} \tag{2}$$

$$q_F = \theta_{AF} - \theta_{FO} = \frac{p_A - p_F + vT_A - vT_F}{Q_A - Q_F} - \frac{p_F - b + vT_F}{Q_F} \tag{3}$$

And the respective profits are

Table 1
Lists the notations used in this paper.

i	LCR ($i = L$)/FSR ($i = F$)/Air ($i = A$)
T_i	total travel time if the passenger takes mode i
q_i	passenger traffic of mode i
p_i	ticket fare of mode i
c_i	unit cost per seat of mode i
π_i	profit of operator i
b	basic benefit gained from the trip
θ	preference of the passenger towards the service quality
Q_i	tangible and intangible service quality in mode i
v	passenger's value of time

$$\pi_A^N = \left(1 - \frac{p_A - p_F + vT_A - vT_F}{Q_A - Q_F}\right)(p_A - c_A) \tag{4}$$

$$\pi_F^N = \left(1 - \frac{p_A - p_F + vT_A - vT_F}{Q_A - Q_F}\right)(p_A - c_A) \tag{5}$$

The passenger surplus for each mode can be expressed as:

$$CS_A^N = \int_{\theta_{AF}}^{1} (b + xQ_A - vT_A - p_A)dx$$

$$CS_F^N = \int_{\theta_{FO}}^{\theta_{AF}} (b + xQ_F - vT_F - p_F)dx$$

Thus, the total social welfare of each mode equals:

$$W_A^N = \pi_A^N + CS_A^N$$

$$W_F^N = \pi_F^N + CS_F^N$$

Differentiating (4) and (5) with respect to p_A and p_F, respectively and considering the first-order conditions, we obtain the optimal FSR and Air fares, respectively, as

$$p_F^{N*} = \frac{Q_A(2b + 2c_F + Q_F - 2vT_F) + Q_F(-2b + c_A - Q_F + v(T_A + T_F))}{4Q_A - Q_F} \tag{6}$$

$$p_A^{N*} = \frac{2Q_A^2 + Q_F(-b + vT_A) + Q_A(b + 2c_A + c_F - 2Q_F - 2vT_A + vT_F)}{4Q_A - Q_F} \tag{7}$$

From (2) and (3) we then get the equilibrium FSR and Air traffic as:

$$q_F^{N*} = \frac{Q_A(Q_A(2b - 2c_F + Q_F - 2vT_F) + Q_F(-2b + c_A + c_F - Q_F + v(T_A + T_F)))}{(Q_A - Q_F)(4Q_A - Q_F)Q_F} \tag{8}$$

$$q_A^{N*} = \frac{2Q_A^2 + Q_F(-b + c_A + vT_A) + Q_A(b - 2c_A + c_F - 2Q_F - 2vT_A + vT_F)}{4Q_A^2 - 5Q_AQ_F + Q_F^2} \tag{9}$$

By substituting (6)–(9) into (4) and (5), we further obtain the equilibrium profits of FSR and Air as:

$$\pi_F^{N*} = \frac{Q_A(Q_A(2b - 2c_F + Q_F - 2vT_F) + Q_F(-2b + c_A + c_F - Q_F + v(T_A + T_F)))^2}{(Q_A - Q_F)Q_F(-4Q_A + Q_F)^2}$$

$$\pi_A^{N*} = \frac{(2Q_A^2 + Q_F(-b + c_A + vT_A) + Q_A(b - 2c_A + c_F - 2Q_F - 2vT_A + vT_F))^2}{(Q_A - Q_F)(-4Q_A + Q_F)^2}$$

3.2. LCR-FSR-air competition

We first derive the passenger traffic of LCR, FSR and Air given fares, which applies to both independently owned and incumbent owned LCR. After doing so, we determine the equilibrium fare prices for both situations.

A passenger is indifferent between FSR and LCR if

$$b + \theta Q_F - vT_F - p_F = b + \theta Q_L - vT_L - p_L$$

i.e. for θ equal to

$$\theta_{FL} = \frac{p_F - p_L + vT_F - vT_L}{Q_F - Q_L}$$

Similarly, a passenger is indifferent between FSR and Air if

$$b + \theta Q_A - vT_A - p_A = b + \theta Q_F - vT_F - p_F$$

i.e. for θ equal to

$$\theta_{AF} = \frac{p_A - p_F + vT_A - vT_F}{Q_A - Q_F}$$

Also, a passenger is indifferent between LCR and not traveling at all if

$$b + \theta Q_L - vT_L - p_L = 0$$

i.e. for θ equal to

$$\theta_{LO} = \frac{-b + p_L + vT_L}{Q_L}$$

From this, we obtain the passenger traffic of LCR, FSR and Air, respectively, as

$$q_L = \theta_{FL} - \theta_{LO} = \frac{p_F - p_L + vT_F - vT_L}{Q_F - Q_L} - \frac{p_L - b + vT_L}{Q_L} \tag{10}$$

$$q_F = \theta_{AF} - \theta_{FL} = \frac{p_A - p_F + vT_A - vT_F}{Q_A - Q_F} - \frac{p_F - p_L + vT_F - vT_L}{Q_F - Q_L} \tag{11}$$

$$q_A = 1 - \theta_{AF} = 1 - \frac{p_A - p_F + vT_A - vT_F}{Q_A - Q_F} \tag{12}$$

Recall that we consider two situations, where the LCR is either independently owned or incumbent to the FSR operator. For both situations, similar to the analysis of the benchmark situation without LCR in Section 3.1, it is now straightforward to express the profits of all the players in terms of the prices only and then derive the equilibrium prices and the corresponding equilibrium passenger traffic quantities and profits as well as welfare. This does lead to the closed-form expressions, but those are rather tedious and not insightful. Therefore, these expressions and their derivations are presented in Appendix A.

Fortunately, these results, along with those of Section 3.1, do allow us to obtain generally valid clear insights into the effects of introducing LCR on prices and profits, both when LCR is independently owned and when it is incumbent owned by FSR operator. Moreover, comparing the results for these two situations provides further insights. These will be presented in the next section.

4. Effects of introducing LCR

As it turns out, the qualitative effects of introducing LCR on air traffic and FSR fares are the same for both considered situations. We will present these results in Section 4.1, before discussing comparative results for both situations in Section 4.2.

4.1. Effects of introducing a new entrant LCR operator

Comparing the equilibrium outcomes without LCR (Section 3.1) and with an LCR operator (Appendix A.1), we obtain the following result.

Proposition 1. Both for incumbent and independently operated LCR, its introduction leads to reduced Air and FSR fares. The reductions increase with the passenger's value of time and travel time of LCR, but decrease with the Air unit seat cost.

This finding is arguably more intuitive for the situation with independently operated LCR. Since LCR is more comparable in quality to FSR than to Air, this first of all implies increased competition for FSR. As a result, the FSR operator lowers its fare. This, in turn, makes the air transport less attractive and the airline reacts by lowering its fare. Even if LCR is run by the same company as FSR, the added competition from LCR still leads to lower FSR fares to keep that option sufficiently attractive, which then again leads to the lower Air fares.

As to the size of the reduction, a higher passenger's time value will increase the fares in FSR-Air competition, making the fares drop even more severely when LCR is introduced. The effect of the LCR travel time is less intuitive. Indeed, a larger LCR travel time makes LCR (for a given fare) less of a threat to FSR and Air. However, to compensate and still attract passengers, LCR charges an even lower fare, which then leads to larger fare reductions for FSR and Air.

If the Air operating cost is higher, then a higher Air fare is necessary for air transport to remain profitable. As a result, the air fare reduction is smaller. In turn, FSR maintains a higher fare as it faces less price competition from Air. Air transport often faces higher landing fees and congestion charges for the more congested routes, implying a higher cost per unit seat on such routes and so lower fare reductions when LCR is introduced.

Related to these fare changes, we also get the following result.

Proposition 2. Both for incumbent and independently operated LCR, its introduction leads to reduced Air traffic. The reduction in Air traffic is increasing with the passenger's value of time and travel time of LCR, but decreasing with the Air unit seat cost.

This is closely related to the fare changes presented in Proposition 1. Because the FSR and Air fares are both reduced, it is clear that traveling becomes more attractive for the potential passengers, even aside from the added LCR option. Although the airline lowers its fare in response to the LCR option, it still loses the market share due to the increased competition with the rail.

Meanwhile, a higher passenger's value of time and travel time of LCR indirectly increases the competitiveness of LCR, thereby allowing the Air traffic to drop even more. On the other hand, especially for the routes which is congested and operated by full-service airlines, in order to maintain profits, the air transport will still set a relatively higher fare to cope with its high operating cost, so that the fluctuation of the Air fare and corresponding traffic is relieved to some extent.

4.2. Incumbent versus independently owned LCR operator

Next, we compare the equilibrium results of fares, passenger traffic as well as profits of introducing the incumbent owned LCR and independently owned LCR and present our findings.

Proposition 3. After introducing an incumbent owned LCR operator, all fares are higher than compared to introducing an independently owned LCR operator.

An incumbent owned LCR operator is less inclined to set a low LCR fare than an independently owned LCR operator, because doing so not only increases the LCR traffic but (ceteris paribus) also implies the lower FSR traffic. Therefore, the LCR fares are higher for an incumbent owned LCR operator and so the FSR fare and (in turn) Air fare stay at a higher level as well.

Proposition 4. Compared to an independently owned LCR operator, the introduction of an incumbent owned LCR operator implies less LCR traffic, more FSR traffic, less rail traffic in total and more Air traffic.

An incumbent owned LCR operator avoids too fierce competition with the FSR by setting a comparatively higher (to independently owned) LCR fare, implying less LCR traffic but more FSR traffic. Less fierce competition also allows the air transport to retain a larger market share and reduces the total rail traffic.

Propositions 3 and 4 combined show clear advantages for policy makers of an independently owned versus an incumbent owned LCR operator, as it leads to lower fares across the board and also lower Air traffic (and so less pollution). However, as our explanations showed, this is the result of more fierce competition amongst the rail operators, which also leads to lower combined rail profits.

Proposition 5. Compared to an independently owned LCR operator, the introduction of an incumbent owned LCR operator leads to both higher FSR and Air profits.

These results are intuitive. If the FSR profit is considered by the LCR operator, then the FSR is indeed able to retain a larger profit compared to the situation where the LCR and FSR are independent competitors. In turn, as this higher FSR profit is obtained by maintaining a higher (compared to independent operators) FSR fare, Air transport faces less fierce competition and obtains higher profits.

Proposition 6. Compared to an independently owned LCR operator, the introduction of an incumbent owned LCR operator leads to a lower LCR consumer surplus.

This result is in line with the previous findings. Competition is less fierce with an incumbent owned LCR operator, leading to higher fares and thereby a lower consumer surplus.

Since the derived expressions for the operators' profits and total welfare are rather complex and difficult to analyse, we next explore them in a numerical study based on the Paris-Marseille route.

5. Numerical study: Paris-Marseille

We apply our model to the Paris-Marseille route, in order to get insight into the effects of introducing LCR on a route where FSR already competes with air transport. Note that in line with the above, we use the abbreviations LCR for low-cost (high-speed) rail and FSR for full-service (high-speed) rail, besides LCA for low-cost air transport and FSA for conventional full-service air transport. Table 2 lists all the estimated model parameter values, where interested readers can refer to Appendix C for the sources and explanations. Note that the total market is normalised to 1 in line with our model.

Table 3 shows the numerical results of the fares, traffic, profits and social welfare and. One striking result is that the introduction of the LCR induces significant negative effects on the incumbents, especially for the independently operated LCR. Specifically, if LCR is independently operated, then its introduction decreases FSR traffic (from 0.35 to 0.28) by 20.0% and air transport (from 0.18 to 0.11) by 38.9%. If LCR is operated by the same company as FSR, then its introduction decreases FSR traffic by 14.3% and Air traffic by 33.3%.

