

**VERTICAL DIFFERENTIATION BETWEEN AIRLINE AND HIGH-SPEED RAIL:  
THE EFFECTS ON INTERMODAL COMPETITION AND COOPERATION**

by

Wenyi Xia

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF  
THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES  
(Business Administration)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

August 2015

© Wenyi Xia, 2015

## **Abstract**

Among the few papers that have studied intermodal competition and cooperation between high-speed rail (HSR) and airlines from an analytical point of view, it is assumed that the two modes are horizontally differentiated. However, empirical evidence seems to suggest that the two modes are vertically differentiated. The aim of this thesis is to study the effects of vertical differentiation between HSR and airlines on fares, traffic volumes and social welfare. The analysis is done for both competition and cooperation scenarios, and is conducted in an asymmetric network with hub airport runways being potentially capacity constrained.

We find that an improvement in rail speed or air-rail connecting time will lead to a decrease of air fare on the routes where HSR and airlines compete. Furthermore, HSR-airlines competition in the connecting markets may result in airlines charging higher-than-monopoly price in the markets where HSR is not present. Although HSR-airlines cooperation can eliminate this kind of negative impacts, cooperation harms social welfare in the markets where HSR and airlines are both present.

Intermodal cooperation benefits some markets while disadvantaging others. In terms of overall social welfare in the network, we suggest that intermodal cooperation should be encouraged if (1) the markets, where air transport is the only mode, are much larger than the other markets; or (2) the connecting markets are much larger than the other markets and airlines cannot serve all markets in the network due to insufficient hub airport runway capacity. Otherwise, intermodal competition should be encouraged.

## **Preface**

This dissertation is original, unpublished, independent work by the author, Wenyi Xia.

# Table of Contents

<b>Abstract.....</b>	<b>ii</b>
<b>Preface.....</b>	<b>iii</b>
<b>Table of Contents .....</b>	<b>iv</b>
<b>List of Tables .....</b>	<b>vii</b>
<b>List of Figures.....</b>	<b>viii</b>
<b>Acknowledgements .....</b>	<b>ix</b>
<b>Dedication .....</b>	<b>x</b>
<b>Chapter 1: Introduction .....</b>	<b>1</b>
1.1    High-speed rail development .....	2
1.2    Airline and high-speed rail.....	4
1.2.1    Competing modes .....	4
1.2.2    Complementary modes .....	5
1.3    Research questions.....	9
1.4    Main results.....	9
1.5    Structure of the thesis.....	10
<b>Chapter 2: Literature Review.....</b>	<b>12</b>
2.1    Vertical differentiation.....	12
2.2    Airlines and high-speed rail competition.....	17
2.2.1    Empirical ex ante studies .....	17
2.2.2    Empirical ex post studies .....	19
2.2.3    Theoretical studies .....	21

2.3	Airlines and high-speed rail cooperation .....	24
<b>Chapter 3: The Model .....</b>		<b>27</b>
3.1	Network structure.....	27
3.2	Utility function.....	29
3.3	Competition scenario .....	36
3.3.1	Equilibrium results without hub airport capacity constraint.....	39
3.3.2	Comparative statics analysis .....	43
3.3.2.1	Impacts of $b_1$ .....	43
3.3.2.2	Impacts of $b_2$ .....	44
3.3.2.3	Impacts of $b_3$ .....	45
3.3.2.4	Impacts of $V_R$ .....	46
3.3.2.5	Impacts of $C_{AR}$ .....	47
3.3.3	Equilibrium results with hub airport capacity constraint .....	48
3.4	Cooperation scenario .....	50
3.4.1	Equilibrium results without hub airport capacity constraint.....	50
3.4.2	Equilibrium results with hub airport capacity constraint .....	52
<b>Chapter 4: Social Welfare Comparison .....</b>		<b>58</b>
4.1	Long-haul case .....	58
4.2	Medium-haul case .....	67
<b>Chapter 5: Conclusion and future research .....</b>		<b>75</b>
5.1	Conclusion .....	75
5.2	Future research.....	77
<b>Bibliography .....</b>		<b>79</b>

Appendix A: Competitive equilibrium with hub airport capacity constraint .....	83
Appendix B: Robustness check .....	86

## List of Tables

Table 1-1: High-speed rail networks of major countries (As of September, 2014).....	3
Table 1-2: Examples of HSR's impacts on air transport .....	5
Table 3-1: A breakdown of total travel time in each market by the available mode(s).....	31
Table 3-2: Traffic volumes of all markets in long-haul case .....	38
Table 3-3: Impacts of increasing $b_1$ on equilibrium prices and quantities.....	44
Table 3-4: Impacts of increasing $b_2$ on equilibrium prices and quantities.....	45
Table 3-5: Impacts of increasing $b_3$ on equilibrium prices and quantities.....	46
Table 3-6: Impacts of increasing $V_R$ on equilibrium prices and quantities .....	47
Table 3-7: Impacts of decreasing $C_{AR}$ on equilibrium prices and quantities .....	48
Table 3-8: Cooperative equilibrium with no hub airport capacity constraint .....	51
Table 4-1: Parameter values for social welfare analysis in long-haul case .....	59
Table 4-2: Traffic volumes of all markets in medium-haul case .....	67
Table 4-3: Parameter values for social welfare analysis in medium-haul case .....	68
Table B-1: A new set of parameters for robustness check.....	86

## List of Figures

Figure 3-1: Network structure.....	27
Figure 3-2: Mode preferences.....	34
Figure 3-3: Traffic volume in market 2 .....	37
Figure 4-1: Social welfare comparison in market 1 for long-haul case.....	61
Figure 4-2: Social welfare comparison in market 2 for long-haul case.....	64
Figure 4-3: Social welfare comparison in market 3 for long-haul case.....	65
Figure 4-4: Overall social welfare comparison for long-haul case.....	66
Figure 4-5: Social welfare comparison in market 1 for medium-haul case.....	70
Figure 4-6: Social welfare comparison in market 2 for medium-haul case.....	71
Figure 4-7: Social welfare comparison in market 3 for medium-haul case.....	72
Figure 4-8: Overall social welfare comparison for medium-haul case.....	73
Figure B-1: Social welfare comparison for robustness check .....	88
Figure B-2: Social welfare comparison with constant marginal costs.....	90

## **Acknowledgements**

I would like to express my deepest gratitude to my thesis supervisor Professor Anming Zhang, who has offered valuable guidance, immeasurable support and continuous encouragement during all stages of this thesis and throughout my master's study.

I offer my gratitude to Professor Robin Lindsey for his very useful class and for spending valuable time on serving as my thesis committee member. I would like to thank Professor Tae Oum for his support and encouragement on my study and also for serving as my thesis committee member.

I am also indebted to Professor David Gillen, Professor Ming Hsin Lin and Professor Tim Huh for their valuable comments and suggestions during the developing stage of this thesis. I would like to thank Elaine Cho and Rita Quill who have provided a wide range of timely and detailed administrative support.

Special thanks are owed to my parents for their unconditional support throughout my years of education. I also thank my husband, Yichuan Ding, for his support.

## **Dedication**

To my parents

## **Chapter 1: Introduction**

Due to continuous technological advancements in rail speed, high-speed rail (HSR) has seen extensive network expansion in many countries. With worldwide rapid growth of HSR networks, there are numerous examples of airlines suffering from negative impacts right after the introduction of HSR. In fact, HSR is believed to be more competitive than air transport in short-to-medium haul passenger markets because of higher service frequencies, cheaper fares, the proximity to city centers and service reliability (e.g., Taniguchi 1992; Albalade et al. 2015; Givoni & Banister 2006; Román et al. 2007). However, due to the increasing concerns of airport runway congestion and environmental issues, HSR, in some cases, can be an alternative to free up slot-constrained hub airports by replacing short-haul flights, while in the meantime enlarge the airports' catchment area for long-haul flights.

Among the few papers that have studied intermodal competition and cooperation between HSR and airlines from an analytical point of view, it is assumed that the two modes are horizontally differentiated (e.g., Yang & Zhang 2012; Jiang & Zhang 2014a; D'Alfonso et al. 2015). However, empirical studies seem to suggest that the two modes are vertically differentiated (e.g., González-Savignat 2004; Behrens & Pels 2012; Fu et al. 2014; Román & Martín 2014). The aim of this thesis is to study the effects of vertical differentiation between HSR and airlines on fares, traffic volumes and social welfare. The analysis is done for both competition and cooperation scenarios, and is conducted in an asymmetric network with hub airport runways being potentially capacity constrained.

To the best of our knowledge, this is the first study that theoretically examines vertical differentiation between airline and HSR. We investigate to what extent and under what conditions intermodal cooperation is beneficial to the society as a whole. Dobruszkes (2011) has pointed out that scholarly publications on HSR and its interactions with other transport modes are much fewer than those on air transport. Hence, this thesis may provide some policy implications on air-rail intermodality.

### **1.1 High-speed rail development**

The first modern HSR, Shinkansen, went into operation in Japan between Tokyo and Osaka in 1964, with a maximum speed of 210 km/h. After that, HSR was first introduced to Europe in 1981 when France inaugurated regular HSR service between Paris and Lyon at a top speed of 270 km/h. This is also the first HSR line to be operated outside Japan (Givoni & Dobruszkes 2013). In 1988, Italy launched HSR service on Rome-Milan line, followed by Germany in 1991 on Hannover-Würzburg and Spain in 1992 on Seville-Madrid. Since then, HSR has expanded to other adjacent European countries, such as Belgium, the Netherlands and United Kingdom. The Trans-European Transport Network started to take shape (Givoni 2006).

Japan remained as the only country to operate HSR service outside Europe until 2000s, when a number of countries in East Asia started HSR services. South Korea launched its HSR service (Korea Train Express) in 2004 in Seoul-Busan corridor. Three years later, Taiwan HSR opened for service between Taipei and Kaohsiung. However, the most remarkable and astonishing development occurred recently in China. Based on its Medium-to-Long-Term Railway Network Plan proposed in 2008, China targets to build at least 16,000 km of high-speed passenger rail network, which consists of four north-south and four east-west trunk lines, by 2020. Although

HSR services started in China less than a decade ago, China by far has the world's longest HSR network and the world's longest single HSR line running 2,298 km from Beijing to Guangzhou. Currently, the daily ridership of China's fast-expanding HSR network exceeds 1.3 million<sup>1</sup>. By 2020, 192 cities of prefectural-level in China will be connected by HSR lines (Fu et al. 2015).

**Table 1-1: High-speed rail networks of major countries (As of September, 2014)**

Country	In Operation (km)	Under Construction (km)	Planned (km)	Total (km)
China	11,132	7,571	3,777	22,480
Japan	2,664	779	179	3,622
South Korea	412	247	49	708
Spain	2,515	1,308	1,702	5,525
France	2,036	757	2,407	5,200
Germany	1,352	466	324	2,142
Italy	923	125	221	1,269
Turkey	688	469	1,758	2,915
USA <sup>2</sup>	362	-	777	1,139

Source: UIC-International Union of Railways (2014)

Table 1-1 shows the HSR networks of some major countries according to the latest statistics from International Union of Railways (UIC 2014). As of September, 2014, the worldwide HSR lines under operation were 22954 km, of which 66% is in Asia and 32% in Europe; 12754 km

<sup>1</sup> See <http://www.cnn.com/2013/04/11/travel/china-high-speed-rail/>

<sup>2</sup> Amtrak's HSR service, Acela Express, is so far the only HSR service in the United States. It started operating on the North East Corridor between Boston and Washington, DC in 2000 at a top speed of 240 km/h. Although it is not shown in Table 1-1, California, at the beginning of 2015, started the construction of HSR project, which is planned to connect San Francisco Bay area with Los Angeles and other major cities in the state. Its first stage is targeted for completion in 2017.

were under construction and 18841 km were in both short-term and medium-to-long-term plans (UIC 2014). By 2025, the length of HSR lines worldwide is expected to reach 54550 km, of which Asia will account for 57% and Europe 39% (UIC 2014).

## **1.2 Airline and high-speed rail**

Airline and HSR have long been regarded as potential competitors, as the white paper (European Commission 2001, page 38) states that: *“We can no longer think of maintaining air links to destinations for where there is a competitive high-speed rail alternative. In this way, capacity could be transferred to routes where no high-speed rail service exists.”* However, as pointed out by Givoni and Banister (2006), there is large potential for HSR and air transport to cooperate and integrate, especially in regions where hub-and-spoke network strategy is widely adopted by airlines. In this section, we introduce real-life examples of HSR and airlines competing against each other and cooperating with each other.

### **1.2.1 Competing modes**

When we take into consideration the time for access, check-in, security checks, boarding, actual flight and de-boarding of air transport, HSR is likely to provide a lower generalized cost of transportation, which is attributed to shorter door-to-door journey time. For instance, the market share of Japanese Shinkansen is always greater than the market share of airlines on routes less than 600 miles in Japan (Albalade & Bel 2012).