The introduction of LCR also leads to fare reductions for both existing transport modes, which are again larger if the LCR operates independently. In that case, the FSR fare drops by 1.7% and the Air fare by 0.7%. When jointly operated, the reductions are 1.5% and 0.6%, respectively. Despite the fare reductions, the FSR and Air still lose market share and so also face the decreased profits.

Although FSR is negatively affected by the introduction of LCR, the combined traffic and profit for the railway industry as a whole increase. The increase in the traffic intensity is more significant, namely (from 0.35 to 0.48) 37.1% when jointly operated and still (from 0.35 to 0.45) 28.6% when independently operated. The combined rail profit is also a considerable (from 1.08 to 1.17) 8.3% higher if LCR and FSR are jointly operated, but only (from 1.08 to 1.10) 1.8% higher otherwise.

Fig. 2 displays the changes in traffic when LCR enters the market. Both when incumbent owned or independently operated, about 1/3 of the LCR traffic is induced (i.e., additional), which is consistent with previous finding for new HSR services (Delaplace and Dobruszkes, 2015; Givoni, 2003). The remaining 2/3 of LCR traffic is shifted from FSR and Air in roughly equal proportions. This does not imply that about half of the shifted LCR passengers used to travel by Air. Instead, most LCR passengers will shift from FSR, whereas others shift from Air to FSR. This supports the claim by SNCF and RENFE that the main target customers

Table 2
Parameter values.

Parameters	Air	FSR	LCR
T_i (Total travel time (h))	4.03	4.32	4.32
c_i (Unit seat cost (euro))	84.74	70.50	57.32
Q_i (Service quality (euro))	90.00	80.00	60.00
v (Passengers' Value of time (euro/h))	26.46		
b (Benefit gained through trip (euro))	150.00		

Table 3
Numerical results.

	Organisation forms	Air	FSR	LCR
Fares	Independently owned	88.89	72.37	60.26
	Incumbent owned	88.97	72.53	61.08
	No LCR	89.51	73.60	–
Traffic	Independently owned	0.11	0.28	0.20
	Incumbent owned	0.12	0.30	0.15
	No LCR	0.18	0.35	–
Railway Traffic	Independently owned	–	0.48	
	Incumbent owned		0.45	
	No LCR		0.35	
Profits	Independently owned	0.13	0.52	0.58
	Incumbent owned	0.15	0.61	0.56
	No LCR	0.31	1.08	–
Railway Profits	Independently owned	–	1.10	
	Incumbent owned		1.17	
	No LCR		1.08	
Social Welfares	Independently owned	4.65	6.94	1.73
	Incumbent owned	4.94	7.05	1.23
	No LCR	6.66	5.96	–
Railway Welfares	Independently owned	–	8.67	
	Incumbent owned		8.28	
	No LCR		5.96	
Total Welfares	Independently owned	13.32		
	Incumbent owned	13.22		
	No LCR	12.62		

for their low-cost high-speed rail services are those customers who are price-sensitive and travel infrequently for leisure purposes (Railway Gazette International, 2019). However, our results also show that indirectly, by lowering FSR fares, a considerable fraction of the induced traffic could come from more service-oriented customers shifting from Air to FSR.

As the introduction of LCR leads to reduce FSR and Air fares and offers passengers another alternative, it is clear that passengers are better off after its introduction. There is also an improvement in the welfare for the operators and passengers combined, namely (from 12.62 to 13.22) by 4.8% when the LCR is incumbent owned and (from 12.62 to 13.32) 5.6% when independently owned. So, the considerable loss in Air profit (by 26.8% when LCR is incumbent owned and 30.2% when independently owned) is more than compensated by the increased combined rail profit and consumer surplus.

5.1. Effects of LCR service quality

Since the service quality of LCR is a key factor to help navigate its position in the LCR-FSR-Air competition, we next perform a numerical sensitivity analysis where we vary the LCR's service quality, while leaving all the other parameters unchanged.

We first focus on the impact of the LCR's service quality on traffic intensities/densities. It is found that the LCR will quit the market if its quality is lower than some threshold, which has value 49.7 if the LCR is incumbent owned and 46.0 if independently owned. With service qualities below this threshold, LCR is unable to profitably compete with FSR and air transport. Figs. 3–6 show that with the introduction of either incumbent or independently owned LCR, the LCR traffic and the total rail traffic increase in the LCR's service quality, while the FSR traffic and Air traffic decrease. As the quality of LCR services increases, competition with FSR and also air transport becomes more fierce, and the LCR is able to increase its market share at the expense of the FSR and air transport. So, from a combined rail perspective, higher LCR service quality always leads to a better performance. However, we should keep in mind that higher service quality will of course come at a cost increase that we do not consider and transport regulation authorities should also pay careful attention to the negative effects of LCR on FSR traffic.

In line with the above effects on traffic intensities, a higher quality and therefore more competitive LCR leads to the higher LCR profit at the expense of the FSR and Air profits, as shown in Figs. 7–10. Note that over the whole quality range considered, the total combined rail profit is higher when LCR is incumbent owned, but the LCR profit is very similar whether it is independently or incumbent owned. From a policy perspective, these findings suggest that introducing jointly operated LCR to accommodate the incumbent is a good way forward, because it leads to more overall railway profit when competing with air transport without causing unrest for the FSR operator. Moreover, having one company operate both LCR and FSR may lead to efficiency gains that were not included in our calculations, e.g. reduced cost from shared services like cleaning, booking system, maintenance and labour.

Finally, we focus on the impact of LCR's service quality on social welfare in Fig. 11. For both the incumbent and independently owned LCR, the total welfare increases in the LCR quality. Apparently, more fierce competition leads to lower fares and ultimately to higher total social welfare. However, a higher LCR quality may harm the consumer surplus from induced passengers who are sensitive to travel fares.

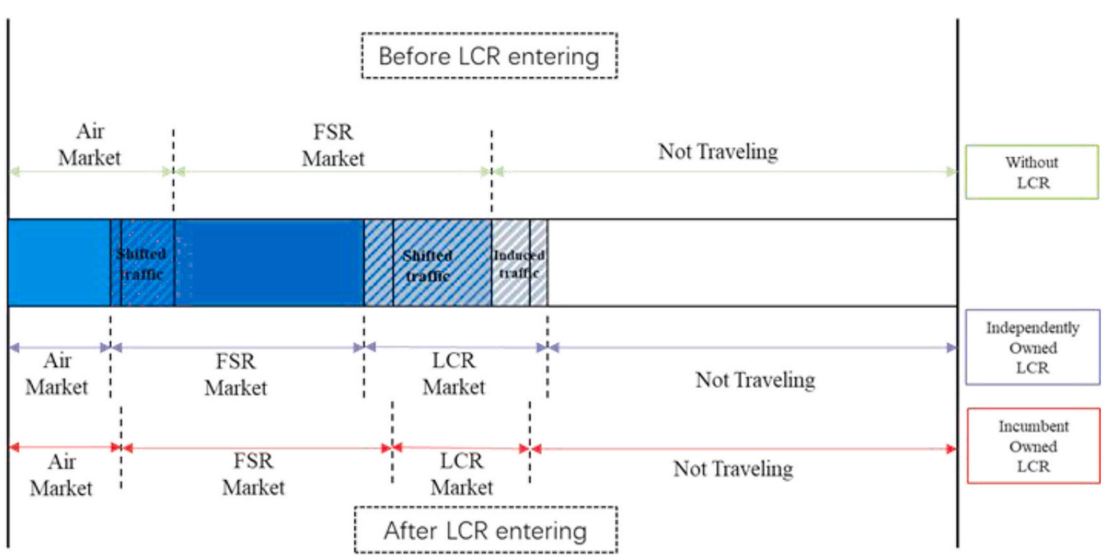

Fig. 2. Market changes after LCR is introduced.

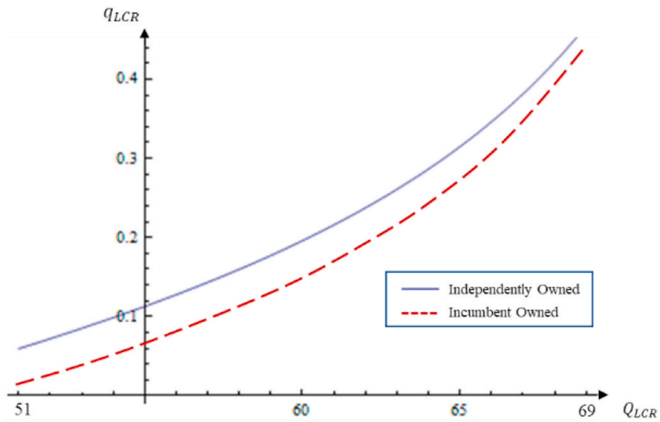

Fig. 3. Effects of LCR service quality.

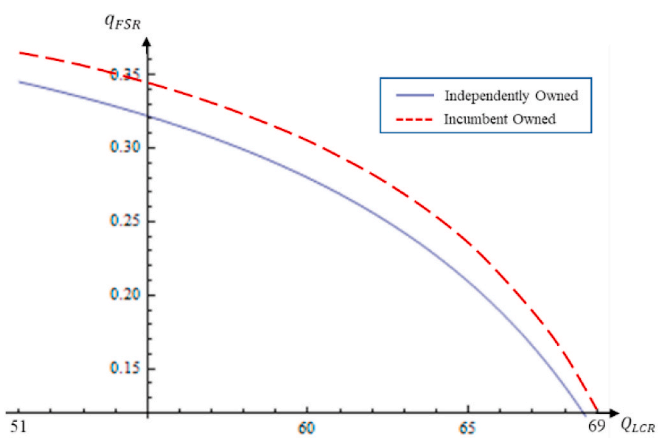

Fig. 4. Effect of LCR service quality. On LCR traffic on FSR traffic.

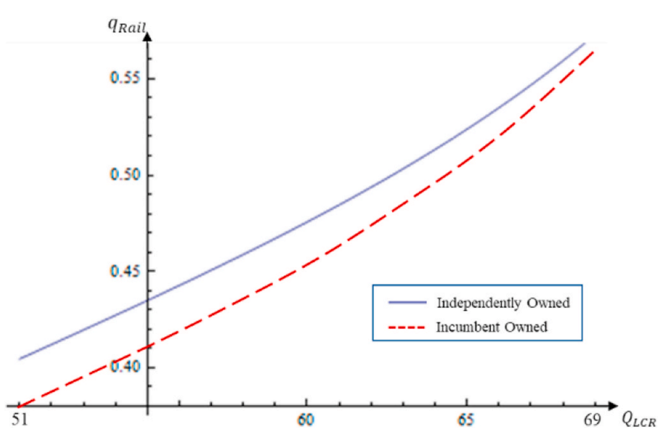

Fig. 5. Effect of LCR service quality.

5.2. Effects of passengers' value of time on LCR-FSR-FSA competition

Obviously, the passengers' value of time is another factor that plays a key role in the choice between rail and air transport and so we study its effect here. It is generally believed that business passengers have a higher value of time than those who travel for a leisure purpose (Yang and Zhang, 2012). On Paris-Marseille and most other routes, there will be a mix of these two types of customers and it is interesting to study how that mix, through the (average) time value for traveling in our model, affects the results.

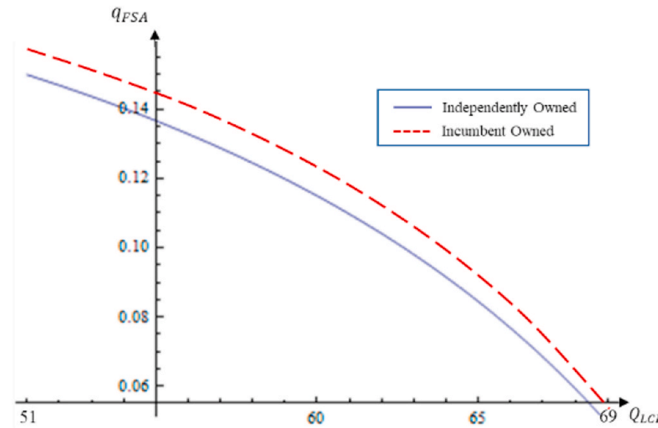

Fig. 6. Effect of LCR service quality. On combined rail traffic on Air traffic.

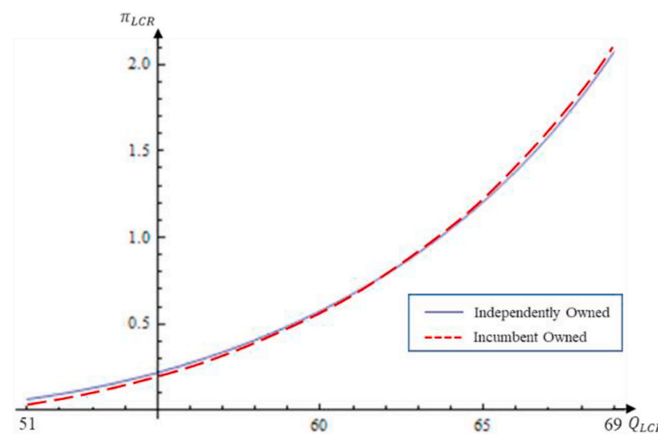

Fig. 7. Effect of LCR service quality.

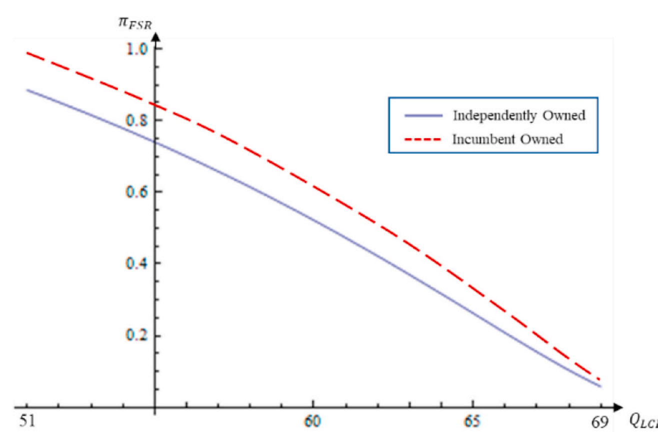

Fig. 8. Effect of LCR service quality. On LCR profit on FSR profit.

Figs. 12–15 show the effect of the time value on the profits. It appears from Figs. 12–14 that introducing LCR becomes relatively less effective in increasing the rail profits as the value of time increases. Apparently, if time is valued very highly, then offering a low-cost slower alternative has relatively less effect as it is not an interesting alternative for many passengers. Related, when LCR enters the market, Fig. 15 shows that a higher time value leads to larger Air profits, as Air fares can be kept at a higher level due to the superior service quality. Interestingly, though, when only FSR and air transport compete, a higher sensitivity towards time reduces air transport profit. Without LCR in the market, FSR can

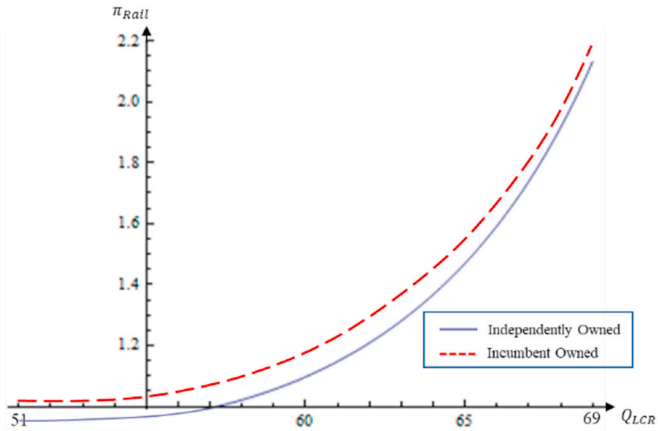

Fig. 9. Effect of LCR service quality.

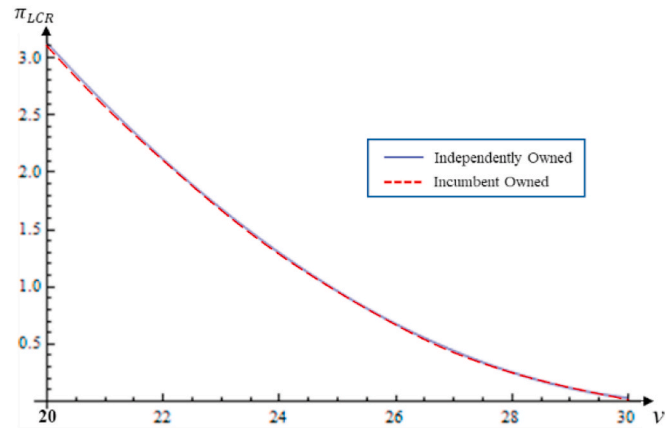

Fig. 12. Effect of value of time.

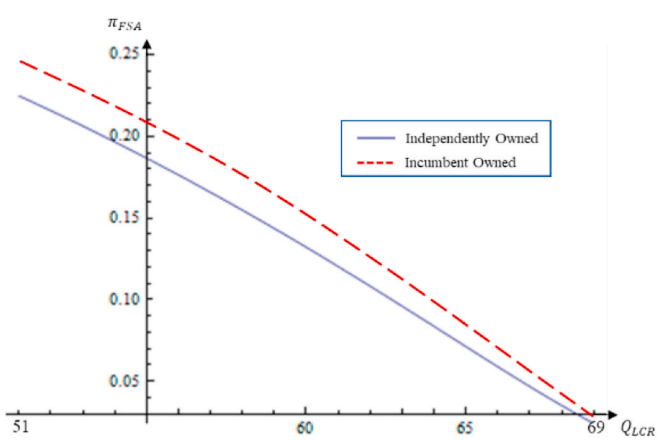

Fig. 10. Effect of LCR service quality. On combined rail profit on Air profit.

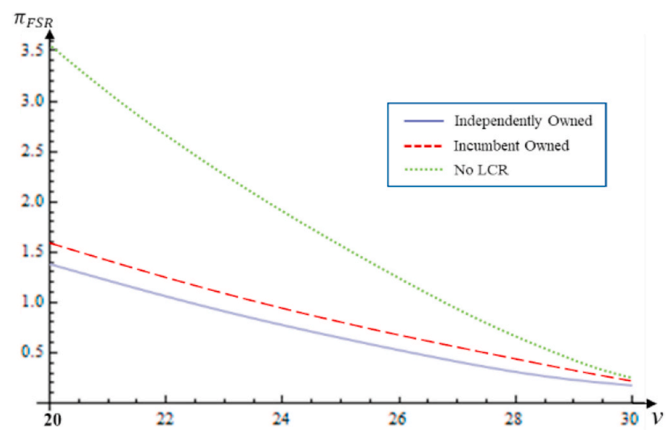

Fig. 13. Effect of value of time on LCR profit on FSR profit.

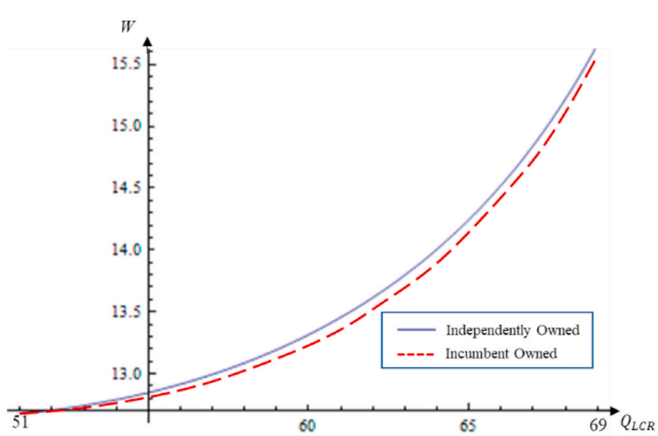

Fig. 11. Effect of LCR service quality on total social welfare.

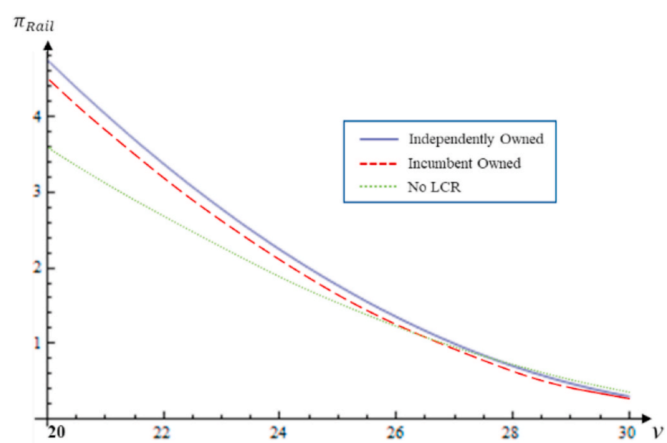

Fig. 14. Effect of value of time on.

concentrate fully on its competition with Air. When the time value increases, then FSR will become a less interesting alternative for passengers, and so it reacts by lowering the fare to stay competitive. The more fierce competition from FSR apparently leads to a lower Air profit, despite the higher time value.

Related, as shown in Fig. 16, the relative improvement in the welfare as a result of introducing the LCR decreases with the value of time. In terms of transport policy, this suggests that the improvement in welfare brought about by the introduction of LCR mainly comes from the induced trips of infrequent passengers. Thus, it is better to introduce LCR on routes where a large fraction of the passengers travel for leisure purposes for a better performance on social welfare.

5.3. *Effects air travel quality*

As discussed in the introductory section, for clarity and tractability we do not consider both FSA and LCA in this study, but rather focused on LCR and FSR vs. Air in general. However, by varying the service quality of Air travel, we can still obtain insight into the effects of the Air travel

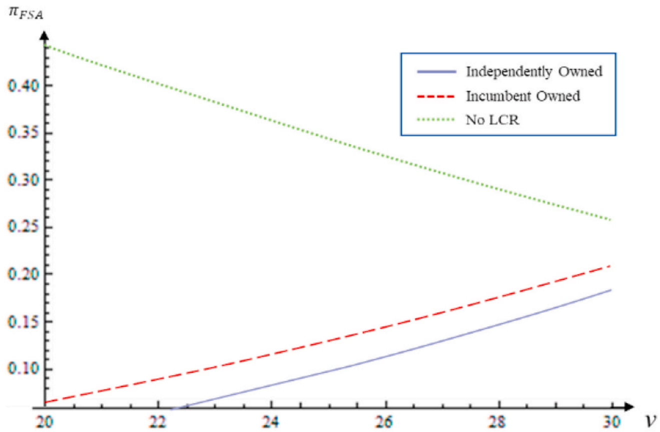

Fig. 15. Effect of value of time. Combined rail profit on Air profit.

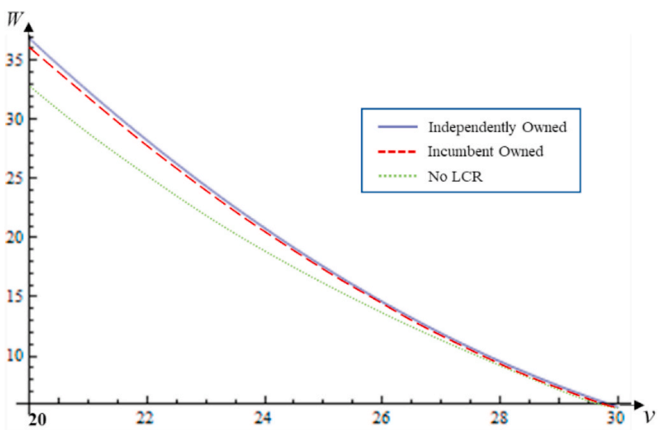

Fig. 16. Effect of value of time on total social welfare.

market on how LCR entry affects the transport market as a whole.