Facing competitive pressure exerted by HSR, airlines have suffered from reduction on market shares, frequencies, passengers and air fares as evidenced by empirical studies (e.g., Clewlow et al. 2014; Behrens & Pels 2012; Dobruszkes 2011). Table 1-2 lists a few examples of the impacts imposed upon air transport by HSR. From this table, we see that even for much longer distance

such as Wuhan to Guangzhou, air transport is still affected following HSR's entry, although it is considered hard for HSR to compete effectively with airlines for distance longer than 1000 km (e.g., Janic 1993; Givoni & Banister 2006; Givoni & Dobruszkes 2013; Fu et al. 2014; Jiang & Zhang 2014a).

**Table 1-2: Examples of HSR's impacts on air transport**

Route	Year of HSR entry	Distance	Impacts
Paris-Lyon	1981	427 km	Air share fell from 31% in 1981 to 7% in 1984 (European Commission 1998).
Madrid-Seville	1992	470 km	Air share fell from 40% in 1991 to 13% in 1994 (European Commission 1998).
London-Paris	1994	492 km	Airlines lost 56% passengers (Givoni & Dobruszkes 2013).
London-Brussels	1994	373 km	Airlines lost 58% passengers (Givoni & Dobruszkes 2013).
Frankfurt-Cologne	2002	177 km	Air services were suspended.
Seoul-Busan	2004	223 km	Air share fell from 42% in 2004 to 17% in 2008 (Givoni & Dobruszkes 2013).
Taipei-Kaohsiung	2007	345 km	Air share fell from 24% to 13% following the HSR entry (Cheng 2010). All flights were suspended in 2012.
Wuhan-Guangzhou	2009	1,069 km	Airlines' daily frequency was reduced from 32 to 17 in 2010 (Fu et al. 2012).

### 1.2.2 Complementary modes

Several leading airports in Europe demonstrate air-rail alliances for which railway services are used as additional spokes of airlines to free up slots and enlarge airports' catchment areas. AIRail

service, which was created in 2001 in Germany, is one example of dedicated air-rail alliances. This alliance is formed among Frankfurt Airport, Deutsche Bahn (German Railway) and Lufthansa. It targets at passengers flying into (or out of) Frankfurt Airport and traveling to (or from) Cologne, Siegburg/Bonn, Düsseldorf, Karlsruhe, Kassel or Stuttgart. One leg of the journey is provided by Lufthansa, whereas the other leg is provided by Deutsche Bahn. Passengers can earn miles on the rail journeys. To offer a seamless and fast transfer service, train schedules have been coordinated with Lufthansa timetables at Frankfurt Airport; outbound passengers can drop off their luggage for connecting flights at the AIRail Terminal and inbound passengers can collect their luggage at the exclusive AIRail baggage claim; single check-in and one combined ticket are offered for the entire trip.

A more flexible air-rail alliance in Germany is Rail & Fly, which is actually a rail ticket option that can be added to an international flight ticket issued by partner airlines at a cost from 29 Euro. The scale of Rail & Fly ticket covers more than 5,600 Deutsche Bahn stations and 17 airports<sup>3</sup>. The rail leg trip can be made one day before departure, one day after arrival to Germany, or on the date of travel. Stopovers are allowed as long as passengers are traveling towards the final destination. However, travelers need to choose the fitting connections and timetables by themselves. Besides, baggage handling, mileage awards and integrated tickets are not offered. So far, 73 airlines and 77 tour operators have engaged in the Rail & Fly program<sup>4</sup>. The purchase of

---

<sup>3</sup> See [http://www.bahn.com/i/view/GBR/en/prices/germany/rail\\_and\\_fly.shtml](http://www.bahn.com/i/view/GBR/en/prices/germany/rail_and_fly.shtml)

<sup>4</sup> For a complete list of partner airlines and tour operators of Rail & Fly program, see [http://www.bahn.com/i/view/mdb/bahnintern/services/mobilitaet\\_service/rail\\_fly\\_airrail/mdb\\_88401\\_20120808\\_aires\\_juli\\_2012\\_internetdarstellung.pdf](http://www.bahn.com/i/view/mdb/bahnintern/services/mobilitaet_service/rail_fly_airrail/mdb_88401_20120808_aires_juli_2012_internetdarstellung.pdf) and [http://www.bahn.com/i/view/mdb/bahnintern/services/mobilitaet\\_service/rail\\_fly\\_airrail/mdb\\_88402\\_rail\\_fly\\_partner\\_reiseveranstalter\\_online\\_stand\\_01\\_07\\_2012.pdf](http://www.bahn.com/i/view/mdb/bahnintern/services/mobilitaet_service/rail_fly_airrail/mdb_88402_rail_fly_partner_reiseveranstalter_online_stand_01_07_2012.pdf).

Rail & Fly ticket should be made at the same time as the flight ticket, but unfortunately not all partner airlines provide clear instructions on how to book the Rail & Fly ticket. In particular, Grimme (2007) points out that Rail & Fly is a “soft alliance” between air and rail and customers may not even be aware of such intermodal product.

Another example is TGV<sup>5</sup> AIR, an alliance formed among SNCF (French National Railway Company), Charles de Gaulle Airport (CDG), Orly Airport (ORY), Air France and multiple French and foreign airlines. It connects international or intercontinental flights at CDG or ORY with HSR services to reach around 20 major French cities, including Provence, Avignon, Bordeaux, Marseille, etc. Integrated baggage handling is not provided. However, in the case of delays of flight or TGV, SNCF and the partner airlines guarantee a seat on the next available train or flight. Since ORY does not have on-site HSR station, free shuttle bus for TGV AIR passengers is offered between Massy TGV train station and ORY by partner airlines.

Air-rail alliance is also a strategy for one airline or rail operator to compete with its rivals. For instance, in order to compete with the incumbent train operator Trenitalia, the new and private HSR operator NTV<sup>6</sup> in Italy joined partnership with Cathay Pacific Airways in November, 2012. Passengers who travel with Cathay Pacific can take a free shuttle bus to Milan Malpensa Airport (MXP), if they board a NTV train to Milano Porta Garibaldi railway station, which is 50 kilometers away from MXP. The agreement first covers the regional areas of Florence and

---

<sup>5</sup> TGV refers to Train à Grande Vitesse, which means high-speed train in French.

<sup>6</sup> NTV refers to Nuovo Trasporto Viaggiatori, which means New Passenger Transport in Italian.

Bologna, and further extends to Turin and Naples. The service undoubtedly improves connection of international and intercontinental travel via MXP.

Other air-rail partnerships in Europe include Austrian AIRail service offered by Austrian Airlines and ÖBB (Austrian Federal Railways), Swiss Airtrain service offered by Swiss International Air Lines and SBB (Swiss Federal Railways), and UK rail-fly service offered by two railway operators—Heathrow Express and First Great Western and two airlines—Singapore Airline and British Airways.

Air-rail cooperation is more common in Europe than other parts of the world, partly because Europe has more railway stations located within practical distance of major airports. The only air-rail alliance in the United States is a code-share program reached between United Airlines and Amtrak. Passengers who make a connection at Newark Liberty International Airport (EWR) can earn miles on the rail journey when they fly United Airlines and travel to or from four Amtrak stations: New Haven Rail Station, Stamford Rail Station, Philadelphia 30th Street Station, and Wilmington Rail Station. It takes passengers approximately 10 minutes by the monorail AirTrain to transfer between EWR rail link station and EWR terminals for air-rail connection. Passengers traveling on certain segments and classes of Acela Express—Amtrak's first HSR service—can also earn miles with no connecting flight required.

VIA Rail, Canada's passenger rail company, signed its first air-rail code-share agreement with Royal Jordanian Airlines in October, 2012. More recently, a partnership between VIA Rail and Hainan Airlines, a Chinese airline, was reached in December 2014. To date, VIA Rail has

concluded alliances with 7 airlines, including Air Transat, Hainan Airlines, Royal Jordanian, Air North, Yukon's Airline, Hawkair and First Air<sup>7</sup>. The alliance allows VIA Rail and partner airlines to sell each other's tickets, coordinate schedules, offer seamless transfer services and share revenue.

### **1.3 Research questions**

Motivated by the expansion of HSR, the competitive pressure faced by airlines and the interesting alliances developed between air and rail modes, our research tries to answer two questions.

- What are the effects of vertical differentiation between airlines and HSR on fares, traffic volumes and social welfare?
- With vertical differentiation, to what extent and under what conditions is intermodal cooperation or competition beneficial to the society?

### **1.4 Main results**

We incorporate different segments of total travel time in the model and derive consumers' mode preferences over different ranges of travel distance. We show that HSR (airline, respectively) is preferred in short-to-medium-haul (long-haul, respectively) market, while, in connecting markets, air-air is preferred for connecting travel when one leg of the journey is medium-to-long-haul markets.

We find that an increase of gross travel benefit in one market will contribute to the increase of both fares and traffic volumes in this market. Furthermore, an improvement of rail speed or air-

---

<sup>7</sup> See <http://www.viarail.ca/en/about-via-rail/media-room/latest-news/76306/17-december-2014-via-rail-canada-sets-foot-china>

rail connecting time will lead to a decrease of air fare on the routes that HSR and airline compete. Moreover, when airline cannot serve all markets due to limited hub airport runway capacity, it will withdraw from the market in which it has less competitive advantage over HSR.

By comparing equilibrium outcomes in the competition and cooperation scenarios, we find that HSR-airline competition in the connecting market may result in airline charging higher-than-monopoly price in the market where HSR is not present. The reason is that in the competition scenario passengers who transfer by air-rail mode buy tickets from the two operators separately. To attract more air-air transfer passengers, the airline increases the price on its segment of the journey to make the air-rail transfer more expensive. This strategy negatively affects passengers in the market where HSR is not present. Although HSR-airline cooperation can eliminate this kind of negative impacts, cooperation harms social welfare in the markets where HSR and airlines are both present.

Since intermodal cooperation benefits some markets while disadvantaging others, in terms of social welfare in the overall network, we suggest that intermodal cooperation should be encouraged if (1) the market, where air transport is the only mode, is much larger than the other markets; or (2) the connecting market is much larger and airline cannot serve all markets in the network due to limited hub airport runway capacity. Otherwise, intermodal competition should be encouraged.

## **1.5 Structure of the thesis**

The rest of the thesis is organized as follows. Chapter 2 reviews related literature. Chapter 3 describes the model to analyze vertical differentiation between HSR and airline and investigates

its effects on equilibrium outcomes. Chapter 4 presents social welfare comparison between cooperation and competition scenarios and its policy implications. The last chapter concludes the thesis.

## Chapter 2: Literature Review

In this chapter, we review three domains of literature that are utilized to set up the model, i.e., vertical differentiation, intermodal competition between airlines and HSR, and intermodal cooperation between airlines and HSR.

### 2.1 Vertical differentiation

There are two types of product differentiation: horizontal differentiation and vertical differentiation. With horizontal differentiation, consumers differ in their preference rankings of goods when their prices are equal (Tirole 1988). For example, for the same products painted in different colors, some people prefer the red one, while others prefer the black one. By contrast, with vertical differentiation all consumers agree over their preference ordering of products when prices are equal (Tirole 1988). For instance, at equal prices, all consumers prefer a Volvo to a Hyundai. However, the less preferred products may also be purchased, because consumers' ultimate choice depends on their income and prices of the products.

In the case of airline markets, full service carriers (FSCs) and low-cost carriers (LCCs) offer vertically differentiated products. LCCs save a huge amount of costs by offering no-frills, operating single-type aircrafts, using secondary airports, flying at off-peak times and so on. Hence, FSCs are preferred to LCCs at equal prices. The competing strategies of FSCs and LCCs with vertical differentiation are investigated in the literature both empirically and theoretically.

Fu et al. (2011) identify and quantify the effects of product differentiation among services provided by two FSCs (American Airlines and United Airlines) and one LCC (Southwest Airlines) in the US domestic airline industry. Aggregated market data of five US domestic routes

originating from Chicago and operated by the three airlines are used to assess the impacts of competition. The data of the initial period after an airline's entry or exit of some markets is deleted to remove the transitory effects. Thus, the data approximates the market equilibrium. The cross elasticity between the two FSCs is found to be significantly higher than the cross elasticity between either one of the FSCs and the LCC, indicating a significant differentiation between the services provided by FSCs and LCCs. A further estimation of price response equations shows that competition among LCCs and among FSCs are much sharper than competition between LCCs and FSCs.

Reisinger (2005) considers a classical leader-follower game, in which the incumbent airline first chooses its product quality, and then the entrant airline chooses its quality in the second stage. In the third stage, both airlines set their prices after observing the quality choice of the other firm. In equilibrium, the incumbent airline chooses the same quality as when there is no entry, while the entrant chooses a lower quality. Moreover, the incumbent substantially reduces its price when entry occurs. The model is further extended to analyze the predation strategy of a FSC to establish its own LCC. Another two stages are added to the sequential game, in which the incumbent airline chooses to build a LCC or not in stage 4. In stage 5, the entrant turns out to survive the predation or not and the incumbent can withdraw its LCC. The result shows that the higher the probability that the entrant goes bankruptcy, the more willing the incumbent is to build its own LCC. No matter whether the entrant finally goes bankruptcy or not, it is always optimal for the incumbent to withdraw its LCC in stage 5.