Figs. 17–20 show that introducing LCR, in either form, is more effective when the air travel quality is low. In particular, we see from Figs. 17 and 18 that the reduction in FSR profit from introducing LCR is rather stable, but that LCR is much more profitable when the air travel quality is lower. In other words, introducing LCR is a more viable alternative when facing (mainly) LCA rather than FSA competition. So, from a (rail) profit perspective, policy makers should stimulate the entrance of LCR on routes with mainly LCA operators in the Air transport market. A look at the welfare effects in Fig. 21 strengthens this find. For

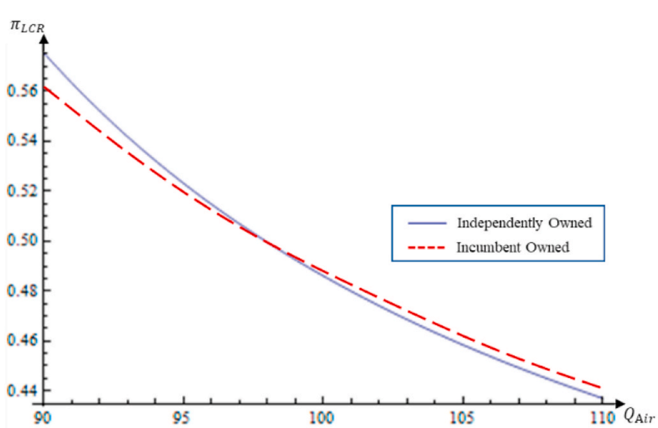

Fig. 17. Effect of Air service quality.

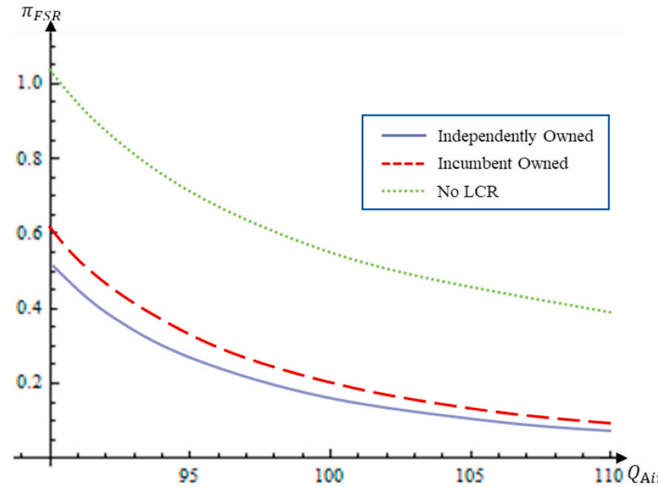

Fig. 18. Effect of Air service quality on LCR profit on FSR profit.

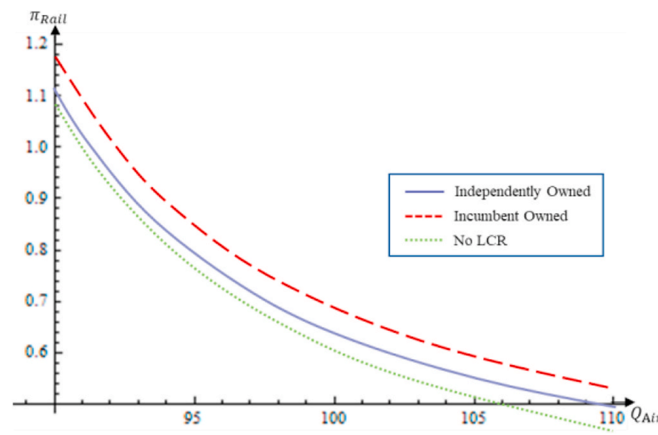

Fig. 19. Effect of Air service quality.

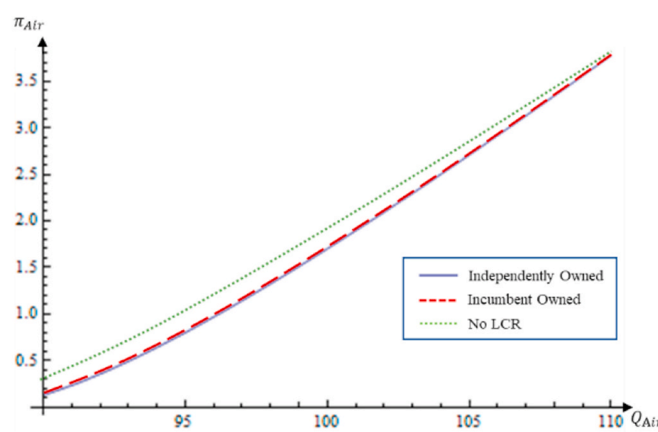

Fig. 20. Effect of Air service quality on combined rail profit on Air profit.

higher Air service quality increases, the increase in welfare of introducing LCR is reduced (see Fig. 19).

6. Conclusion

We studied the competitive advantages of introducing low-cost high-speed rail into the competition between high-speed rail and air transport. So far this had only been studied from a strategic perspective and

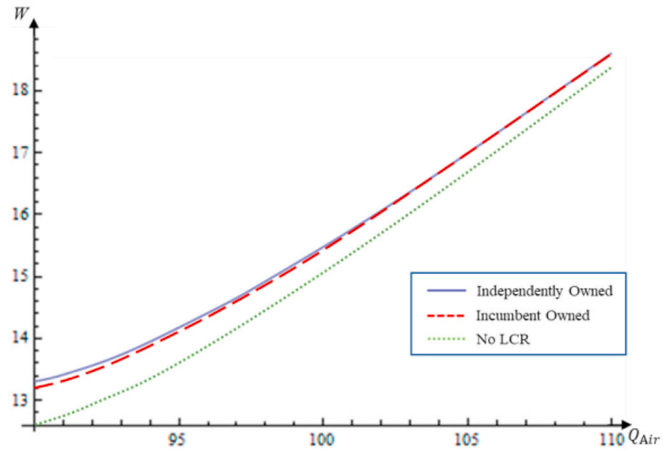

Fig. 21. Effect of Air service quality on total social welfare.

we presented the first analytical and numerical results of introducing LCR on fares, market shares, profits and social welfares, taking the Paris-Marseille route as a case.

In line with the undergoing liberalization of railway, we considered both an incumbent owned LCR operator (by the same company that operates FSR, as is the case for Ouigo) and an independently owned LCR operator as the new entrant. We analytically found that for both situations, introducing LCR leads to reduced FSR and Air fares and to reduced Air traffic. Moreover, the reduction in fares and Air traffic is increasing in passenger's value of time and travel time of LCR, while decreasing in the Air unit seat cost. Comparatively, we found that (i) all fares after introducing an incumbent owned LCR operator are higher than after introducing an independently owned LCR operator; (ii) compared to an independently owned LCR operator, the introduction of an incumbent owned LCR operator implies less LCR traffic, more FSR traffic, less rail traffic in total and more Air traffic; (iii) compared to an independently owned LCR operator, the introduction of an incumbent owned LCR operator leads to more FSR profit; (iv) compared to an independently owned LCR operator, the introduction of an incumbent owned LCR operator leads to a lower LCR consumer surplus.

Using publicly available sources, we collected the data from the French transport market for Paris-Marseille and then applied these to the model. We found that the introduction of LCR induces significant negative effects on incumbents, especially for an independently operated LCR. Specifically, if the LCR is independently operated, then its introduction decreases the FSR traffic by 20.0% and air transport by 38.9%. When jointly operated, the reductions are 14.3% and 33.3%, respectively. The introduction of LCR also leads to fare reductions. If the LCR operates independently, the FSR fare drops by 1.7% and the Air fare by 0.7%. When jointly operated, the reductions are 1.5% and 0.6%, respectively. Despite the fare reductions, FSR and Air still lose market share and so also face decreased profits. On the other hand, although FSR is negatively affected by the introduction of LCR, the combined traffic and profit for the railway industry as a whole increase. The increase in the traffic intensity is more significant, namely 37.1% when jointly operated and still 28.6% when independently operated. In addition, LCR induces around 30% new traffic when operated independently, and 27% when LCR is owned by the incumbent. The combined rail profit is also a considerable 8.3% higher if LCR and FSR are jointly operated, but only 1.8% otherwise. There is also an improvement in the welfare for the operators and passengers combined, namely 4.8% when LCR is incumbent owned and 5.6% when independently owned.

A further sensitivity study on the Paris-Marseille route showed that the there is a certain threshold service quality below which LCR is not profitable. Also, the LCR traffic as well as total rail traffic increase in the LCR's service quality, while the FSR traffic and Air traffic decrease. As for the passenger's value of time, our results showed that if time is valued more highly, offering a low-cost alternative is less effective. By observing the impacts of the Air service quality, it was found that both from a rail profit and welfare perspective, introducing LCR is much more effective when the Air service quality is low, i.e., when competing with (mainly) LCA operators in the air transport market.

The theoretical and methodological implications of this study are as follows. For a vertical differentiated model where the three types of transport modes (FSR, LCR, FSA) compete in an open market, we provided the first analytical and numerical results on the effects of LCR introduction on the optimal fares and corresponding traffic, profits and welfare in equilibrium. Moreover, our modelling process provides a method for operators from the railway and aviation industries to determine their optimal pricing policy and forecast their performances when a new LCR entrant is about to be introduced.

Operational and management insights are as follows. For the railway industry, the introduction of LCR can help to compete with air transport and LCAs in particular, as well as stimulate development in overall output of the railway industry and social welfare. However, the accompanying cost could be damaging to the incumbent FSR operator. An appropriate market positioning is the key to solve this. The new LCR entrant and policy makers should carefully consider how they compete with both FSR and air transport in terms of service quality and pricing.

Furthermore, when considering welfare besides helping the railway industry gain a competitive advantage, it is better to introduce LCR, as an alternative to FSR, on routes where a large fraction of the passengers who are sensitive to fares and travel for leisure purposes. This provides the largest welfare increase as well as rail profit increase. Note that the construction of high-speed rail lines requires large investments, these were not directly considered in this study, but they make it all the more important to ensure that LCR and rail as a whole can achieve a substantial operational profit. For instance, implementing LCR on e.g. the Lanzhou-Wulumuqi route in western China, with relatively low competition from FSA, can be used as a feasible and innovative business model to redeem those lines that have deficit and financing problems.

As to the trade-off between incumbent or independently owned LCR, the lower degree of liberalization of high-speed railway suggests that introducing jointly operated LCR to accommodate the incumbent may be an easier way forward at this stage for many countries, because it helps to regulate the newly entered LCR in the above aspects and also yields more profit for the railway industry. Full liberalization does increase the total welfare even further, and may be considered at a later stage.

For the aviation industry, the introduction of LCR is expected to have a substantial impact. Especially for LCA operators it presents a considerable threat. To a lesser extent this also applies to FSA operators, but for those it could also bring new opportunities - competition from LCR forces FSR to focus more on the low-end market, and FSA could opt to focus more on high-end customers. Therefore, the introduction of a new LCR entrant could trigger the reorganization of airline networks with fewer incumbent LCAs (to avoid competing with an incumbent owned LCR, which is government supported) and potentially new FSAs focusing in the high-end market.

Our research into the price competition between LCR, FSR and Air was of an exploratory nature and has a number of limitations and corresponding avenues for future research. First, we did not consider the government's role in providing subsidy programs to stimulate LCR and their effects on welfare. For instance, introducing competition in the profitable high-speed rail lines may induce more cross-subsidization to the non-profitable lines and thus decline the social welfare due to the cost imposed on rising public fund (Wu et al., 2014). Second, we did not consider capacity limitations on the railway infrastructure and airport slots, or related issues such as congestion and delays, or the financial consequences of different capacity requirements. Third, we did not consider situations where both low-cost and full-service air operators exist on a route. Fourth and related, we assumed that the Air option is viewed by the passengers as offering the highest quality, but this may not always be the case, especially in the case of a low-cost air provider. Fifth, we considered a single fare price and service quality per operator, where especially the full-service operators tend to offer multiple options in real life. Sixth, our numerical analysis considered a single case/route, namely Paris-Marseille. Other cases may of course lead to different results and, as in any case, model parameters are never exactly known but can only be estimated (although we did perform a sensitivity study for key model parameters. Seventh, we did not consider the wider context in which railway and airline companies operate. For instance, in Europe there has been an ongoing debate on how to connect all major cities using high-speed rail. Although there is general agreement amongst policy makers that this is important to reduce air travel, especially on international routed of, say, up to 700 km (Zhang et al., 2019), differing views on railway liberalization and social welfare have hampered progress.

CRediT authorship contribution statement

Yixiao Wang: Conceptualization, Methodology, Writing - original draft, Investigation, Software. **Luoyi Sun:** Conceptualization, Methodology, Writing - original draft, Investigation. **Ruud H. Teunter:** Conceptualization, Writing - original draft, Writing - review & editing, Supervision. **Jianhong Wu:** Project administration, Funding acquisition, Writing - review & editing, Supervision. **Guowei Hua:** Project administration, Funding acquisition, Supervision.

Acknowledgements

We thank the editor and two anonymous referees for their helpful comments on an earlier version of our paper. We also thank Prof. Anming Zhang from University of British Columbia for his helpful comments and support on this work. This work was supported by the Beijing Jiaotong University's Fund under grant number 2019JBM340, National Social Science Fund of China under grant number 2017ZDA084, National Natural Science Foundation of China under grant number 71831001 and China Scholarship Council.

Appendix A. Equilibrium results

A.1. Equilibrium results of LCR-FSR-Air competition with an incumbent owned operator.

By substituting (10)–(12) into (1) and differentiating it with respect to p_L, p_F and p_A, respectively, and considering the first-order conditions, we derive the optimal fares of the LCR, FSR and Air, respectively. It is easy to derive the results of the fares of the LCR, FSR and Air in equilibrium by combining the optimal fares of the LCR, FSR and Air, as follows.

Letting μ be $2Q_A(2Q_F - Q_L) - Q_F(Q_F + Q_L)$, the equilibrium results of the fares of LCR, FSR and air transport are, respectively, given by

$$p_L^{IC*} = \big(Q_L^2(3b - 2c_A - c_F - v(2T_A + T_F)) + Q_F Q_L(2c_A - 2b + c_F - 3c_L + 2Q_L + v(2T_A + T_F - T_L)) - Q_F^2(b + c_L + 2Q_L - vT_L) + 2Q_A\big(Q_F(2b + 2c_L + Q_L - 2vT_L) - Q_L(2b + Q_L - 2vT_L)\big)\big)/2\mu \tag{13}$$

$$p_F^{IC*} = \big(Q_A\big(Q_F^2 - Q_L(b + c_F - vT_F) - Q_F\big(Q_F^2 + Q_L(c_A - b + c_F + vT_A) + Q_F(b - c_A + c_L - Q_L - v(T_A + T_F - T_L))\big) + Q_F(b + 2c_F + c_L - Q_L - 2vT_F + vT_L)\big)\big)/\mu \tag{14}$$

$$p_A^{IC*} = \big(Q_A^2(4Q_F - 2Q_L) - Q_F(Q_L(2c_A - b + c_F + vT_F) + Q_F(b + c_L - 2Q_L - 2vT_A + vT_L)) + Q_A\big(Q_F(b + 4c_A + 2c_F + c_L + v(2T_F - 4T_A + T_L)) - 4Q_F^2 - Q_L(b + 2c_A + c_F - 2vT_A + vT_F)\big)\big)/2\mu \tag{15}$$

Therefore, by substituting (13)–(15) into (10)–(12), we derive the equilibrium traffic of the LCR, FSR and Air transport as follows:

$$q_L^{IC*} = (Q_L(b - c_F - vT_F) + Q_F(c_L - b + vT_L)) / 2Q_L(Q_L - Q_F) \tag{16}$$

$$q_F^{IC*} = (Q_A - Q_L)\big(Q_F\big(-Q_F^2 + Q_L(b - c_A - vT_A) + Q_F(c_A - b + c_F - c_L + Q_L + v(T_A + T_F - T_L))\big) + Q_A\big(Q_F^2 + Q_L(c_F - b + vT_F) + Q_F(b - 2c_F + c_L - Q_L - 2vT_F + vT_L)\big)\big)/(Q_A - Q_F)(Q_F - Q_L)\mu \tag{17}$$

$$q_A^{IC*} = Q_A^2(4Q_F - 2Q_L) - Q_F(Q_L(c_F - b + vT_F) + Q_F(b - 2c_A + c_L - 2Q_L - 2vT_A + vT_L)) + Q_A\big(Q_F(b - 4c_A + 2c_F + c_L + v(2T_F - 4T_A + T_L)) - 4Q_F^2 - Q_L(b - 2c_A + c_F - 2vT_A + vT_F)\big)/2(Q_A - Q_F)\mu \tag{18}$$

By substituting (13)–(18) into (1), we further derive the equilibrium profit of the LCR, FSR and Air transport as follows:

$$\pi_L^{IC*} = (Q_L(b - c_F - vT_F) + Q_F(c_L - b + vT_L))(Q_L(2c_A - 3b + c_F + 2vT_A + vT_F) + 2Q_A(2b - 2c_L + Q_L - 2vT_L) + Q_F(c_L - b - 2Q_L + vT_L))/(-4Q_L\mu)$$

$$\pi_F^{IC*} = \big(Q_A - Q_L\big)\big(Q_F\big(-Q_F^2 + Q_L\big(b - c_A - vT_A\big) + Q_F\big(c_A - b + c_F - c_L + Q_L + v(T_A + T_F - T_L)\big)\big) + Q_A\big(Q_F^2 + Q_L\big(-b + c_F + vT_F\big) + Q_F\big(b - 2c_F + c_L - Q_L - 2vT_F + vT_L\big)\big)\big)^2 / \big(Q_A - Q_F\big)\big(Q_F - Q_L\big)\mu^2$$

$$\pi_A^{IC*} = \big(Q_A^2\big(4Q_F - 2Q_L\big) - Q_F\big(Q_L\big(-b + c_F + vT_F\big) + Q_F\big(b - 2c_A + c_L - 2Q_L - 2vT_A + vT_L\big)\big) + Q_A\big(-4Q_F^2 - Q_L\big(b - 2c_A + c_F - 2vT_A + vT_F\big) + Q_F\big(b - 4c_A + 2c_F + c_L - 4vT_A + 2vT_F + vT_L\big)\big)\big)^2 / 4\big(Q_A - Q_F\big)\mu^2$$

A.2. Equilibrium results of LCR-FSR-Air competition with an independently owned operator.

The objective function for an independently owned LCR is:

$$\pi_L + \pi_F = q_L(p_L - c_L) + q_F(p_F - c_F) \tag{19}$$

By substituting (10)–(11) into (19) and substituting (12) into (1), then differentiating (19) with respect to p_L and differentiating (1) with respect to p_F and p_A, respectively and considering the first-order conditions, we derive the optimal fares of the LCR, FSR and Air, respectively. It is easy to derive the results of the fares of the LCR, FSR and Air in equilibrium by combining the optimal fares of the LCR, FSR and Air, as follows.

For the case that an independent LCR operator is introduced, letting σ be $2Q_A(4Q_F - Q_L) - 2Q_F(Q_F + 2Q_L)$, the equilibrium results of the fares of LCR, FSR and Air are, respectively, given by:

$$p_L^{ID*} = \left(Q_L^2(3b - c_A - 2c_F - v(T_A + 2T_F)) - Q_F^2(b + c_L + Q_L - vT_L) + Q_FQ_L(c_A - 2b - 3c_L + Q_L + v(T_A + T_L)) + Q_A(Q_F(4b + 4c_L + Q_L - 4vT_L) + Q_L(2c_F - 4b - Q_L + 2v(T_F + T_L))))\right)/\sigma \tag{20}$$

$$p_F^{ID*} = Q_A\left(Q_F^2 + Q_L(vT_F - b) + Q_F(b + 2c_F + c_L - Q_L - 2vT_F + vT_L)\right)\big)/\sigma + 2\big(- Q_F\left(Q_F^2 + Q_L\left(c_A - b + 2c_F + vT_A\right) + Q_F(b - c_A + c_L - Q_L - v(T_A + T_F - T_L)\right)\big) \tag{21}$$

$$p_A^{ID*} = \left(Q_A^2(4Q_F - Q_L) - Q_F(- Q_L(b - 3c_A - 2c_F + vT_A - 2vT_F) + Q_F(b + c_L - 3Q_L - 2vT_A + vT_L)) + Q_A\left(- 4Q_F^2 - Q_L(b + c_A - vT_A) + Q_F(b + 4c_A + 2c_F + c_L - 2Q_L + v(- 4T_A + 2T_F + T_L))\right)\right)/\sigma \tag{22}$$

Therefore, by substituting (20)–(22) into (10)–(12), we derive the traffic in equilibrium of the LCR, FSR and Air as follows:

$$q_L^{ID*} = \left(Q_F\left(Q_L^2(- 3b + c_A + 2c_F + vT_A + 2vT_F) + Q_F^2(b - c_L + Q_L - vT_L) - Q_FQ_L(- 2b + c_A + c_L + Q_L + v(T_A + T_L)) + Q_A(- Q_F(4b - 4c_L + Q_L - 4vT_L) + Q_L(4b - 2c_F - 2c_L + Q_L - 2v(T_F + T_L))))\right)\right) / ((Q_F - Q_L)Q_L\sigma) \tag{23}$$

$$q_F^{ID*} = \left((Q_A - Q_L)\left(Q_F\left(- Q_F^2 + Q_L(b - c_A - vT_A) + Q_F(- b + c_A + c_F - c_L + Q_L + v(T_A + T_F - T_L))\right) + Q_A\left(Q_F^2 + Q_L(- b + c_F + vT_F) + Q_F(b - 2c_F + c_L - Q_L - 2vT_F + vT_L)\right)\right)\right) / ((Q_A - Q_F)(Q_F - Q_L)(Q_A(4Q_F - Q_L) - Q_F(Q_F + 2Q_L))) \tag{24}$$

$$q_A^{ID*} = \left(Q_A^2(4Q_F - Q_L) + Q_F(Q_L(b + c_A - 2c_F + vT_A - 2vT_F) - Q_F(b - 2c_A + c_L - 3Q_L - 2vT_A + vT_L)) + Q_A\left(- 4Q_F^2 + Q_L(- b + c_A + vT_A) + Q_F(b - 4c_A + 2c_F + c_L - 2Q_L + v(- 4T_A + 2T_F + T_L))\right)\right) / ((Q_A - Q_F)\sigma) \tag{25}$$

By substituting (20)–(25) into (1), we further derive the equilibrium profit of the LCR, FSR and Air as follows:

$$\pi_L^{ID*} = \Big(Q_F\big(Q_L^2\left(- 3b + c_A + 2c_F + vT_A + 2vT_F\right) + Q_F^2\left(b - c_L + Q_L - vT_L\right)$$
$$- Q_FQ_L(- 2b + c_A + c_L + Q_L + v(T_A + T_L)) + Q_A(- Q_F(4b - 4c_L + Q_L - 4vT_L) +$$
$$Q_L\left(4b - 2c_F - 2c_L + Q_L - 2v(T_F + T_L)\right)))\big)^2\Big) / \left((Q_F - Q_L)Q_L\sigma^2\right)$$

$$\pi_F^{ID*} = 4\Big((Q_A - Q_L)\left(Q_F\left(- Q_F^2 + Q_L\left(b - c_A - vT_A\right) + Q_F\left(- b + c_A + c_F - c_L + Q_L + \right.\right.\right.$$
$$v(T_A + T_F - T_L))\big)\big) + Q_A\left(Q_F^2 + Q_L\left(- b + c_F + vT_F\right) + Q_F\left(b - 2c_F + c_L - Q_L - 2vT_F\right.\right.$$
$$+vT_L)))^2\Big) / \left((Q_A - Q_F)\left(Q_F - Q_L\right)\sigma^2\right)$$

$$\pi_A^{ID*} = \Big(Q_A^2\left(4Q_F - Q_L\right) + Q_F\left(Q_L\left(b + c_A - 2c_F + vT_A - 2vT_F\right) - Q_F\left(b - 2c_A + c_L\right.\right.$$
$$- 3Q_L - 2vT_A + vT_L\big)\big) + Q_A\left(- 4Q_F^2 + Q_L\left(- b + c_A + vT_A\right) + Q_F\left(b - 4c_A + 2c_F + \right.\right.$$
$$c_L - 2Q_L + v(- 4T_A + 2T_F + T_L))))^2 / \left((Q_A - Q_F)\sigma^2\right)$$

Appendix B. Proofs of Propositions

Proof of Proposition 1.