Unlike FSCs and LCCs, HSR and airlines are not obviously vertically differentiated. How airlines and HSR are vertically differentiated largely depends on the total travel time and whether the trip is non-stop or requires connection. HSR is found to be the dominant transport mode for travel distance between 300 km to 700 km (Fu et al. 2014; Román et al. 2007; Yamaguchi et al. 2008), partly due to the lesser total travel time of HSR than plane or other transport modes. On travel distances between 1200 km to 1600 km, air transport is found to be the dominant mode, with market share varying between 50-80% (Janic 2003). In fact, HSR can hardly be an effective competitor of airlines in long-haul markets, as airlines can offer much faster services even with the consideration of the longer access and terminal times of air transport. Therefore, HSR is found to be preferred in short-to-medium-haul markets, while air transport is found to be preferred in long-haul markets (Janic 1993; Janic 2003). In terms of connecting trips, air-air transfer service is found to be preferred to air-rail transfer service (Grimme 2007; Román and Martín 2014), because of the disutility of changing to another transport mode. The empirical studies which find that HSR and airlines seem to be vertically differentiated are reviewed in details below.

Behrens and Pels (2012) use passenger survey data for the years 2003-2009 in London-Paris market to investigate the intermodal competition effects on passenger preferences and the market shares of the HSR and airlines serving this market. Since 2007, due to the opening of High Speed 1 track, travel time by HSR has been largely reduced between London and Paris. Thus, the data could capture the effects of HSR development on travel behavior. Multinomial and mixed logit models are estimated. The model specification includes an alternative specific constant, which can capture unobserved heterogeneity between airlines and HSR. The estimates of the alternative

specific constants before December 2006, when the rail speed was not improved, are all found to be insignificant. However, the alternative specific constants estimated after 2007 are all found to be significant and positive. This result suggests that the HSR alternative has valuable unobserved characteristics, which may be attributed to in-vehicle comfort and the use of electronic devices on board. Therefore, this paper empirically shows that vertical differentiation between HSR and airlines appears to be important.

Fu et al. (2014) estimate consumer preference and travel demand for air and HSR travel in Japan's domestic intercity transport markets with aggregated origin-destination data. A tri-level nested logit model is used for estimation by the Generalized Method of Moments (GMM) approach. Passengers first choose travel either by air or rail option or outside options. Then, within the air or rail travel option, passengers choose between air and rail. Finally, within the air option, they choose from various air travel products, which are the combination of airports, carriers, class and connection. The estimation shows that substitution among different air fare classes is much closer than air and rail substitution, indicating that Japanese consumers do not regard air and rail services as close substitutes. However, the air and rail substitution is still found to be stronger than the substitution between air or rail and an outside option. The study shows clear product differentiation between air and rail travel in Japan.

González-Savignat (2004) evaluates the potentials of a hypothetical (at that time) HSR to compete with air services on the Madrid-Barcelona route. A choice-based sampling survey is conducted, targeting at air travelers currently using air services on the Madrid-Barcelona route. The choice set includes two alternatives (air and HSR), each having four attributes with three

levels of variation. From the estimation results of the logit discrete choice models, travelers are found to assign different monetary value of time to in-vehicle travel time, access time and frequency delay. Interestingly, the alternative specific constants for HSR in all models are estimated to be positive, reflecting a relative preference for traveling by HSR under *ceteris paribus* conditions. The author argues that this positive effect on the probability of HSR travel may be due to the possible delays associated with air travel because of airport congestion. This result again shows that HSR and airlines are vertically differentiated.

Román and Martín (2014) conduct a discrete choice experiment which offers travelers the choice between the current air-air connecting alternative and a proposed air-rail connecting alternative in order to estimate passengers' willingness-to-pay for the main attributes of a proposed integration of HSR and air transport at Madrid Barajas Airport. Different multinomial logit and mixed logit models are estimated using the survey data. The attributes considered in the paper include travel cost, in-vehicle travel time, connecting time, access time to destination, fare integration and baggage integration. The experiment focuses on the routes from major European cities to cities in mainland Spain via Madrid-Barajas Airport. Therefore, the results obtained in the study might not be applicable if one segment is a long-haul intercontinental flight. The estimation results indicate that baggage integration is perceived important only by individuals who check in their luggage and travel for leisure purpose. Moreover, schedule coordination is crucial, especially for work trips. The estimated alternative specific constants for the air-air option of all models have a positive sign, which implies vertical differentiation between air-air transfer and air-rail transfer services. The result suggests that there is certain disutility of changing transport mode.

## **2.2 Airlines and high-speed rail competition**

There is a broad range of academic literature on HSR development and its competitive impacts on other transportation modes. Such literature can be classified into three categories: empirical ex ante studies, empirical ex post studies and theoretical studies. The empirical ex ante studies investigate the demands, potentials and possible impacts of HSR before it is to be built or operated. The majority of these studies analyze and predict mode choices between two cities or in a specific corridor, by utilizing “stated preference” (SP) data, “revealed preference” (RP) data or previous studies in similar markets. The empirical ex post studies examine the impacts of HSR after a certain period of HSR operation with aggregated market data. Lastly, the theoretical studies analyze the competitive interactions between HSR and airlines with a game-theoretic approach. This thesis falls into the third category. We consider both competitive and cooperative interactions between HSR and airlines.

### **2.2.1 Empirical ex ante studies**

Hensher (1997) estimates the demand for a proposed HSR service along Sydney-Canberra corridor with SP data. Mode choice models are estimated for eight market segments, two trip purposes (business and non-business), four current modes (car, plane, scheduled coach and nonscheduled coach) and a proposed HSR. Four fare classes are adopted in the SP survey for HSR and air travel. However, the study does not capture induced demand among non-travelers due to the introduction of HSR.

Levinson et al. (1997) examine the long-run full costs of HSR proposed for the Los Angeles-San Francisco corridor and compare the estimated costs of HSR with the costs of air transport and highways. The full costs that this study investigates include infrastructure, fleet capital and

operating expenses, user costs and social costs. The study shows that the average full costs of HSR are slightly higher than the costs of highway travel, but are much higher than of air travel. This estimation result is attributed to the fact that airports are far less costly to build and expand and that noise problem of air transport is less severe than of HSR and highways, which spread over entire corridors. The paper concludes that considerable public subsidy is needed for HSR to be competitive with air transport. The authors, in particular, point out that the decision to proceed with HSR in Europe and Japan would be different if air transport there was fully liberalized at that time, and as a result of air transport deregulation, HSR may face serious difficulties in the United States.

Park and Ha (2006) conduct a SP survey eight months before the opening of Seoul-Daegu HSR line to forecast the effects of HSR on air travel demand in this market. Three attributes are considered to influence transport modal choice, i.e. access and egress time, fare, and frequency, but travel time is left out. The authors forecast a significant negative impact on airline industry by the first HSR in South Korean, and estimate an 84% reduction in air travel demand. The estimation is further compared with the actual demand reduction, which is 72%.

Román et al. (2007) analyze the potential of the HSR to compete with air transport in the Madrid-Barcelona corridor by estimating disaggregated mode choice modes with mixed RP and SP data. RP data is collected from a survey about travel preferences of the four principal modes: car, bus, conventional train and air transport. SP data is collected from air transport users who face a stated choice experiment between the current air transport and the proposed HSR alternative. The estimation shows that business and other non-leisure passengers have higher

values of travel time savings and the willingness-to-pay for reduction in delay time is higher for HSR than for air transport. The Madrid-Barcelona corridor is characterized by high frequency air services, with more than 60 flights per day in 2007. Different policy scenarios are analyzed to estimate the market share of the proposed HSR. It is found that even under the least favorable conditions for airlines, such as significant delays and increases in access and waiting times, the market share of HSR would not exceed 35%.

Ortúzar and Simonetti (2008) study the hypothetical HSR in the Santiago-Concepcion market by modeling intercity mode choices with both SP and RP data. One RP dataset and two SP datasets are utilized in model estimation. Several models are estimated, either using single dataset or mixed datasets. The models with mixed datasets are estimated base on the assumption that the variance of the error in SP case can be equated with the variance in RP case by multiplying by an unknown scalar. The variables considered include travel time, fare, comfort, delay, etc. The signs of the coefficients in the estimated models are expected.

### **2.2.2 Empirical ex post studies**

Dobruszkes (2011) studies HSR and air transport competition in Western Europe from a supply-oriented perspective and examines empirically five city-pairs. It is found that travel time is an important factor for HSR to compete successfully with airlines. In addition to travel time, some other variables are also found to affect competition between the two modes, e.g., frequencies, fares, airlines' hubs and geographical structures of urban regions.

Clewlöw et al. (2014) investigate the improved rail travel time and the presence of LCC on air travel demand by estimating linear regression models with data collected for France, Germany,

Spain, Italy and UK from 1995 to 2009. Three levels of air travel demand are examined: (1) demand between city pairs; the data for cities with multiple airports are aggregated to determine the traffic between city pairs; (2) demand between airport pairs; demographic data at a more precise regional level are used instead of the mega-city level data used in (1); (3) demand at airport level; domestic, intra-EU and total airport level traffic are studied. The study shows that the introduction of HSR plays a significant role in reducing domestic air passenger traffic, while LCC has a more significant influence in increasing flights in medium-haul and intra-EU markets.

Wei et al. (2014) study the effects on airfares of two HSR events in China, i.e., the launch of Shanghai-Beijing HSR line in June 30, 2011 and the HSR collision on July 23, 2011, by using difference-in-difference approach. Ten routes along the Shanghai-Beijing HSR line that have air services are taken as treatment group, while another twenty routes that are not in the HSR line are taken as control group. Air fare data for the two groups are collected shortly before and after the two events. The estimation results show that the average air fares along the HSR line fall after the launch and rise after the accident. It is also found that FSCs are less vulnerable to a new competitor than LCCs in term of price changes. A further examination on the market structure shows that price changes are most drastic in duopoly market, less drastic in competitive market and the least drastic in monopoly market.

Albalade et al. (2015) study the impacts of HSR on air service frequencies and the number of seats offered by airlines by estimating random effects linear regression models with domestic route data in France, Germany, Italy and Spain. The results show that airlines do reduce the number of seats on the domestic routes that are subjected to HSR competition, but the

frequencies of air services do not suffer significant reduction on these routes. Furthermore, the reduction in air services is found to be greater at airports that do not have an on-site HSR station. This result provides indirect evidence that HSR acts as feeders at hub airports with on-site HSR stations.

### **2.2.3 Theoretical studies**

Yang and Zhang (2012) investigate the competition between air transport and HSR over a single origin-destination link. The catchment areas of HSR and air transport are identified by setting up an adapted Hotelling model of spatial competition. The model captures gross benefit of travel, access time, in-vehicle time, expected schedule delay and value of time. HSR is assumed to maximize a weighted sum of social welfare and its own profit, whereas the airline is a profit maximizer. The authors find that air fares decrease, while rail fares increase, in airport access time. Moreover, both air fare and rail fare fall as the weight of welfare in HSR's objective function rises. The authors then extend the analysis to heterogeneous passengers and find that when airline engages in price discrimination, less business passengers and more leisure passengers travel by air transport.

Another interesting paper is Jiang and Zhang (2014b). The paper addresses the impacts of HSR competition on airline's long-term strategies, such as market coverage and network choices, instead of capacity adjustments and price cuts, which are both short-term strategies of an airline. The paper considers a network structure in which both airline and HSR serve a trunk route linking two major cities. The two major cities then connect the fringe markets only by air services. As for the theoretical model, a two stage game is developed such that airline first decides its market coverage and network structure and then its traffic in the trunk market. The

authors find that if the trunk market is sufficiently large, when the airline is faced with more competition from the HSR, airline will cover more fringe markets that are previously ignored and will thus move towards a hub-and-spoke network. Furthermore, the paper shows that the introduction of HSR or the improvement of HSR competition will induce the airline to reach the network structure and market coverage that are closer to the social optimal one. This paper offers an analytical explanation of the phenomena that hub-and-spoke network is not widely adopted in some markets, such as China, and that airlines, facing increasing competition from HSR, are seeking opportunities aboard.

D'Alfonso et al. (2015) develop a duopoly model to investigate the impact of air transport and HSR competition on the environment and social welfare. The paper considers a single link where one airline and HSR compete. The full cost incurred by travelers consists of the fare of the chosen transport mode and the value of total travel time. The paper shows that when HSR does not emit sufficiently lower pollution than airline, the gain from shifting air passengers to a cleaner mode is not able to offset the pollution due to newly generated traffic. To compete with HSR, airline may adjust aircraft sizes and service frequencies, which will also affect the environment. The paper shows analytically that the introduction of HSR will be beneficial to the environment on a per seat basis only if the market size is large enough. In some cases, HSR may not operate at the maximum designed speed. The increase in rail speed will also affect the environment. The paper finds that when the increase in emission due to the increase in rail speed is sufficiently high, the overall emission level of airline and HSR may be higher than the emission level when only airline is present in the market. When environmental externalities are

taken into account in the social welfare assessment, it is found that the introduction of HSR may not always be socially beneficial.

Adler et al. (2010) propose a network competition model with three types of private transport operators, i.e., FSC, LCC and HSR, to analyze different policy options, such as infrastructure investments, rail infrastructure access charges and environmental charges, and also their effects on market equilibria. The profit of each operator is a function of its market share, potential demand, price and costs. FSCs and HSR operators maximize their respective profits with respect to various aircraft/train sizes, frequencies and prices for business and leisure passengers, while LCCs maximize their profits with respect to a single aircraft type, frequencies and a uniform price. A European case study is conducted to illustrate the model. Parameters from previous studies are selected to specify passengers' utility function and airlines' cost functions. The results suggest that despite the huge fixed cost of investment, HSR should be encouraged throughout Europe from a social welfare perspective.