(1). We compare the fares of both air transport and the incumbent FSR operator after introducing an incumbent owned LCR operator.

$$p_F^{IC*} - p_F^{N*} = \frac{(Q_A - Q_F)Q_F(Q_L(3b - 2c_A - c_F - 2vT_A - vT_F) - 2Q_A(2b - 2c_L + Q_L - 2vT_L) + Q_F(b - c_L + 2Q_L - vT_L))}{(4Q_A - Q_F)\mu}$$

i. Obviously, $(4Q_A - Q_F)\mu > 0$ and $(Q_A - Q_F)Q_F > 0$ as $Q_A > Q_F > Q_L > 0$.
ii. Since $q_L^{IC*} > 0$, we have $Q_L(b - c_F - vT_F) + Q_F(c_L - b + vT_L) < 0$ through (15). Because $\pi_L^{IC*} = (Q_L(b - c_F - vT_F) + Q_F(c_L - b + vT_L))(Q_L(2c_A - 3b + c_F + 2vT_A + vT_F) + 2Q_A(2b - 2c_L + Q_L - 2vT_L) + Q_F(c_L - b - 2Q_L + vT_L))/(- 4Q_L\mu) > 0$, $- 4Q_L\mu < 0$, $Q_L(b - c_F - vT_F) + Q_F(c_L - b + vT_L) < 0$, we have

$$Q_L(2c_A - 3b + c_F + 2vT_A + vT_F) + 2Q_A(2b - 2c_L + Q_L - 2vT_L) + Q_F(c_L - b - 2Q_L + vT_L) > 0. \tag{26}$$

Thus, we have $p_F^{IC*} - p_F^{N*} < 0$ by considering i and (26).

Differentiating $p_F^{IC*} - p_F^{N*}$ with respect to v, we have

$$\frac{\partial\left(p_F^{IC*}-p_F^{N*}\right)}{\partial v}=\frac{(Q_A-Q_F)Q_F((4Q_A-Q_F)T_L-Q_L(2T_A+T_F))}{(4Q_A-Q_F)(Q_A(4Q_F-2Q_L)-Q_F(Q_F+Q_L))}$$

Since $Q_A > Q_F > Q_L$, $T_L > T_A$ and $T_F > T_A$ it is straightforward to get

$$\frac{\partial\left(p_F^{IC*}-p_F^{N*}\right)}{\partial v}>0$$

Similarly, differentiating $p_F^{IC*}-p_F^{N*}$ with respect to T_L, we have

$$\frac{\partial\left(p_F^{IC*}-p_F^{N*}\right)}{\partial T_L}=\frac{v(Q_A-Q_F)Q_F}{Q_A(4Q_F-2Q_L)-Q_F(Q_F+Q_L)}>0$$

Similarly, differentiating $p_F^{IC*}-p_F^{N*}$ with respect to c_A, we have

$$\frac{\partial\left(p_F^{IC*}-p_F^{N*}\right)}{\partial c_A}=-\frac{2Q_F(Q_A-Q_F)Q_L}{(4Q_A-Q_F)(Q_A(4Q_F-2Q_L)-Q_F(Q_F+Q_L))}<0$$

For air transport we have

$$p_A^{IC*}-p_A^{N*}=\frac{(Q_A-Q_F)Q_F(Q_L(3b-2c_A-c_F-2vT_A-vT_F)-2Q_A(2b-2c_L+Q_L-2vT_L)+Q_F(b-c_L+2Q_L-vT_L))}{2(4Q_A-Q_F)\mu}<0$$

Which is the same as $p_F^{IC*}-p_F^{N*}<0$. Thus, we have

$$\frac{\partial\left(p_A^{IC*}-p_A^{N*}\right)}{\partial v}>0$$

Similarly, differentiating $p_A^{IC*}-p_A^{N*}$ with respect to T_L, we have

$$\frac{\partial\left(p_A^{IC*}-p_A^{N*}\right)}{\partial T_L}=\frac{v(Q_A-Q_F)Q_F}{2Q_A(4Q_F-2Q_L)-2Q_F(Q_F+Q_L)}>0$$

Similarly, differentiating $p_A^{IC*}-p_A^{N*}$ with respect to c_A, we have

$$\frac{\partial\left(p_A^{IC*}-p_A^{N*}\right)}{\partial c_A}=-\frac{Q_F(Q_A-Q_F)Q_L}{(4Q_A-Q_F)(Q_A(4Q_F-2Q_L)-Q_F(Q_F+Q_L))}<0$$

(2). We compare the fares of both air transport and incumbent FSR operator after introducing an independently owned LCR operator.

For FSR we have:

$$p_F^{ID*}-p_F^{N*}=\left(-2\left(Q_A-Q_F\right)\left(Q_A\left(2Q_L\left(b-c_F-vT_F\right)+Q_F\left(4b-4c_L+3Q_L\right.\right.\right.\right.$$
$$\left.-4vT_L\right)))+Q_F(Q_L(3c_A-5b+2c_F+3vT_A+2vT_F)+Q_F(c_L-b-3Q_L+vT_L))))$$
$$/(4Q_A-Q_F)\sigma$$

i. It is obvious $Q_A-Q_F>0$ and $(4Q_A-Q_F)\sigma>0$ as $Q_A>Q_F>Q_L>0$.
ii. To ensure all the three operators compete each other, the passenger who is indifferent in choosing between air transport and independently owned LCR has positive utility (notice that this passenger will choose FSR in reality as it lets him gain more utility), which yields

$$b-p_L^{ID*}-vT_L+\frac{Q_L\left(p_A^{ID*}-p_L^{ID*}+vT_A-vT_L\right)}{Q_A-Q_L}=(Q_A(2Q_L(b-c_H-vT_H)+Q_H(4b-4c_L+3Q_L-4vT_L))+Q_H(Q_L(3c_A-5b+2c_H+3vT_A+2vT_H)$$
$$+Q_H(c_L-b-3Q_L+vT_L)))\Big/\sigma>0$$

Because $\sigma>0$, we have

$$2Q_L(b-c_H-vT_H)+Q_H(4b-4c_L+3Q_L-4vT_L))+Q_H(Q_L(-5b+3c_A+2c_H+3vT_A+2vT_H)+Q_H(-b+c_L-3Q_L+vT_L)>0 \quad (27)$$

Thus, we have $p_F^{ID*}-p_F^{N*}<0$ by considering i. and (27).
Differentiating $p_F^{ID*}-p_F^{N*}$ with respect to v, we have

$$\frac{\partial\left(p_F^{ID*}-p_F^{N*}\right)}{\partial v}=\frac{2(Q_A-Q_F)(Q_L(Q_F(4Q_A-Q_F)T_L-3Q_FT_A+2(Q_A-Q_F)T_F))}{(4Q_A-Q_F)((4Q_F-Q_L)(2Q_A)-2Q_F(Q_F+2Q_L))}>0$$

Since $Q_A > Q_F > Q_L$, $T_L > T_A$ and $T_F > T_A$ it is straightforward to get

$$\frac{\partial\left(p_F^{ID*}-p_F^{N*}\right)}{\partial v}>0$$

Similarly, differentiating $p_F^{ID*} - p_F^{N*}$ with respect to T_L, we have

$$\frac{\partial\left(p_F^{ID*} - p_F^{N*}\right)}{\partial T_L} = \frac{2vQ_F(Q_A - Q_F)}{(4Q_F - Q_L)(2Q_A) - 2Q_F(Q_F + 2Q_L)} > 0$$

Similarly, differentiating $p_F^{ID*} - p_F^{N*}$ with respect to c_A, we have

$$\frac{\partial\left(p_F^{ID*} - p_F^{N*}\right)}{\partial c_A} = -\frac{6(Q_A - Q_F)Q_F Q_L}{(4Q_A - Q_F)((4Q_F - Q_L)(2Q_A) - 2Q_F(Q_F + 2Q_L))} < 0$$

For air transport we have:

$$p_A^{ID*} - p_A^{N*} = \left(-\left(Q_A - Q_F\right)\left(Q_A\left(2Q_L\left(b - c_F - vT_F\right) + Q_F\left(4b - 4c_L + 3Q_L - 4vT_L\right)\right) + Q_F\left(Q_L(3c_A - 5b + 2c_F + 3vT_A + 2vT_F) + Q_F(c_L - b - 3Q_L + vT_L)\right)\right)\right) \Big/$$

$(4Q_A - Q_F)\sigma < 0$, which is the same as $p_F^{ID*} - p_F^{N*} < 0$. Thus, we have

$$\frac{\partial\left(p_A^{ID*} - p_A^{N*}\right)}{\partial v} > 0$$

Similarly, differentiating $p_A^{ID*} - p_A^{N*}$ with respect to T_L, we have

$$\frac{\partial\left(p_A^{ID*} - p_A^{N*}\right)}{\partial T_L} = \frac{vQ_F(Q_A - Q_F)}{(4Q_F - Q_L)(2Q_A) - 2Q_F(Q_F + 2Q_L)} > 0$$

Similarly, differentiating $p_A^{ID*} - p_A^{N*}$ with respect to c_A, we have

$$\frac{\partial\left(p_A^{ID*} - p_A^{N*}\right)}{\partial c_A} = -\frac{3(Q_A - Q_F)Q_F Q_L}{(4Q_A - Q_F)((4Q_F - Q_L)(2Q_A) - 2Q_F(Q_F + 2Q_L))} < 0$$

Proof of Proposition 2.