Takebayashi (2015) considers a network structure of two gateway airports, which are connected by both air services and HSR. The network also includes a third airport, which connects the two gateway airports only by air services. Two airlines and one HSR operator are considered in the network. The author proposes a bi-level air transport market model. In the upper level, carriers are leaders and maximize their own profits with respect to price and frequency and are subjected to different constraints in each market. In the lower level, passengers are followers and minimize their travel disutility, which is a function of travel time, connection cost, fare and frequency. A numerical analysis follows the proposed model. The results show that improving connectivity

between airport and high-speed railway station increases air-rail transfer passengers while decreasing air-air transfer passengers. It is suggested that the gateway airport with smaller international travel demand and worse connectivity needs to improve its connectivity drastically so as to serve as a gateway.

### 2.3 Airlines and high-speed rail cooperation

As reviewed in the above section, an extensive literature on the intermodal interaction between HSR and air transport has been developed, focused mainly on competition aspect. The complementarities between the two modes began to draw serious attention in transportation literature only recently.

Jiang and Zhang (2014a) analyze the effects of cooperation between a hub-and-spoke airline and HSR. The authors follow Singh and Vives (1984) in assuming a quadratic and strictly concave utility function:  $U(q_1, q_2) = \alpha_1 q_1 + \alpha_2 q_2 - (\beta_1 q_1^2 + 2\gamma q_1 q_2 + \beta_2 q_2^2)/2$ , where  $\alpha_i$ ,  $\beta_i$  and  $\gamma$  are parameters,  $q_i$  is the amount of good  $i$ , which, in the setting of this paper, is the number of passengers served by a transport mode. The representative consumer maximizes  $U(q_1, q_2) - \sum_{i=1}^2 p_i q_i$ , where  $p_i$  is the price of good  $i$ . The inverse demand function can then be derived:  $p_i = \alpha_i - \beta_i q_i - \gamma q_j$ . The theoretic model is built upon the inverse demand functions  $p = \alpha - q$  if only one mode is present in the market and  $p^i = \alpha - q^i - \gamma q^j$  if both airline and HSR are present in the market.  $\gamma$  is interpreted as modal substitutability.  $\alpha$  is interpreted as the market size, which is assumed to be the same across all markets. In the simulation part of the paper, the authors try to capture vertical differentiation between the two modes by assigning different values of  $\alpha$  to the two modes. This is not a satisfactory way to capture vertical differentiation, because, given different  $\alpha$ , the model still cannot reflect that consumers agree over the

preference ordering of transport modes at equal prices, which is the definition of vertical differentiation. The reason is that a consumer's utility is assumed to be a function of the amounts of goods produced by firms, not a function of quality. In the analytical part of the paper, it is assumed that the two transportation modes are purely horizontally differentiated and the marginal costs of the two modes are normalized to 0. The equilibrium results under both competition and cooperation scenarios are derived for different ranges of hub airport capacity. The social welfare of one scenario is compared with the other. The study finds that cooperation is welfare-enhancing when modal substitutability is low, while if substitutability is high, cooperation is welfare-enhancing only when hub airport capacity is significantly constrained. In the simulation part of the paper, further considerations are also given to demand and cost asymmetries, heterogeneous passenger types and economies of traffic density.

Socorro and Vicens (2013) also follows Singh and Vives (1984) in assuming a quadratic and strictly concave utility function as discussed above. Unlike in Jiang and Zhang (2014a), they assume that the market sizes  $\alpha_i$  are different and that the marginal cost is lower for HSR than the air mode. The linear demand function used in the paper is  $q_i = \beta - P_i - d P_j$ , where  $i$  and  $j$  indicate the modes. The parameter  $d$  measures the degree of product differentiation. It takes values close to 0 when airline and HSR are considered as independent products, and takes value of 1 when the two are perfect substitutes. Since there are two kinds of product differentiation, the one parameter  $d$  is not enough to identify whether differentiation is vertical or horizontal. Jiang and Zhang (2014a) do not discuss the interpretation of  $d$ . The paper shows that airline and HSR integration is more likely to be welfare enhancing if the hub airport is capacity constrained. The integration reduces aircraft emission only when the hub airport capacity constraint is not severe.

The authors further introduce in the network a second airline, which only operates the “international” route (accessible only by air) and gains access to the “domestic” market (accessible by both air and HSR) via its integration with the HSR. This kind of integration is found to benefit consumers.

The network structure used in this thesis is closest to the one in Jiang and Zhang (2014a) and Socorro and Vicens (2013). However, they both impose strict assumptions on passengers’ mode choice when airline and HSR cooperate or compete. For example, Jiang and Zhang (2014a) assume that when HSR and airline compete, passengers in connecting market can only travel by air-air transfer, while when they cooperate, air-air and air-rail are both available to connecting passengers. Socorro and Vicens (2013) assume that only air service is available in connecting market under the competition scenario, while, under the integration scenario, only air-rail service is available in connecting market and only HSR is available in the non-stop market where airline and HSR compete under the competition scenario.

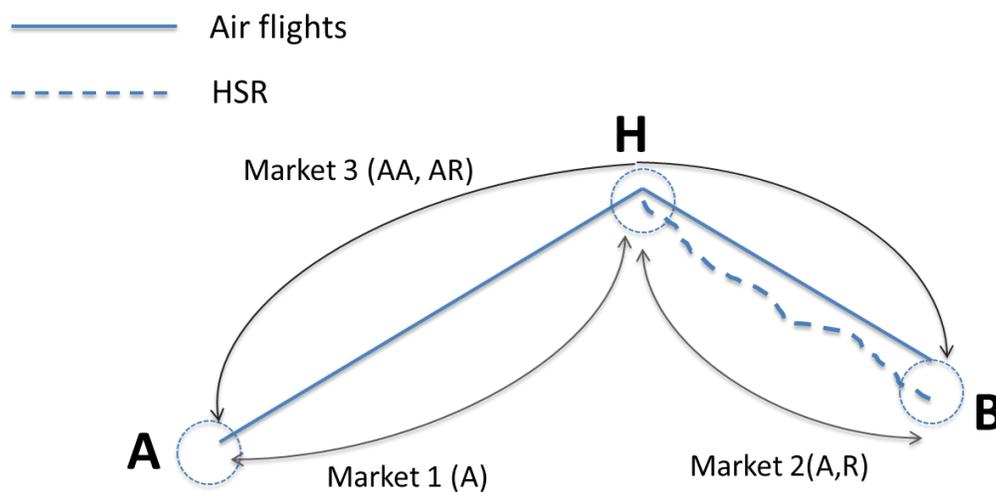
An important feature of our analysis is that we do not make any assumptions on passengers’ decisions. In other words, a passenger’s mode choice is endogenous in our model. Moreover, our main focus is vertical differentiation between air transport and HSR. Due to the assumed utility function, neither of the above two papers can address vertical differentiation between the two modes. To the best of our knowledge, this thesis is the first study that theoretically considers the effects of vertical differentiation between HSR and airlines.

## Chapter 3: The Model

### 3.1 Network structure

In order to address both cooperation and competition scenarios of HSR and air transport with a consideration of potential runway capacity constraint at the hub airport, we apply a network structure as shown in Figure 3-1.

Figure 3-1: Network structure



H indicates the hub city. To travel between city A and city H, air is the only accessible transport mode. Link A-H can be interpreted as the international market or transoceanic market<sup>8</sup>. Both air and rail services are in operation in link B-H, which can be interpreted as domestic market linking a hub city H with a secondary city B. As depicted in Figure 3-1, travel distance of rail is generally longer than that of flight, because trains do not necessarily follow direct routes due to geography and/or technical reasons (Yang & Zhang 2012; Givoni 2006; D'Alfonso et al. 2015).

---

<sup>8</sup> Note that link A-H does not just mean one single route. It could represent an aggregated market of several international/transoceanic routes.

Moreover, railway station is usually closer to the city center than airport, as also depicted in Figure 3-1. Therefore, the access and egress time of HSR is more likely to be shorter than that of air transport. Those characteristics are captured in our model.

Passengers between city A and city B have to transfer via the hub city H, either by air-rail or by air-air connecting mode. There are a few airports in the world that are integrated with railway stations, e.g., Frankfurt Airport, Paris CDG Airport, Shanghai Hongqiao Airport and Schiphol Amsterdam Airport. However, most airports are not provided with on-site railway infrastructure. Therefore, in our model, we assume that the connecting cost of air-rail is higher than that of air-air travel.

To save notations in our model, we name link A-H as market 1, link B-H as market 2 and link A-B as market 3. We list the transport mode(s) available in each market in the parentheses in Figure 3-1. This network structure is closest to the one used in Jiang and Zhang (2014a) and Socorro and Vicens (2013). However, the differences are, as mentioned earlier in Section 2.3, that we do not impose assumptions on a passenger's mode choice and our main focus is the effects of vertical differentiation between HSR and air transport. We incorporate different connecting costs between air-air and air-rail services, and also different access/egress time and in-vehicle time between air and rail modes, which are not considered in Jiang and Zhang (2014a) and Socorro and Vicens (2013).

We assume one airline and one HSR in the network as Jiang and Zhang (2014a), Jiang and Zhang (2014b) and Yang and Zhang (2012) for three reasons. First, although several airlines may

be present in a market, there is some evidence that airlines may cooperatively compete against HSR. For instance, airlines in Taiwan responded to HSR competition by entering into cooperation agreements (Albalade et al. 2015). Second, an elaborate air-rail alliance is most likely to be formed between one FSC and one HSR, such as AIRail discussed in Section 1.2.2. Third, introducing a third or more players would make the model much more complicated and difficult to interpret. Therefore, we consider two players in our game setting.

In reality, airlines and railroads have much larger networks than the three-market network considered in this thesis. However, this three-market network can capture a large part of the whole picture for two reasons. First, link A-H can be interpreted as an aggregated market of all the similar markets, e.g.,  $A_1$ -H,  $A_2$ -H to  $A_N$ -H. The same applies to the link B-H. In this sense, the network is expanded. Second, not every hub city has the potential to cooperate with HSR, since some hub cities do not have HSR services or the distance between the hub airport and HSR station is too far away to make cooperation possible. In this sense, the cooperation between the two modes is a regional phenomenon. Thus, it is not necessary to incorporate the entire network to analyze it. Admittedly, it is very difficult to incorporate entire real-world networks in a theoretical study. Even many empirical studies only focus on part of the network due to the limitation of data.

### **3.2 Utility function**

A common approach to model vertical differentiation is to assume a consumer's utility to be  $U = \theta S - P$  if she buys the product and 0 if she does not buy. Each consumer either consumes one unit of the product or does not consume at all.  $S$  is the service or product quality,  $P$  is the price and  $\theta$  is a consumer's taste parameter, which is a positive number and follows a

certain distribution. The taste parameter  $\theta$  can also be interpreted as the inverse of the marginal rate of substitution between income and quality.

There are numerous studies which have demonstrated that travel time is the main determinant in mode choice (e.g., Bhat 1997; Koppelman & Wen 2000; Steer Davies Gleave 2006; Dobruszkes 2011; Behrens & Pels 2012; Fu et al. 2014; IATA 2003). In order to reflect total travel time in assessing the quality of a transport mode and to capture the effects of travel distance, speed, connecting time, access time, etc., we assume the quality of HSR or airline follows a linear function of total travel time in our model, i.e.,  $S = b - T$ , where  $b$  is the gross benefit of travel and  $T$  is the total travel time. Although several other factors, such as comfort, on-board amenities, dining choices, safety, etc., may also affect the service quality of a transport mode, our main interests are vertical differentiation that arises from the differences in travel time between HSR and airline over different ranges of travel distance. Hence, the utility function in our model can be expressed as:

$$U_j^i = \theta(b_j - T_j^i) - P_j^i \quad (1)$$

- $i$ : travel mode,  $i = A, R, AA$  or  $AR$ ;
- $j$ : the market,  $j = 1, 2, \text{ or } 3$ ;
- $\theta \sim UNIF(0, 1)$ , depending on individual passengers;
- $b_j$ : gross travel benefit in market  $j$ ;
- $T_j^i$ : total travel time in market  $j$  by mode  $i$ ;
- $P_j^i$ : fare in market  $j$  by mode  $i$ .

The superscript  $i$  indicates the travel mode, which is A for air, R for rail, and AA, AR for connecting services. The subscript  $j$  indicates the markets. The parameter  $b_j$  is the gross benefit of travel, which only depends on the market and is measured in hours.  $T_j^i$  is the total travel time and  $P_j^i$  is the fare in market  $j$  by mode  $i$ .  $\theta$  is a passenger's preference for quality. A passenger with a high  $\theta$  is more willing to pay for high quality. Thus, a high  $\theta$  stands for business travelers, while a low  $\theta$  represents leisure passengers. For simplicity, we assume  $\theta$  is uniformly distributed between  $[0, 1]$  in all three markets. In other words, we normalize the consumer mass to be 1. In order to assess the effects of distance, rail speed and connecting time on market equilibrium, we break down the total travel time into several components. The details are presented in Table 3-1.

**Table 3-1: A breakdown of total travel time in each market by the available mode(s)**

Market	Total travel time
Market 1	$T_1^A = \alpha_1^A + \frac{d_1^A}{V_A}$
Market 2	$T_2^A = \alpha_2^A + \frac{d_2^A}{V_A}$
	$T_2^R = \alpha_2^R + \frac{d_2^R}{V_R}$
Market 3	$T_3^{AA} = \alpha_3^{AA} + \frac{d_1^A + d_2^A}{V_A} + c_3^{AA}$
	$T_3^{AR} = \alpha_3^{AR} + \frac{d_1^A}{V_A} + \frac{d_2^R}{V_R} + c_3^{AR}$

—  $\alpha_j^i$  : the access time, egress time and the time spent at the terminal in market  $j$  by mode  $i$ ;

- $d_j^i$  : the travel distance;
- $V_j$  : the speed of rail or air transport;
- $\frac{d_j^i}{V_j}$  : in-vehicle travel time;
- $c_j^i$  : connecting cost incurred by passengers in market 3, depending on whether they transfer by air-air or air-rail.

We make the following five assumptions regarding the different components of total travel time.

- i)  $\alpha_2^A > \alpha_2^R$
- ii)  $\alpha_3^{AA} > \alpha_3^{AR}$
- iii)  $d_2^A < d_2^R$
- iv)  $c_3^{AA} < c_3^{AR}$
- v)  $c_3^{AR-comp} > c_3^{AR-coop}$

Assumption i) means that access time, egress time and the time at the terminal by airline are longer than by HSR. The reason is that railway stations are usually located closer to the city center than airports. Passengers also spend less time by rail on security, custom checks, check-in and waiting time at the terminal. For the same reasons, in the connecting market, when both legs are air travel, the access and egress time is longer than when one leg is air travel and the other leg is rail travel. This justifies Assumption ii). Assumption iii) reflects the fact that the travel distance by air is shorter than by rail.

Connecting time is a very important determinant of the competition between HSR and air transport (IATA 2003). Thus, we make two assumptions regarding the connecting time. In Assumption iv), the connecting time of air-air is assumed to be shorter than that of air-rail. We make this assumption because when railway station is not situated in the airport, changing another mode takes more time. Even when railway infrastructure is provided at the airport, transferring by air-rail may still need more time, because baggage handling system of air-air connection is usually more efficient and changing another transport mode probably means changing to another terminal. In addition, empirical evidence shows that there is certain disutility of changing a transport mode (Román & Martín 2014). In Assumption v), we assume that the air-rail connecting time under cooperation scenario is shorter than that under competition scenario. When airline and HSR cooperate, they are very likely to offer shuttle bus, coordinated schedule or even integrated baggage handling to reduce connecting time.

One travel mode is preferred to the other if the net travel benefit of this mode is larger.

Specifically, in market 2, air transport is preferred if  $b_2 - T_2^A > b_2 - T_2^R$ . By plugging in the breakdown of total travel time, we show that if  $d_2^A > d_{m2} = \frac{V_A[(\alpha_2^A - \alpha_2^R)V_R - \Delta d]}{V_A - V_R}$ , passengers all prefer traveling by air in market 2 at equal prices.  $d_{m2}$  is the threshold of air distance in market 2 for air transport to be preferred, and  $\Delta d$  is the difference of travel distance between rail and air in market 2.

In market 3, air-air connection is preferred to air-rail connection if  $b_3 - T_3^{AA} > b_3 - T_3^{AR}$ .

Similarly, we show that, at equal prices, passenger all prefer transfer by air-air if  $d_2^A > d_{m3} =$

$\frac{V_A[(\alpha_3^{AA} - \alpha_3^{AR}) - (c_3^{AR} - c_3^{AA})V_R - \Delta d]}{V_A - V_R}$ .  $d_{m3}$  is the threshold of air distance in market 2 for air-air

connection to be preferred. Note that the common component of travel time in market 1 cancels out when comparing total travel time between air-air and air-rail in market 3. Thus, travel distance in market 2 alone determines the preferred mode in both market 2 and market 3.

According to the justifications of Assumption i) and ii),  $\alpha_2^A - \alpha_2^R \geq \alpha_3^{AA} - \alpha_3^{AR}$  always holds, because the difference in access and egress time between rail and air travel is larger if both origin and destination are airports or are railway stations as in market 2. Therefore, based on the aforementioned assumptions, it is straightforward to show that  $d_{m2} > d_{m3}$ . The relationship is depicted Figure 3-2.

**Figure 3-2: Mode preferences**

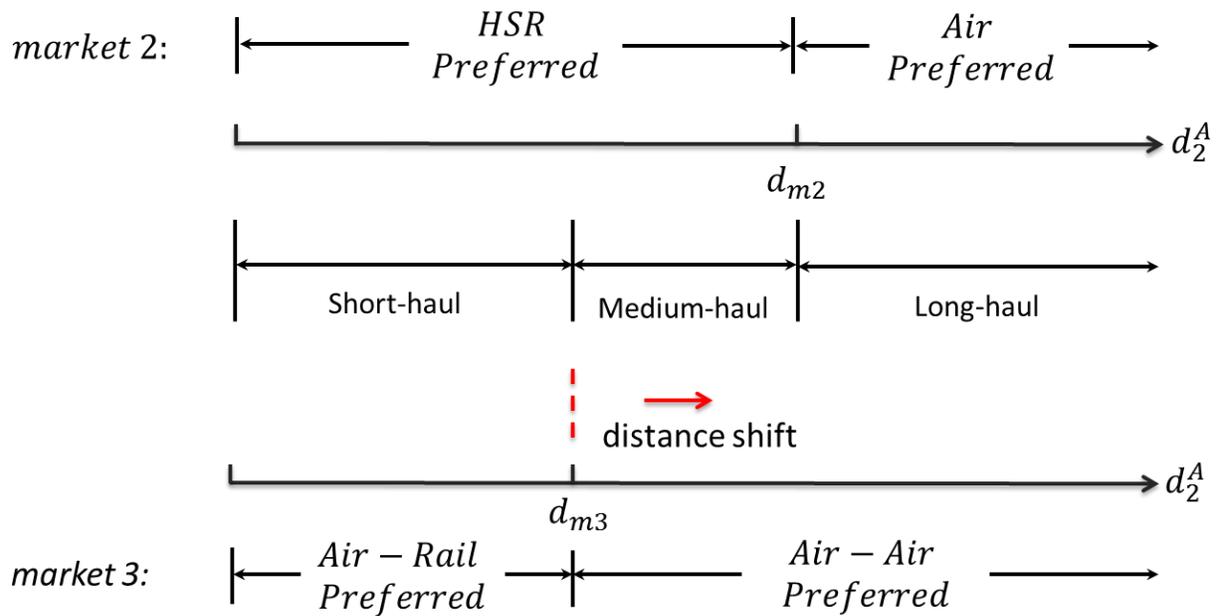


Figure 3-2 illustrates three ranges of air travel distance in market 2, i.e., long-haul, medium-haul and short-haul. In other words, long-haul, medium-haul and short-haul are determined by the air travel distance in market 2. In long-haul case where the air travel distance in market 2 is longer than  $d_{m2}$ , passengers always prefer traveling by air no matter in market 2 or market 3. However, when the air travel distance in market 2 is shorter than  $d_{m3}$ —which is the short-haul case, passengers always prefer HSR in market 2 and air-rail transfer in market 3. For medium-haul case in which air travel distance in market 2 lies between  $d_{m3}$  and  $d_{m2}$ , HSR is always preferred in market 2, whereas air-air transfer is preferred in market 3.

The result illustrated in Figure 3-2 is also true in practice. Studies have found that it is very difficult for air transport to compete effectively with HSR in short-haul markets (e.g., GAO 2009; Clewlow et al. 2014; Park & Ha 2006; Fu et al. 2014). In particular, the introduction of HSR on routes of around 300 km almost leads to a withdrawal of air services (Givoni 2006).

Moreover, our model shows a distance shift ( $d_{m2} > d_{m3}$ ) between the case that air travel is preferred in market 2 and the case that air-air connecting service is preferred in market 3. In other words, even though the distance of one leg of the trip is relatively short, connecting passengers still prefer air-air to air-rail service. This result is also plausible. For instance, when Deutsche Bahn started HSR service between Frankfurt and Cologne, Lufthansa still retained operation between the two cities mainly to serve premier connecting passengers (Grimme 2007). Note that the air distance between Frankfurt and Cologne is only 177 km. Another example is in the London-Paris market, where although HSR captured 77% market share, airlines continued to offer high frequencies (around 60 flights a day) between Heathrow and CDG mainly to serve

transfer passengers and to feed traffic to long-haul routes (Givoni & Banister 2006). The possible disutility of changing another transport mode may also contribute to the distance shift for air-air travel to be preferred in the connecting market.

There is little competition and substitution between air and rail in short-haul markets and there are many examples that airlines exit the short-haul markets after HSR entry. In addition, other transport modes, such as buses and cars, will come into play in short-haul markets and may even represent a large market share in some cases. Therefore, the short-haul case in which HSR is preferred in both market 2 and market 3 is not of our interest. For the medium-haul case and the long-haul case, the equilibrium analysis follows similar patterns and logic. Hence we only show one of them. Therefore, for the rest of Chapter 3, we analyze equilibrium outcome in the long-haul case where air services are preferred in both the connecting market and the non-stop market in which the airline faces direct competition from HSR. We will analyze social welfare for both medium-haul and long-haul cases in Chapter 4 Social Welfare Comparison.

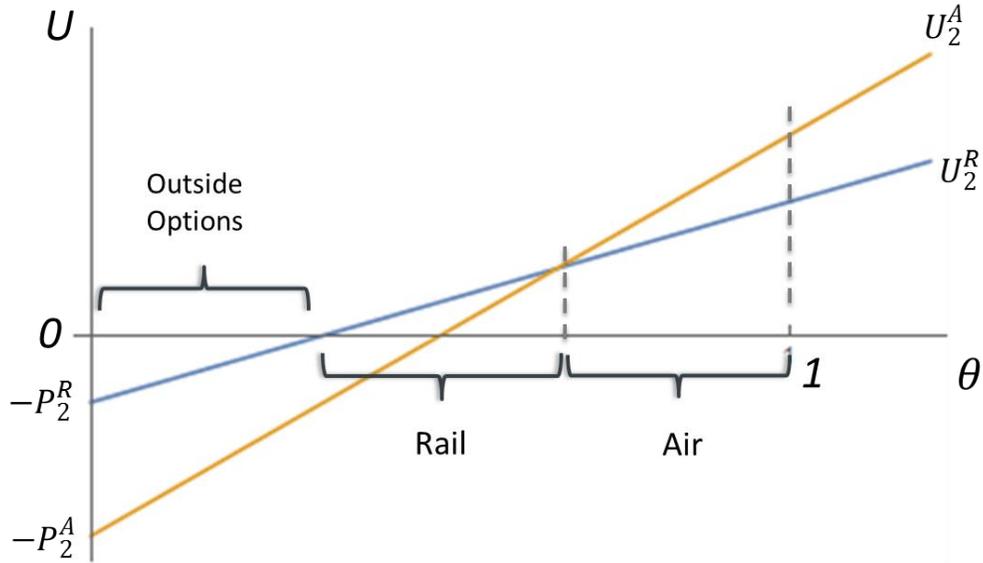
### 3.3 Competition scenario

Assume that air travel is preferred in both market 2 and market 3. We can derive the demand functions in each market and by each mode. In market 1, airline acts as a monopoly. The marginal consumer who is indifferent between flying and not flying is characterized by  $U_1^A = \theta S_1^A - P_1^A = 0$ , which gives  $\theta = \frac{P_1^A}{S_1^A}$ . Thus, the number of air travel passengers in market 1 is:

$$q_1^A = 1 - \frac{P_1^A}{S_1^A} \quad (2)$$

In market 2, the utility function of air travel  $U_2^A = \theta S_2^A - P_2^A$  and the utility function of rail travel  $U_2^R = \theta S_2^R - P_2^R$  can be depicted in Figure 3-3.

Figure 3-3: Traffic volume in market 2



As we assume  $S_2^A > S_2^R$ , the slope of the utility of air travel is steeper. The intercepts are the negative values of the prices of the two modes. Air travel is chosen by travelers if their utility function satisfies  $U_2^A > U_2^R \geq 0$ , whereas HSR is chosen if  $U_2^R > U_2^A$  and  $U_2^R \geq 0$ . If  $U_2^R < 0$ , passengers with such utility will choose outside options or not travel at all. The traffic volume in market 2 can be expressed as:

$$q_2^A = 1 - \frac{P_2^A - P_2^R}{S_2^A - S_2^R} \quad (3a)$$

$$q_2^R = \frac{P_2^A - P_2^R}{S_2^A - S_2^R} - \frac{P_2^R}{S_2^R} \quad (3b)$$

Similarly, the traffic volume in market 3 can be expressed as:

$$q_3^{AA} = 1 - \frac{P_3^{AA} - P_3^{AR}}{S_3^{AA} - S_3^{AR}} \quad (4a)$$

$$q_3^{AR} = \frac{P_3^{AA} - P_3^{AR}}{S_3^{AA} - S_3^{AR}} - \frac{P_3^{AR}}{S_3^{AR}} \quad (4b)$$

Recall that  $\theta$  is uniformly distributed between 0 and 1. To ensure that equilibrium quantities are within the range  $[0, 1]$ , we impose restrictions and summarize traffic volumes of all markets in Table 3-2. Under competition scenario, passengers traveling by air-rail have to buy the tickets separately from the two operators, i.e.  $P_3^{AR} = P_1^A + P_2^R$ .