(1) We compare the passenger traffic of air transport after introducing an incumbent owned LCR operator with the duopoly case, which gives

$$q_A^{IC*} - q_A^{N*} = -\frac{Q_F(Q_L(2c_A - 3b + c_F + 2vT_A + vT_F) + 2Q_A(2b - 2c_L + Q_L - 2vT_L) + Q_F(c_L - b - 2Q_L + vT_L))}{2\mu(4Q_A - Q_F)}$$

Since $Q_F > 0$ and $2\mu(4Q_A - Q_F) > 0$ as $Q_A > Q_F > Q_L > 0$, (24) is negative, it is obvious that $q_A^{IC*} - q_A^{N*} < 0$.
Differentiating $q_A^{IC*} - q_A^{N*}$ with respect to v we have

$$\frac{\partial\left(q_A^{IC*} - q_A^{N*}\right)}{\partial v} = \frac{Q_F((4Q_A + Q_F)T_L - Q_L(2T_A + T_F))}{2(4Q_A - Q_F)(Q_A(4Q_F - 2Q_L) - Q_F(Q_F + Q_L))}$$

Since $Q_A > Q_F > Q_L$, $T_L > T_A$ and $T_F > T_A$ it is straightforward to get

$$\frac{\partial\left(q_A^{IC*} - q_A^{N*}\right)}{\partial v} > 0$$

Similarly, differentiating $q_A^{IC*} - q_A^{N*}$ with respect to T_L, we have

$$\frac{\partial\left(q_A^{IC*} - q_A^{N*}\right)}{\partial T_L} = \frac{vQ_F}{Q_A(8Q_F - 4Q_L) - 2Q_F(Q_F + Q_L)} > 0$$

Similarly, differentiating $q_A^{IC*} - q_A^{N*}$ with respect to c_A, we have

$$\frac{\partial\left(q_A^{IC*} - q_A^{N*}\right)}{\partial c_A} = -\frac{Q_F Q_L}{(4Q_A - Q_F)(2Q_A(2Q_F - Q_L) - Q_F(Q_F + Q_L))} < 0$$

(2) We compare the passenger traffic of air transport after introducing an independently owned LCR operator with the duopoly case, which gives

$$q_A^{ID*} - q_A^{N*} = (Q_F(Q_L(5b - 3c_A - 2c_F - 3vT_A - 2vT_F) + Q_F(b - c_L + 3Q_L - vT_L)) + Q_A(2Q_L(-b + c_F + vT_F) + Q_F(-4b + 4c_L - 3Q_L + 4vT_L))) \Big/ (2(4Q_A - Q_F)(Q_A - Q_F)Q_L)$$

Since $2(4Q_A - Q_F)(Q_A - Q_F)Q_L > 0$ as $Q_A > Q_F > Q_L > 0$, (25) is positive, it is obvious $q_A^{ID*} - q_A^{N*} < 0$.
Differentiating $q_A^{ID*} - q_A^{N*}$ with respect to v we have

$$\frac{\partial\left(q_A^{ID*} - q_A^{N*}\right)}{\partial v} = \frac{Q_L(Q_F(4Q_A - Q_F)T_L - 3Q_F T_A + 2(Q_A - Q_F)T_F)}{2(Q_A - Q_F)(4Q_A - Q_F)Q_L}$$

Since $Q_A > Q_F > Q_L$, $T_L > T_A$ and $T_F > T_A$ it is straightforward to know

$$\frac{\partial\left(q_A^{ID*} - q_A^{N*}\right)}{\partial v} > 0$$

Similarly, differentiating $q_A^{ID*} - q_A^{N*}$ with respect to T_L, we have

$$\frac{\partial\left(q_A^{ID*}-q_A^{N*}\right)}{\partial T_L}=\frac{vQ_F}{2Q_L(Q_A-Q_F)}>0$$

And differentiating $q_A^{ID*}-q_A^{N*}$ with respect to c_A, we have

$$\frac{\partial\left(q_A^{ID*}-q_A^{N*}\right)}{\partial c_A}=-\frac{3Q_F}{2(4Q_A-Q_F)(Q_A-Q_F)}<0$$

Proof of Proposition 3.

Comparing the fares (LCR, FSR, Air) of introducing an incumbent owned LCR operator with of introducing an independently owned LCR operator, letting γ be $Q_L(Q_F(-Q_F^2+Q_L(b-c_A-vT_A)+Q_F(-b+c_A+c_F-c_L+Q_L+v(T_A+T_F-T_L)))+Q_A(Q_F^2+Q_L(-b+c_F+vT_F)+Q_F(b-2c_F+c_L-Q_L-2vT_F+vT_L)))$, we have.

For LCR: $p_L^{IC*}-p_L^{ID*}=\gamma(4Q_A-Q_F-3Q_L)/[2\mu^2+\mu(Q_A-Q_F)Q_L]$.

i. Obviously, $4Q_A-Q_F-3Q_L>0$ and $2\mu^2+\mu(Q_A-Q_F)Q_L$ as $Q_A>Q_F>Q_L>0$.
ii. Since $q_F^{IC*}>0$, it is easy to get $\gamma>0$.Thus, $p_L^{IC*}-p_L^{ID*}>0$. Similarly, it is easy to get:

For FSR: $p_F^{IC*}-p_F^{ID*}=\gamma(Q_A-Q_F)/[\mu^2+\mu(Q_A-Q_F)Q_L]\rangle 0$;

For Air: $p_A^{IC*}-p_A^{ID*}=\gamma(Q_A-Q_F)/[2\mu^2+\mu(Q_A-Q_F)Q_L]\rangle 0$.

Proof of Proposition 4.

(1) Comparing the passenger traffic of the incumbent owned LCR operator and the independently owned LCR operator, we have

$$q_L^{IC*}-q_L^{ID*}=\gamma/[-2Q_L(Q_F-Q_L)[\mu+(Q_A-Q_F)Q_L]]$$

Since $\gamma>0$, $Q_F-Q_L>0$, $\mu+(Q_A-Q_F)Q_L>0$, we have $q_L^{IC*}-q_L^{ID*}<0$

(2) By comparing q_F^{IC*} and q_F^{ID*} taking into consider $Q_A>Q_F$, we have

$$q_F^{IC*}-q_F^{ID*}=\gamma(Q_A-Q_L)\,/\,[(Q_F-Q_L)[\mu^2+\mu(Q_A-Q_F)Q_L]]$$

Since $\gamma>0$ $Q_A-Q_L>0$, $Q_F-Q_L>0$, $\mu^2+\mu(Q_A-Q_F)Q_L>0$, we have. $q_F^{IC*}-q_F^{ID*}>0$

(3) Comparing the passenger traffic of incumbent FSR operator of introducing an incumbent owned LCR operator with of introducing an independently owned LCR operator, we have

$$q_F^{IC*}+q_L^{IC*}-\left(q_F^{ID*}+q_L^{ID*}\right)=-\gamma\left(4Q_A-Q_F-2Q_L\right))\,/\,Q_L\left[2\mu^2+\mu\left(Q_A-Q_F\right)Q_L\right]$$

Since $\gamma>0$, $4Q_A-Q_F-2Q_L>0$, $Q_L[2\mu^2+\mu(Q_A-Q_F)Q_L]\rangle 0$, we have $q_F^{IC*}+q_L^{IC*}-(q_F^{ID*}+q_L^{ID*})<0$

(4) Comparing the passenger traffic of air transport of introducing an incumbent owned LCR operator with of introducing an independently owned LCR operator, we have

$$q_A^{IC*}-q_A^{ID*}=\gamma/\left[2\mu^2+\mu(Q_A-Q_F)Q_L\right]$$

Since $\gamma>0$, $2\mu^2+\mu(Q_A-Q_F)Q_L>0$, we have $q_A^{IC*}-q_A^{ID*}>0$.

Proof of proposition 5.

Since $p_A^{IC*}-p_A^{ID*}>0$, $q_A^{IC*}-q_A^{ID*}>0$, it is easy to have $\pi_A^{IC*}-\pi_A^{ID*}>0$.

Proof of Proposition 6.

By comparing CS_L^{IC*} and CS_L^{ID*}, we have $CS_L^{IC*}-CS_L^{ID*}=\frac{1}{2}(b-p_L^{IC*}-vT_L+(Q_L(p_H^{IC*}-p_L^{IC*}+vT_H-vT_L))/(Q_H-Q_L))q_L^{IC*}-\frac{1}{2}(b-p_L^{ID*}-vT_L+(Q_L(p_H^{ID*}-p_L^{ID*}+vT_H-vT_L))/(Q_H-Q_L))q_L^{ID*}$

As $(b-p_L^{IC*}-vT_L+(Q_L(p_H^{IC*}-p_L^{IC*}+vT_H-vT_L))/(Q_H-Q_L))-(b-p_L^{ID*}-vT_L+(Q_L(p_H^{ID*}-p_L^{ID*}+vT_H-vT_L))/(Q_H-Q_L))=(Q_L(Q_H(-Q_H^2+Q_L(b-c_A-vT_A)+Q_H(-b+c_A+c_H-c_L+Q_L+v(T_A+T_H-T_L)))+Q_A(Q_H^2+Q_L(-b+c_H+vT_H)+Q_H(b-2c_H+c_L-Q_L-2vT_H+vT_L))))/(2(Q_H-Q_L)(Q_A(-4Q_H+Q_L)+Q_H(Q_H+2Q_L)))$.,

It is easy to know this term is negative if $q_H^{ID*}=((Q_A-Q_L)(Q_H(-Q_H^2+Q_L(b-c_A-vT_A)+Q_H(-b+c_A+c_H-c_L+Q_L+v(T_A+T_H-T_L)))+Q_A(Q_H^2+Q_L(-b+c_H+vT_H)+Q_H(b-2c_H+c_L-Q_L-2vT_H+vT_L))))/((Q_A-Q_H)(Q_H-Q_L)(Q_A(4Q_H-Q_L)-Q_H(Q_H+2Q_L)))>0$. Since $q_L^{IC*}<q_L^{ID*}$, we have

$$CS_L^{IC*}-CS_L^{ID*}<0$$

Appendix C. Sources of parameter evaluations

Our numerical study is based on the Paris-Marseille market, where LCR-LSR-Air indeed compete. Note that for Air, there is only FSA but no LCA in the market so far. In this appendix, we explain how the parameter estimates, as listed in Table 4 and Table 5 were derived from the different sources, including research papers, statistics from official websites and experiences from professionals in industry.

First, we focus on the passenger's side.

(1) **Total travel time:** We split the total travel time for passengers for each mode into: access time, in terminal/station time, take-off time for aviation, on-board time, landing time for aviation and egress time.

Access time (egress time): We captured the time spent from the city centre to airport/station (airport/station to city centre) by using the real time navigation of Google in terms of self-driving mode in a working day afternoon on November 18th, 2019. The specific route we referred is Hotel de Ville- Charles de Gaulles Airport for Paris and Hotel de Ville- Marseille Provence Airport for Marseille. We obtained the in terminal/station time and take-off/landing time for aviation directly from Adler et al. (2010).

On-board time of Air, FSR and LCR: We directly gained them from the official website of Air France (https://www.airfrance.co.uk/), inOui (https://en.oui.sncf/en/tgv-inoui) and Ouigo (https://ventes.ouigo.com/).

Table 4
Components of Total travel time.

Components	Air	FSR	LCR
Access time (h)	0.78	0.20	0.20
In terminal time (h)	1.00	0.50	0.50
Take-off time (h)	0.25	–	–
On-board time (h)	1.25	3.35	3.35
Landing time (h)	0.25	–	–
Egress time (h)	0.50	0.27	0.27
T_i(Total travel time (h))	4.03	4.32	4.32

(2) **Passenger value of time:** We estimated this term by using average income per hour in France as a proxy. The average income (40,220 euros) and working hours (1520 h) per person in 2018 in France is gained from the OECD official website (https://data.oecd.org/earnwage/average-wages.htm; https://data.oecd.org/emp/hours-worked.htm). Thus, we derived the average income per hour in France, which is 26.46 euros/h.
(3) **Benefit gained through trip:** We somewhat arbitrarily set this value after consultation with travellers and professionals from the railway, aviation and tourism industry.

Next, we turn to the operators' side.

(4) **Unit cost per seat:** Similar to D'Alfonso et al. (2016), we first gained the cost per ASK (available seat per kilometre) reported by IATA (2006), which is 10.69 Eurocents/ASK. The Air length of Paris to Marseille is 660 km in total. Thus, the unit cost per seat of air transport is 84.74 Euros.