**Table 3-2: Traffic volumes of all markets in long-haul case**

Market	Traffic Volume
Market 1(Only air)	$q_1^A = \min\left\{\left[1 - \frac{P_1^A}{S_1^A}\right]^+, 1\right\}$
Market 2 (Air)	$q_2^A = \min\left\{\left[1 - \frac{P_2^A - P_2^R}{S_2^A - S_2^R}\right]^+, 1\right\}$
Market 2 (HSR)	$q_2^R = \min\left\{\left[\frac{P_2^A - P_2^R}{S_2^A - S_2^R} - \frac{P_2^R}{S_2^R}\right]^+, 1\right\}$
Market 3 (Air-Air)	$q_3^{AA} = \min\left\{\left[1 - \frac{P_3^{AA} - P_3^{AR}}{S_3^{AA} - S_3^{AR}}\right]^+, 1\right\}$
Market 3 (Air-HSR)	$q_3^{AR} = \min\left\{\left[\frac{P_3^{AA} - P_3^{AR}}{S_3^{AA} - S_3^{AR}} - \frac{P_3^{AR}}{S_3^{AR}}\right]^+, 1\right\}$

### **3.3.1 Equilibrium results without hub airport capacity constraint**

We assume airline and HSR engage in price competition. Also, we assume the objective of the two players is revenue maximization instead of profit maximization, which means we do not consider marginal costs in the objective functions. The main reason for this assumption is tractability. With positive marginal costs, the formulae will be much more complicated and the results are hard to interpret. In Appendix B, we numerically examine the effects of constant marginal costs and show that incorporating constant marginal costs of the two transport operators will not alter the main conclusion of the analysis.

However, both airline and railroad industries have demonstrated economies of traffic density (Brueckner and Spiller 1994; Harris 1977; Graham et al. 2003). Although there are several studies that estimate the cost function of conventional rail (Braeutigam and Spiller 1994; McGeehan 1993), few studies have estimated the cost functions of HSR or compared the costs of airlines and HSR. Therefore, we left the effects of economies of traffic density on the model results for future work.

For ease of reference, we say airport capacity instead of hub airport runway capacity in the following sections. In this section, we first analyze the equilibrium outcome without considering airport capacity constraint. In section 3.3.3, we then assume that the hub airport has a binding capacity constraint. We do not consider the potential runway capacity constraint of the other two airports, i.e., airport A and airport B, because we want to focus on the hub airport, which is more

likely to be capacity constrained. We assume that HSR is not subjected to rail track capacity constraint<sup>9</sup>. The optimization problem is expressed as follows:

$$\begin{aligned} \text{Airline: } & \max_{\{P_1^A, P_2^A, P_3^{AA}\}} P_1^A q_1^A + P_2^A q_2^A + P_3^{AA} q_3^{AA} + P_1^A q_3^{AR} \\ & s. t. P_1^A, P_2^A, P_3^{AA} \geq 0 \end{aligned}$$

$$\begin{aligned} \text{HSR: } & \max_{\{P_2^R\}} P_2^R (q_2^R + q_3^{AR}) \\ & s. t. P_2^R \geq 0 \end{aligned}$$

$q_3^{AR}$  is in the objective function of both players because air-rail passengers buy tickets from them separately. Plugging in the traffic volumes shown in equation (2) to (4), we derive closed-form solution for equilibrium quantities and prices. As we assume that  $S_1^A > 0, S_2^A > S_2^R > 0$  and  $S_3^{AA} > S_3^{AR} > 0$ , it can be shown from the equilibrium results that all equilibrium quantities are within the range of 0 and 1 except for  $q_3^{AR*}$ , which might be 0 depending on the combination of parameters. When  $q_3^{AR*} = 0$ , a few subcases should be discussed and the equilibrium may not be unique. However, we mainly focus on the case that  $q_3^{AR*} > 0$ , which is more interesting,

---

<sup>9</sup> Rail capacity may be a problem when passenger and freight trains are running on the same tracks. However, compared with airport runway capacity, rail track capacity constraint is a much less serious problem, especially for HSR operations, although some HSRs that operate on conventional rail lines might be affected by slower local or freight trains. In China, some HSRs that operate between second-tier cities run on upgraded conventional tracks and can reach a maximum speed of 250 km/m, while HSRs between top-tier cities run on high-speed dedicated tracks with a maximum speed of 350 km/m. In fact, HSRs largely increase capacity on the route because (1) HSRs usually supplement existing trains and free capacity on the conventional network for use by freight and regional passenger services; (2) HSRs are able to offer higher frequencies, which is feasible due to the higher speed and the most up-to-date signaling systems that allow relatively short headway between trains without compromising safety; (3) longer trains with higher capacities can be used to transport more passengers and freight (Givoni 2006). In fact, one of the main reasons for building HSRs is to increase route capacity. For instance, by the mid-1950s, the Japanese Tōkaidō Line was operating at full capacity, which promoted government's decision to construct the first Shinkansen. This was also the case for France, Italy and China. Excess rail network capacity in the 1970s and 1980s in the UK was one of the main reasons for not considering HSR development (Givoni 2006). Therefore, it is reasonable to assume that HSR is not subjected to capacity constraint.

because airline and HSR are not only competing for non-stop passengers but also for connecting passengers.

The non-arbitrage condition  $P_1^A + P_2^A \geq P_3^{AA}$  is not imposed on the airline's objective. A check on the equilibrium outcome in the next page gives that

$$P_1^{A*} + P_2^{A*} - P_3^{AA*} = \frac{(S_2^A - S_2^R) - (S_3^{AA} - S_3^{AR})}{2} = \frac{(T_2^R - T_2^A) - (T_3^{AR} - T_3^{AA})}{2} = \frac{(\alpha_3^{AA} - \alpha_3^{AR}) - (\alpha_2^A - \alpha_2^R) - (c_3^{AR} - c_3^{AA})}{2}.$$

Recall some of the practical assumptions made in deriving short-haul, medium-haul and long-haul cases are  $\alpha_3^{AA} - \alpha_3^{AR} \leq \alpha_2^A - \alpha_2^R$  and  $c_3^{AR} > c_3^{AA}$ . Unfortunately, it turns out that the non-arbitrage condition is violated. This is the limitation of our model because we consider purely vertical differentiation between airlines and HSR. However, in reality, few people would bother to check flight tickets in the two segments of the trip when they have to connect. Also, buying connecting flight allows passengers to transfer within the terminals and checked baggage is usually forwarded to the final destination. Therefore, it is reasonable to not offer the option of buying separate air tickets for passengers in market 3. In this sense, our model is not affected by the non-arbitrage condition.

Equilibrium prices and quantities under competition scenario with no airport capacity constraint and  $q_3^{AR*} > 0$ :

$$P_1^{A*} = \frac{S_1^A S_3^{AR} (3S_2^R S_3^{AA} (S_2^A - S_2^R) + S_3^{AR} (4S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}))}{3S_1^A S_2^R S_3^{AA} (S_2^A - S_2^R) + S_3^{AR} (4S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) (S_1^A + S_3^{AR}) + S_2^R S_3^{AR} (S_2^A - S_2^R) (4S_3^{AA} - S_3^{AR})} \quad (5a)$$

$$P_2^{A*} = \frac{(S_2^A - S_2^R) (S_2^R (S_2^A - S_2^R) (3S_1^A S_3^{AA} + S_3^{AR} (4S_3^{AA} - S_3^{AR})) + (S_3^{AA} - S_3^{AR}) S_3^{AR} (S_1^A (4S_2^A - S_2^R) + S_3^{AR} (4S_2^A + S_2^R)))}{2(3S_1^A S_2^R S_3^{AA} (S_2^A - S_2^R) + S_3^{AR} (4S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) (S_1^A + S_3^{AR}) + S_2^R S_3^{AR} (S_2^A - S_2^R) (4S_3^{AA} - S_3^{AR}))} \quad (5b)$$

$$P_2^{R*} = \frac{2S_2^R (S_3^{AR})^2 (S_2^A - S_2^R) (S_3^{AA} - S_3^{AR})}{3S_1^A S_2^R S_3^{AA} (S_2^A - S_2^R) + S_3^{AR} (4S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) (S_1^A + S_3^{AR}) + S_2^R S_3^{AR} (S_2^A - S_2^R) (4S_3^{AA} - S_3^{AR})} \quad (5c)$$

$$P_3^{AA*} = \frac{S_2^R (S_2^A - S_2^R) (3S_1^A S_3^{AA} (S_3^{AA} + S_3^{AR}) + S_3^{AR} (S_3^{AA} - S_3^{AR}) (4S_3^{AA} + S_3^{AR})) + S_3^{AR} (4S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) (S_1^A (S_3^{AA} + S_3^{AR}) + S_3^{AR} (S_3^{AA} - S_3^{AR}))}{3S_1^A S_2^R S_3^{AA} (S_2^A - S_2^R) + S_3^{AR} (4S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) (S_1^A + S_3^{AR}) + S_2^R S_3^{AR} (S_2^A - S_2^R) (4S_3^{AA} - S_3^{AR})} \quad (5d)$$

$$P_3^{AR*} = P_1^{A*} + P_2^{R*} \quad (5e)$$

$$q_1^{A*} = \frac{3S_1^A S_2^R S_3^{AA} (S_2^A - S_2^R) + S_1^A S_3^{AR} (4S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) + S_2^R S_3^{AR} (S_2^A - S_2^R) (S_3^{AA} - S_3^{AR})}{3S_1^A S_2^R S_3^{AA} (S_2^A - S_2^R) + S_3^{AR} (4S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) (S_1^A + S_3^{AR}) + S_2^R S_3^{AR} (S_2^A - S_2^R) (4S_3^{AA} - S_3^{AR})} \quad (6a)$$

$$q_2^{A*} = \frac{3S_1^A S_2^R S_3^{AA} (S_2^A - S_2^R) + (S_1^A (4S_2^A - S_2^R) + S_3^{AR} (4S_2^A + S_2^R)) S_3^{AR} (S_3^{AA} - S_3^{AR}) + S_2^R S_3^{AR} (S_2^A - S_2^R) (4S_3^{AA} - S_3^{AR})}{2(3S_1^A S_2^R S_3^{AA} (S_2^A - S_2^R) + S_3^{AR} (4S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) (S_1^A + S_3^{AR}) + S_2^R S_3^{AR} (S_2^A - S_2^R) (4S_3^{AA} - S_3^{AR}))} \quad (6b)$$

$$q_2^{R*} = \frac{S_2^R (S_2^A - S_2^R) (3S_1^A S_3^{AA} + S_3^{AR} (4S_3^{AA} - S_3^{AR})) + S_3^{AR} (S_3^{AA} - S_3^{AR}) (S_1^A (4S_2^A - S_2^R) + S_2^R S_3^{AR})}{2(3S_1^A S_2^R S_3^{AA} (S_2^A - S_2^R) + S_3^{AR} (4S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) (S_1^A + S_3^{AR}) + S_2^R S_3^{AR} (S_2^A - S_2^R) (4S_3^{AA} - S_3^{AR}))} \quad (6c)$$

$$q_3^{AA*} = \frac{3S_1^A S_2^R S_3^{AA} (S_2^A - S_2^R) + S_3^{AR} (4S_2^A - S_2^R) (S_1^A + S_3^{AR}) (S_3^{AA} - S_3^{AR}) + S_2^R S_3^{AR} (S_2^A - S_2^R) (4S_3^{AA} + S_3^{AR})}{2(3S_1^A S_2^R S_3^{AA} (S_2^A - S_2^R) + S_3^{AR} (4S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) (S_1^A + S_3^{AR}) + S_2^R S_3^{AR} (S_2^A - S_2^R) (4S_3^{AA} - S_3^{AR}))} \quad (6d)$$

$$q_3^{AR*} = \frac{S_2^R (S_2^A - S_2^R) ((S_3^{AR})^2 - 3S_1^A S_3^{AA}) + S_3^{AR} (4S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) (S_3^{AR} - S_1^A)}{2(3S_1^A S_2^R S_3^{AA} (S_2^A - S_2^R) + S_3^{AR} (4S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) (S_1^A + S_3^{AR}) + S_2^R S_3^{AR} (S_2^A - S_2^R) (4S_3^{AA} - S_3^{AR}))} \quad (6e)$$

### 3.3.2 Comparative statics analysis

In this section, we study how the equilibrium prices and quantities change as gross benefits of travel, rail speed and air-rail connecting time change. We differentiate equilibrium prices and quantities in Equation (5) to (6) with respect to the factor we want to investigate and determine the sign of the first-order derivative. The analysis is conducted by using Mathematica 10.