As for the FSR, we used the estimation of the FSR total operating cost, which is 0.094 euros/ASK from Givoni (2003). The rail length of Paris to Marseille is 750 km in total. Thus, the unit cost per seat of FSR is 70.50 Euros.

Unfortunately, we failed of find an accurate number noting down the unit cost per seat of LCR from public sources. Since Ouigo shares the same features in terms of labour, rolling stock, railway network, stations and booking systems etc. with inOui from SNCF, we assumed the difference of unit cost between LCR and FSR majorly owns to the increased seat density which is achieved by cancelling the first-class, bar and luggage rack out of traditional carriage of FSR. Thus, the unit cost per seat of LCR was estimated as 57.32 Euros since Ouigo has 23% more seats than inOui (Delaplace and Dobruszkes, 2015).

(5) **Service quality:** We split this term into the basic services, on-board services and services from cabin crew, which are listed in Table 5.

Table 5
Components of Service quality.

Components	Air	FSR	LCR
Basic services	25	20	20
On-board services	25	45	–
Services from cabin crew	40	15	40
Q_i(Service quality (Euro))	90.00	80.00	60.00

Basic services: This term refers to the services maintained through booking system and in terminal/station services (security check, shopping, ticket inspection etc.). As it was hard to evaluate the exact value, we arbitrarily set this term as 25 Euros for the air transport and 20 Euros for the FSR and LCR.

On-board services: For the air transport, we assumed the on-board services consist one check-in baggage which is worth 15 Euros according to the Air France baggage regulation, as well as the drink and snack which is worth 10 Euros. For the FSR, we assumed the on-board services consist one check-in baggage which is worth 10 Euros (Average cost for the first check-in luggage of Air France and the large suitcase for OUIGO), socket which is worth 10 Euros, Wi-Fi which is worth 15 Euros and bar which is worth 10 Euros. For LCR, we assumed there is no on-board services posted to the basic ticket price.

Services from cabin crew: We assumed that this term is related to the labour investment of each operator and one cabin crew can serve 50 persons in same time, since one cabin crew must be added for each additional 50 seats for an aircraft, according to worldwide regulatory experiences in passenger aviation.

For air transport, assuming the number of cabin crew is 5 for the A321 aircraft (one of most frequently used aircraft in Paris-Marseille) which has 185 seats. The total labour cost is $5*1.25*26.46 \approx 165.37$ Euros considering on-board time and average time value. Thus, the services from the cabin crew is worth approximately 40 Euros per person where 4 groups in total needed to be served.

For FSR, according to the lay out described by Delaplace and Dobruszkes (2015), assuming the number of the cabin crew is 2 for a 510-seat train.

The total labour cost is $2*3.35*26.46 \approx 177.28$ Euros. Thus, the services from the cabin crew is worth approximately 15 Euros per person where 11 groups in total needed to be served.

For LCR, according to the lay out described by Delaplace and Dobruszkes (2015), assuming the number of the cabin crew is 6 for a 634-seat train. The total labour cost is $6*3.35*26.46 \approx 531.84$ Euros. Thus, the services from the cabin crew is worth approximately 40 euros per person where 13 groups in total needed to be served.

References

Abda, M.B., Belobaba, P.P., Swelbar, W.S., 2012. Impacts of LCC growth on domestic traffic and fares at largest US airports. J. Air Transport. Manag. 18 (1), 21–25.
Adler, N., Pels, E., Nash, C., 2010. High-speed rail and air transport competition: game engineering as tool for cost-benefit analysis. Transp. Res. Part B Methodol. 44 (7), 812–833.
Albalate, D., Bel, G., 2012. High-speed rail: lessons for policy makers from experiences abroad. Publ. Adm. Rev. 72 (3), 336–349.
Albalate, D., Bel, G., Fageda, X., 2015. Competition and cooperation between high-speedrail and air transportation services in Europe. J. Transport Geogr. 42 (Suppl. C), 166–174.
Alderighi, M., Cento, A., Nijkamp, P., Rietveld, P., 2012. Competition in the European aviation market: the entry of low-cost airlines. J. Transport Geogr. 24, 223–233.
Asahi, R., Murakami, H., 2017. Effects of Southwest Airlines' entry and airport dominance. J. Air Transport. Manag. 64, 86–90.
Behrens, C., Pels, E., 2012. Intermodal competition in the London-Paris passenger market: high-speed rail and air transport. J. Urban Econ. 71 (3), 278–288.
Bilotkach, V., Fageda, X., Flores-Fillol, R., 2010. Scheduled service versus personal transportation: the role of distance. Reg. Sci. Urban Econ. 40 (1), 60–72.
Bukovac, S., Douglas, I., 2019. The potential impact of High Speed Rail development on Australian aviation. J. Urban Econ. 78, 164–174.
Chiambaretto, P., Fernandez, A.S., 2014. Transferring low-cost marketing practices from air to rail services: the ouigo case. Res. Transp. Bus. Manag. 10, 40–44.
Clewlow, R.R., Sussman, J.M., Balakrishnan, H., 2014. The impact of high-speed rail and low-cost carriers on European air passenger traffic. Transport Pol. 33, 136–143.
Daraban, B., Fournier, G.M., 2008. Incumbent responses to low-cost airline entry and exit: a spatial autoregressive panel data analysis. Res. Transport. Econ. 24 (1), 15–24.
Davies Gleave, Steer, 2006. Air and Rail Competition and Complementarity. Final Report for DG TR. Commission for the European Communities.
Delaplace, M., Dobruszkes, F., 2015. From low-cost airlines to low-cost high-speed rail? The French case. Transport Pol. 38, 73–85.
Detzen, D., Jain, P.K., Likitapiwat, T., Rubin, R.M., 2012. The impact of low cost airline entry on competition, network expansion and stock valuations. J. Air Transport. Manag. 18 (1), 59–63.
D'Alfonso, T., Jiang, C., Bracaglia, V., 2015. Would competition between air transport and high-speed rail benefit environment and social welfare? Transp. Res. Part B Methodol. 74, 118–137.
D'Alfonso, T., Jiang, C., Bracaglia, V., 2016. Air transport and high-speed rail competition: environmental implications and mitigation strategies. Transport. Res. Pol. Pract. 92, 261–276.
Friebel, G., Niffka, M., 2009. The functioning of inter-modal competition in the transportation market: evidence from the entry of low-cost airlines in Germany. Rev. Netw. Econ. 8 (2), 189–211.
Fu, X., Lei, Z., Wang, K., Yan, J., 2015. Low cost carrier competition and route entry in an emerging but regulated aviation market-The case of China. Transport. Res. A-Pol. 79, 3–16.
Givoni, M., 2003. Evaluating aircraft and HST operating costs. In: Cederlund, K., Silbersky, U. (Eds.), Nectar Cluster 1 Workshop. New Trends in European Air Traffic. Lund University, Lund, Sweden.
Gonzalezsavignat, M., Wu, H., Paul, V., 2004. Competition in air transport. the case of the high speed train. J. Transport Econ. Pol. 38 (1), 77–107.
Graf, L., 2005. Incompatibilities of the low-cost and network carrier business models within the same airline grouping. J. Air Transport. Manag. 11 (5), 313–327.
Hazledine, T., 2011. Legacy carriers fight back: pricing and product differentiation in modern airline marketing. J. Air Transport. Manag. 17 (2), 130–135.
Homsombat, W., Lei, Z., Fu, X., 2014. Competitive effects of the airlines-within-airlines strategy - pricing and route entry patterns. Transport. Res E-Log. 63, 1–16.
Hu, Q., Zhang, A., Zhang, Y., 2019. Why are regional jets less used in emerging economies? A real options valuation approach. Transport Pol. 79, 125–136.
(International Air Transport Association), Iata, 2006. Airline Cost Performance. Canada, Montreal.
Jarach, D., Zerbini, F., Miniero, G., 2009. When legacy carriers converge with low-cost carriers: exploring the fusion of European airline business models through a case-based analysis. J. Air Transport. Manag. 15 (6), 287–293.
Jiang, C., Li, X., 2016. Low cost carrier and high-speed rail: a macroeconomic comparison between Japan and Western Europe. Res. Transp. Bus. Manag. 21, 3–10.
Jiang, C., Zhang, A., 2014. Effects of high-speed rail and airline cooperation under hub airport capacity constraint. Transp. Res. Part B Methodol. 60, 33–49.
Jiang, C., Zhang, A., 2016. Airline network choice and market coverage under high-speed rail competition. Transport. Res. Pol. Pract. 92, 248–260.
Kawamori, T., Lin, M.H., 2013. Airline mergers with low cost carriers. Econ. Transp. 2 (2–3), 63–71.
Li, H., Strauss, J., Lu, L., 2019. The impact of high-speed rail on civil aviation in China. Transport Pol. 74, 187–200.
Morrell, P., 2005. Airlines within airlines: an analysis of US network airline responses to Low Cost Carriers. J. Air Transport. Manag. 11 (5), 303–312.
Nash, C., 2008. Passenger railway reform in the last 20 years - european experience reconsidered. Res. Transport. Econ. 22 (1), 61–70.
Oliveira, A.V.M., Huse, C., 2009. Localized competitive advantage and price reactions to entry: full-service vs. low-cost airlines in recently liberalized emerging markets. Transport. Res E-Log. 45 (2), 307–320.
Railway Gazette International, 2019. RENFE to launch Avlo low-cost high speed rail for everyone. article. https://www.railwaygazette.com/high-speed/renfe-to-launch-avlo-low-cost-high-speed-rail-for-everyone/55343.
Sauter-Servaes, T., Nash, A., 2007. Applying Low-Cost Airline Pricing Strategies to European Railroads, TRB 2007 Annual Meeting CD-ROM.
Tsunoda, Y., 2018. Transportation policy for high-speed rail competing with airlines. Transport. Res. Pol. Pract. 116, 350–360.
Wan, Y., Ha, H.-K., Yoshida, Y., Zhang, A., 2016. Airlines' reaction to high-speed rail entries: empirical study of the Northeast Asian market. Transport. Res. Pol. Pract. 94, 532–557.
Wang, K., Xia, W., Zhang, A., 2017. Should China further expand its high-speed rail network? Consider the low-cost carrier factor. Transport. Res. Pol. Pract. 100, 105–120.
Wang, K., Zhang, A., Zhang, Y., 2018. Key determinants of airline pricing and air travel demand in China and India: policy, ownership and LCC competition. Transport Pol. 63, 80–89.
Wu, J., Nash, C.A., Wang, D., 2014. Is high speed rail an appropriate solution to China's rail capacity problems? J. Transport Geogr. 40, 100–111.
Xia, W., Zhang, A., 2017. Air and high-speed rail transport integration on profits and welfare: effects of air-rail connecting time. J. Air Transport. Manag. 65, 181–190.
Xia, W., Wang, K., Zhang, A., 2018. Air transport and high-speed rail interactions in China: review on impacts of low-cost carriers, rail speed and modal integration. In: Fu, X., Peoples, J. (Eds.), Airline Economics in Asia, Advances in Airline Economics, ume 7. Elsevier, pp. 103–122 (Chapter 6).
Yang, H., Zhang, A., 2012. Effects of high-speed rail and air transport competition on prices, profits and welfare. Transport. Res. Part B 46 (10), 1322–1333.
Zhang, Y., Zhang, A., 2016. Determinants of air passenger flows in China and gravity model: deregulation, LCCs and high-speed rail. J. Transport Econ. Pol. 50 (3), 287–303.
Zhang, A., Wan, Y., Yang, H., 2019. Impacts of high-speed rail on airlines, airports and regional economies: a survey of recent research. Transport Pol. 81, A1–A19.
Zhang, R., Johnson, D., Zhao, W., Nash, C., 2019. Competition of airline and high-speed rail in terms of price and frequency: empirical study from China. Transport Pol. 78, 8–18.