#### 3.3.2.1 Impacts of $b_1$

$b_1$  is the gross benefit of travel in market 1. When  $b_1$  becomes larger, more passengers in market 1 tend to travel. We show that when  $b_1$  increases, equilibrium price and quantity in market 1 will both increase. The reason is that as more people in market 1 are willing to travel, airline in market 1 is able to increase the price without sacrificing revenue.

However, the increase of air fare in market 1 will negatively affect air-rail connecting passengers in market 3. Consequently, HSR in market 2 will lower its price, because it wants to attract air-rail connecting passengers who have to purchase tickets from HSR for the rail segment of their two-leg journey. The decrease of  $P_2^R$  induces airline to reduce its price in market 2 as well, since HSR and airline compete in market 2. The overall effect of increasing  $P_1^A$  and decreasing  $P_2^R$  turns out to be positive, resulting in the increase of  $P_3^{AR}$ , which, in turn, leads to  $P_3^{AA}$  to increase, because airline and HSR compete for connecting passengers in market 3.

Traffic volumes response to price changes accordingly. Although airline raises air fare in market 1, the traffic volume still increases due to the greater increase of gross travel benefit in market 1. The increase of both air-air and air-rail connecting prices leads to the decline of traffic volumes in market 3. As a response to the decrease of  $P_2^R$ ,  $q_2^R$  increases. As airline reacts by reducing its

price in market 2 but to a lesser extent than HSR's price reduction,  $q_2^A$  still decreases.

Nevertheless, the overall traffic volume in market 2 increases. The impacts of increasing  $b_1$  on equilibrium prices and quantities are shown in Table 3-3.

**Table 3-3: Impacts of increasing  $b_1$  on equilibrium prices and quantities**

$b_1 \uparrow$	Market 1	Market 2		Market 3	
Prices	$P_1^A \uparrow$	$P_2^A \downarrow$	$P_2^R \downarrow$	$P_3^{AA} \uparrow$	$P_3^{AR} = P_1^A + P_2^R \uparrow$
Quantities	$q_1^A \uparrow$	$q_2^A \downarrow$	$q_2^R \uparrow$	$q_3^{AA} \downarrow$	$q_3^{AR} \downarrow$
		$q_2^A + q_2^R \uparrow$			

### 3.3.2.2 Impacts of $b_2$

When  $b_2$  increases, passengers in market 2 are more likely to travel. Thus, both air fare and rail fare in market 2 increase. Moreover, despite the rising prices, the number of passengers traveling in market 2 either by air or by HSR will still increase, because the gross travel benefit increase outweighs the price increase.

As the rail price in market 2 increases, it renders air-rail transfer in market 3 less attractive. Since airline still want to obtain revenues from passengers traveling by air-rail, it will lower air fare in market 1, which leads to the increase of traffic volume in market 1. However, as  $P_3^{AR}$  increases overall, it triggers the price increase of the competing mode air-air transfer and the decrease of air-rail traffic volume. As  $P_3^{AR}$  increases greater than  $P_3^{AA}$ , the number of passengers travelling by air-air connection still increases. But the overall traffic volume in market 3 decreases. The impacts of increasing  $b_2$  on equilibrium prices and quantities are shown in Table 3-4.

**Table 3-4: Impacts of increasing  $b_2$  on equilibrium prices and quantities**

$b_2 \uparrow$	Market 1	Market 2		Market 3	
Prices	$P_1^A \downarrow$	$P_2^A \uparrow$	$P_2^R \uparrow$	$P_3^{AA} \uparrow$	$P_3^{AR} = P_1^A + P_2^R \uparrow$
Quantities	$q_1^A \uparrow$	$q_2^A \uparrow$	$q_2^R \uparrow$	$q_3^{AA} \uparrow$	$q_3^{AR} \downarrow$
				$q_3^{AA} + q_3^{AR} \downarrow$	

### 3.3.2.3 Impacts of $b_3$

When we increase  $b_3$ , similar to the case of increasing  $b_1$  and  $b_2$ , the prices and quantities in market 3 will all increase. As  $P_3^{AR}$  is composed of prices in both legs, both  $P_1^A$  and  $P_2^R$  will increase. The increase of rail price in market 2 will lead to the increase of air price in market 2. As both modes in market 2 increase their price, the overall traffic volume in market 2 decreases.

However, air traffic increases with the increase of air fare in market 2. Therefore, air price increases to a lesser extent than rail price in market 2. Another way to explain this is that if the price increase is the same for the two modes, air traffic will remain the same, but rail and overall traffic will decrease. Note that in Figure 3-3, if the two utility curves shift down the same amount, the x-coordinate of their intersection point does not change and thus air traffic volume remains the same. In addition, the intersection point between the rail utility curve and the x axis shifts to the right, so rail and overall traffic volume decrease. Since air traffic increases in market 2, it must be that air fare increases to a lesser extent than rail price in market 2. Thus, air passengers in market 2 still increases, while air passengers in market 1 and rail passengers in market 2 will decrease. In summary, when more people in market 3 are willing to travel, the air and rail prices

in all markets increase. The impacts of increasing  $b_3$  on equilibrium prices and quantities are shown in Table 3-5.

**Table 3-5: Impacts of increasing  $b_3$  on equilibrium prices and quantities**

$b_3 \uparrow$	Market 1	Market 2		Market 3	
Prices	$P_1^A \uparrow$	$P_2^A \uparrow$	$P_2^R \uparrow$	$P_3^{AA} \uparrow$	$P_3^{AR} = P_1^A + P_2^R \uparrow$
Quantities	$q_1^A \downarrow$	$q_2^A \uparrow$	$q_2^R \downarrow$	$q_3^{AA} \uparrow$	$q_3^{AR} \uparrow$
		$q_2^A + q_2^R \downarrow$			

### 3.3.2.4 Impacts of $V_R$

When rail speed goes up, it will shorten the travel time in two markets, i.e., market 2 where passengers travel by HSR and market 3 where passengers transfer by HSR. We show that when rail speed increases, it will negatively affect air fares in market 2 and market 3, which are both subjected to HSR competition.

However, it is unclear whether rail price will go up or not. On the one hand, HSR has the incentive to raise its price when the rail speed goes up, since rail mode becomes more competitive. On the other hand, since airline will definitely lower its prices in the markets where the two modes compete, HSR is also likely to reduce its price, depending on the extent of air fare decrease. The overall effect on rail price is unclear. The price effects on traffic volumes are also unclear. The impacts of increasing rail speed on equilibrium prices and quantities are shown in Table 3-6.

**Table 3-6: Impacts of increasing  $V_R$  on equilibrium prices and quantities**

$V_R \uparrow$	Market 1	Market 2		Market 3	
Prices	$P_1^A$ unclear	$P_2^A \downarrow$	$P_2^R$ unclear	$P_3^{AA} \downarrow$	$P_3^{AR}$ unclear

### 3.3.2.5 Impacts of $C_{AR}$

The decrease of air-rail connecting time will reduce the total travel time of air-rail transfer passengers. Therefore, air-rail mode becomes more attractive in market 3. Threatened by this effect, air fare in market 3 goes down. In the meantime, airline will increase air fare in market 1 in an effort to make air-rail mode unattractive so as to shift some passengers in market 3 to transfer by air-air mode.

It is unclear whether rail fare in market 2 will increase or not. On the one hand, HSR tends to increase its price due to the improvement of air-rail connecting time. On the other hand, it may also reduce rail price due to the increase of air fare in market 1 and the decrease of air-air fare in market 3. As for the possibilities to both increase and decrease  $P_2^R$ , it is unclear whether  $P_3^{AR}$  will increase or not. As  $P_2^A$  responds accordingly to  $P_2^R$ , the effect on  $P_2^A$  remains ambiguous.

Traffic volumes change correspondingly to the prices in each market. As a result,  $q_1^A$  decreases and  $q_3^{AA}$  increases. The changes of traffic volumes in market 2 are unclear. Even though the air-rail connection improves, the number of passengers that transfer by air-rail does not necessarily increase, but the overall traffic volume in market 3 increases. Table 3-7 shows the impacts of decreasing air-rail connection time on equilibrium prices and quantities.

**Table 3-7: Impacts of decreasing  $C_{AR}$  on equilibrium prices and quantities**

$c_{AR} \downarrow$	Market 1	Market 3	
Prices	$P_1^A \uparrow$	$P_3^{AA} \downarrow$	$P_3^{AR}$ unclear
Quantities	$q_1^A \downarrow$	$q_3^{AA} \uparrow$	$q_3^{AR}$ unclear
		$q_3^{AA} + q_3^{AR} \uparrow$	

We summarize the comparative statics analysis in Proposition 1.

**Proposition 1:** (1) An increase of gross travel benefit in market 1 (market 2, respectively) contributes to an increase of prices in market 1 (market 2, respectively) and market 3, and a decrease of prices in market 2 (market 1, respectively); (2) An increase of gross travel benefit in market 3 results in an increase of prices in all three markets; (3) An improvement of rail speed leads to a decrease of air fares in market 2 and market 3, but the effect on rail price is ambiguous; (4) An decrease of air-rail connection time in market 3 induces air fare to decrease in market 3 and increase in market 1, but the effect on rail price is ambiguous.

### 3.3.3 Equilibrium results with hub airport capacity constraint

Due to the fact that most of the world's hub airports have limited runway capacity, we add a constraint in the airline's objective function. The optimization problem is expressed as follows.

$$\text{Airline: } \max_{\{P_1^A, P_2^A, P_3^{AA}\}} P_1^A q_1^A + P_2^A q_2^A + P_3^{AA} q_3^{AA} + P_1^A q_3^{AR}$$

$$s. t. q_1^A + q_2^A + 2q_3^{AA} + q_3^{AR} \leq K$$

$$P_1^A, P_2^A, P_3^{AA} \geq 0$$

$$\text{HSR: } \max_{\{P_2^R\}} P_2^R (q_2^R + q_3^{AR})$$

$$s. t. P_2^R \geq 0$$

$K$  indicates airport capacity. As air-air connecting passengers use the runway twice, the traffic volume by air-air mode is multiplied by 2 in the constraint. The results of the optimization problem are discussed and shown in Appendix A.

From the equilibrium results in Appendix A, we can observe that as airport capacity becomes smaller, air fares in all markets increase, while air traffic volumes decrease. When airport capacity is heavily constrained, airline may have to withdraw from certain markets. It is crucial for airline to decide which market to abandon first. As airline is the monopoly in market 1, usually it will keep market 1, unless  $S_1^A$  is sufficiently small that retaining market 1 is the least profitable. The minimum value of  $S_1^A$  for airline to keep market 1 follows a very complicated expression of the service quality parameters. However, this is rarely the case that airline, due to limited airport capacity, will give up market 1 where it faces no threat from HSR.

Airline's pricing strategy in market 1 and HSR's pricing strategy in market 2 will both affect air-rail transfer passengers, which complicates airline's decision on whether to abandon the air-rail market when airport capacity is insufficient. However, airline's decision on market 2 and market 3 is more straightforward. Serving market 3 occupies twice more capacity, while serving market 2 is not very profitable due to the direct threat from HSR. It turns out that airline will keep market 2 if  $S_2^A - S_2^R > S_3^{AA} - S_3^{AR}$ , while airline will keep market 3 if  $S_2^A - S_2^R < S_3^{AA} - S_3^{AR}$ .

The difference of the net travel benefit between air and HSR can be interpreted as the competitive advantage of air travel over HSR. In the case of market 2 and market 3, airline will keep the one in which it has larger competitive advantage. We will see in the next subsection that

under cooperation scenario, airline's decision on which market to withdraw due to limited airport capacity is more straightforward.

### 3.4 Cooperation scenario

Under cooperation scenario, airline and HSR choose their prices in each market to maximize the overall revenue in the network. In the analysis of cooperation scenario, we do not distinguish between merger and alliance. Merger means that the two transport operators are merged as one operator, whereas alliance means that an agreement is reached between the two operators to achieve their goal but the two operators still remain as separate firms. However, it is reasonable to assume that the objective of HSR-airline alliance in this regional network is overall revenue maximization. Passengers travel by air-rail mode in market 3 buy integrated air-rail tickets instead of buying tickets in each leg separately as in the competition scenario. We discuss the equilibrium outcome without and with airport capacity constraint in the following two subsections respectively.

#### 3.4.1 Equilibrium results without hub airport capacity constraint

When there is no airport capacity constraint under cooperation scenario, the objective function of airline and HSR is expressed as follows.

$$\begin{aligned} \text{Airline and HSR: } & \max_{\{P_1^A, P_2^A, P_2^R, P_3^{AA}, P_3^{AR}\}} P_1^A q_1^A + P_2^A q_2^A + P_2^R q_2^R + P_3^{AA} q_3^{AA} + P_3^{AR} q_3^{AR} \\ & \text{s. t. } P_1^A, P_2^A, P_2^R, P_3^{AA}, P_3^{AR} \geq 0 \end{aligned}$$

Solving the optimization problem gives the equilibrium results shown in Table 3-8. In our model, neither the airline nor the HSR operator price discriminates between markets. In practice, they

can price discriminate between markets when passengers in one market differ from passengers in the other markets. For example, one market could mainly consist of business passengers who have higher willingness-to-pay, while the other market mainly consists of leisure passengers who have higher price elasticity of demand. However, since markets usually have a mixture of leisure and business passengers, we do not consider price discrimination between markets. The equilibrium results when airport capacity is not constrained under cooperation scenario can be summarized in Proposition 2.

**Table 3-8: Cooperative equilibrium with no hub airport capacity constraint**

	Market 1	Market 2		Market 3	
Prices	$P_1^{A*} = \frac{S_1^A}{2}$	$P_2^{A*} = \frac{S_2^A}{2}$	$P_2^{R*} = \frac{S_2^R}{2}$	$P_3^{AA*} = \frac{S_3^{AA}}{2}$	$P_3^{AR*} = \frac{S_3^{AR}}{2}$
Quantities	$q_1^{A*} = \frac{1}{2}$	$q_2^{A*} = \frac{1}{2}$	$q_2^{R*} = 0$	$q_3^{AA*} = \frac{1}{2}$	$q_3^{AR*} = 0$

***Proposition 2:*** When hub airport is not subjected to capacity constraint and when air travel is always preferred, intermodal cooperation of airline and HSR results in monopoly prices in all three markets and no passengers traveling by HSR.

In our model, when the two operators that produce differentiated transport products integrate, the optimal strategy of the integrated operator is to drop the product with inferior quality and only sell the product with superior quality at the monopoly price. However, this is not always the optimal strategy of a monopolist. If consumers can be grouped based on their preferences and consumers from one group will not be attracted to the products offered to the other groups, the

monopolist will produce variants targeted for different groups. In other words, it depends on the distribution of consumers' taste parameters. Also, note that we do not take into consideration the marginal costs of the two modes. If the superior goods are much more costly to produce than the inferior goods, it may still be optimal to keep the inferior goods in the market.

When capacity constraint comes into play, airline will increase air fares, because the supply of air services may still be insufficient to meet market demand even though airline charges monopoly prices. From Table 3-8, obviously, when  $K < q_1^{A*} + q_2^{A*} + 2q_3^{AA*} + q_3^{AR*} = 2$ , airport capacity becomes a binding constraint.

### 3.4.2 Equilibrium results with hub airport capacity constraint

With the consideration of constrained airport capacity, the objective function of airline and HSR is expressed as follows.

$$\begin{aligned} \text{Airline and HSR: } & \max_{\{P_1^A, P_2^A, P_2^R, P_3^{AA}, P_3^{AR}\}} P_1^A q_1^A + P_2^A q_2^A + P_2^R q_2^R + P_3^{AA} q_3^{AA} + P_3^{AR} q_3^{AR} \\ & s. t. \quad q_1^A + q_2^A + 2q_3^{AA} + q_3^{AR} \leq K \\ & \quad P_1^A, P_2^A, P_2^R, P_3^{AA}, P_3^{AR} \geq 0 \end{aligned}$$

Solving the optimization problem gives equilibrium prices in Equation (7a) to (7e) and equilibrium quantities in Equation (8a) to (8e).

Equilibrium prices under cooperation scenario with airport capacity constraint:

$$P_1^{A*} = \frac{S_1^A \left( S_1^A \left( (S_2^A - S_2^R) S_3^{AA} + (S_3^{AA} - S_3^{AR}) S_3^{AR} \right) + (5 - 2K) (S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) S_3^{AR} \right)}{2 \left( S_1^A \left( (S_2^A - S_2^R) S_3^{AA} + (S_3^{AA} - S_3^{AR}) S_3^{AR} \right) + (S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) S_3^{AR} \right)} \quad (7a)$$

$$P_2^{A*} = \frac{S_1^A S_2^A \left( (S_2^A - S_2^R) S_3^{AA} + (S_3^{AA} - S_3^{AR}) S_3^{AR} \right) + \left( S_2^A + 2S_1^A (2 - K) \right) (S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) S_3^{AR}}{2 \left( S_1^A \left( (S_2^A - S_2^R) S_3^{AA} + (S_3^{AA} - S_3^{AR}) S_3^{AR} \right) + (S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) S_3^{AR} \right)} \quad (7b)$$

$$P_2^{R*} = \frac{S_2^R}{2} \quad (7c)$$

$$P_3^{AA*} = \frac{S_1^A S_3^{AA} \left( (S_2^A - S_2^R) S_3^{AA} + (S_3^{AA} - S_3^{AR}) S_3^{AR} \right) + (S_3^{AA} + 4S_1^A (2 - K)) (S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) S_3^{AR}}{2 \left( S_1^A \left( (S_2^A - S_2^R) S_3^{AA} + (S_3^{AA} - S_3^{AR}) S_3^{AR} \right) + (S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) S_3^{AR} \right)} \quad (7d)$$

$$P_3^{AR*} = \frac{S_3^{AR} \left( S_1^A \left( (S_2^A - S_2^R) S_3^{AA} + (S_3^{AA} - S_3^{AR}) S_3^{AR} \right) + (S_3^{AR} + 2S_1^A (2 - K)) (S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) \right)}{2 \left( S_1^A \left( (S_2^A - S_2^R) S_3^{AA} + (S_3^{AA} - S_3^{AR}) S_3^{AR} \right) + (S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) S_3^{AR} \right)} \quad (7e)$$

Equilibrium quantities under cooperation scenario with airport capacity constraint:

$$q_1^{A*} = \frac{S_1^A \left( (S_2^A - S_2^R) S_3^{AA} + (S_3^{AA} - S_3^{AR}) S_3^{AR} \right) + (2K - 3) (S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) S_3^{AR}}{2 \left( S_1^A \left( (S_2^A - S_2^R) S_3^{AA} + (S_3^{AA} - S_3^{AR}) S_3^{AR} \right) + (S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) S_3^{AR} \right)} \quad (8a)$$

$$q_2^{A*} = \frac{(S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) S_3^{AR} + S_1^A \left( (S_2^A - S_2^R) S_3^{AA} + (2K - 3) (S_3^{AA} - S_3^{AR}) S_3^{AR} \right)}{2 \left( S_1^A \left( (S_2^A - S_2^R) S_3^{AA} + (S_3^{AA} - S_3^{AR}) S_3^{AR} \right) + (S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) S_3^{AR} \right)} \quad (8b)$$

$$q_2^{R*} = \frac{(2 - K) S_1^A (S_3^{AA} - S_3^{AR}) S_3^{AR}}{S_1^A \left( (S_2^A - S_2^R) S_3^{AA} + (S_3^{AA} - S_3^{AR}) S_3^{AR} \right) + (S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) S_3^{AR}} \quad (8c)$$

$$q_3^{AA*} = \frac{S_1^A \left( (S_2^A - S_2^R) S_3^{AA} + (S_3^{AA} - S_3^{AR}) S_3^{AR} \right) + \left( (S_3^{AA} - S_3^{AR}) - 2S_1^A (2 - K) \right) (S_2^A - S_2^R) S_3^{AR}}{2 \left( S_1^A \left( (S_2^A - S_2^R) S_3^{AA} + (S_3^{AA} - S_3^{AR}) S_3^{AR} \right) + (S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) S_3^{AR} \right)} \quad (8d)$$

$$q_3^{AR*} = \frac{(2 - K) S_1^A (S_2^A - S_2^R) (2S_3^{AR} - S_3^{AA})}{S_1^A \left( (S_2^A - S_2^R) S_3^{AA} + (S_3^{AA} - S_3^{AR}) S_3^{AR} \right) + (S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) S_3^{AR}} \quad (8e)$$

Note that this closed-form solution applies when  $K \leq 2$  and all markets can still be served. When airport capacity is so small that airline cannot support air services in all markets, the above objective function of airline and HSR should be reformulated to drop the air traffic in the market

that airline is not going to supply. The market that airline will withdraw from first depends on service quality parameters. Hence, Proposition 3 can be derived.

**Proposition 3:** Under cooperation scenario (1) when airline cannot serve all three markets due to limited airport capacity, it will first withdraw from market 1 if  $S_1^A < S_2^A - S_2^R$  and  $S_1^A < S_3^{AA} - S_3^{AR}$ , first withdraw from market 2 if  $S_2^A - S_2^R < S_3^{AA} - S_3^{AR}$  and  $S_2^A - S_2^R < S_1^A$ , and first withdraw from market 3 if  $S_3^{AA} - S_3^{AR} < S_2^A - S_2^R$  and  $S_3^{AA} - S_3^{AR} < S_1^A$ ; (2) if  $2S_3^{AR} < S_3^{AA}$ , airline and HSR will not serve air-rail connecting passengers, even though airport capacity is constrained; (3) HSR will not provide services unless hub airport is subjected to capacity constraint.

***Proof:***

Part (1):

From equation (8a), we can derive the capacity  $K_{q_1^A}$  that makes  $q_1^{A*} = 0$ :

$$K_{q_1^A} = \frac{3(S_2^A - S_2^R)(S_3^{AA} - S_3^{AR})S_3^{AR} - S_1^A((S_2^A - S_2^R)S_3^{AA} + (S_3^{AA} - S_3^{AR})S_3^{AR})}{2(S_2^A - S_2^R)(S_3^{AA} - S_3^{AR})S_3^{AR}}$$

Similarly,

$$K_{q_2^A} = \frac{S_1^A(3(S_3^{AA} - S_3^{AR})S_3^{AR} - S_3^{AA}(S_2^A - S_2^R)) - (S_2^A - S_2^R)(S_3^{AA} - S_3^{AR})S_3^{AR}}{2S_1^A(S_3^{AA} - S_3^{AR})S_3^{AR}}$$

$$K_{q_3^{AA}} = \frac{S_1^A((4S_3^{AR} - S_3^{AA})(S_2^A - S_2^R) - S_3^{AR}(S_3^{AA} - S_3^{AR})) - (S_2^A - S_2^R)(S_3^{AA} - S_3^{AR})S_3^{AR}}{2S_1^A(S_2^A - S_2^R)S_3^{AR}}$$

A comparison of  $K_{q_1^A}$ ,  $K_{q_2^A}$  and  $K_{q_3^{AA}}$  gives airline's decision on which market to withdraw from first due to limited airport capacity. For instance, if  $K_{q_3^{AA}} < K_{q_2^A}$  and  $K_{q_1^A} < K_{q_2^A}$ , airline will withdraw air service in market 2 but will still remain in market 1 and market 3 when airport capacity becomes smaller than  $K_{q_2^A}$ .

Recall that we have assumed  $S_2^A > S_2^R$  and  $S_3^{AA} > S_3^{AR}$ .

$$K_{q_3^{AA}} - K_{q_2^A} = \frac{((S_2^A - S_2^R) - (S_3^{AA} - S_3^{AR}))(S_1^A((S_2^A - S_2^R)S_3^{AA} + (S_3^{AA} - S_3^{AR})S_3^{AR})) + (S_2^A - S_2^R)(S_3^{AA} - S_3^{AR})S_3^{AR}}{2S_1^A(S_2^A - S_2^R)(S_3^{AA} - S_3^{AR})S_3^{AR}}$$

$$K_{q_2^A} - K_{q_1^A} = \frac{(S_1^A - (S_2^A - S_2^R))(S_1^A((S_2^A - S_2^R)S_3^{AA} + (S_3^{AA} - S_3^{AR})S_3^{AR})) + (S_2^A - S_2^R)(S_3^{AA} - S_3^{AR})S_3^{AR}}{2S_1^A(S_2^A - S_2^R)(S_3^{AA} - S_3^{AR})S_3^{AR}}$$

$$K_{q_3^{AA}} - K_{q_1^A} = \frac{(S_1^A - (S_3^{AA} - S_3^{AR}))(S_1^A((S_2^A - S_2^R)S_3^{AA} + (S_3^{AA} - S_3^{AR})S_3^{AR})) + (S_2^A - S_2^R)(S_3^{AA} - S_3^{AR})S_3^{AR}}{2S_1^A(S_2^A - S_2^R)(S_3^{AA} - S_3^{AR})S_3^{AR}}$$

Hence, we have:

$$K_{q_3^{AA}} > K_{q_2^A} \Leftrightarrow S_2^A - S_2^R > S_3^{AA} - S_3^{AR}$$

$$K_{q_3^{AA}} > K_{q_1^A} \Leftrightarrow S_1^A > S_3^{AA} - S_3^{AR}$$

$$K_{q_2^A} > K_{q_1^A} \Leftrightarrow S_1^A > S_2^A - S_2^R$$

*Q.E.D.*

Part (2):

From equation (8e), it is straightforward to observe that  $q_3^{AR*} > 0 \Leftrightarrow 2S_3^{AR} > S_3^{AA}$ .

*Q.E.D.*

Part (3):

From equation (8c), it is straightforward to observe that  $q_2^{R*} > 0 \Leftrightarrow K < 2$ .

From equation (8e), if  $2S_3^{AR}$  is larger than  $S_3^{AA}$ , it can be observed that  $q_3^{AR*} > 0 \Leftrightarrow K < 2$ .

*Q.E.D.*

Part (1) of Proposition 3 implies that when airline cannot supply all markets, it will abandon the one with the lowest competitive advantage over HSR. This is intuitive because maintaining the markets with relatively higher competitive advantage enables airline and HSR to make more revenue by charging higher price. Part (2) reflects the attractiveness of providing air-rail connecting service. Even though air-rail connecting passengers occupy airport runway only once, airline and HSR will not be motivated to provide air-rail service if the service quality of air-rail connection is not perceived sufficiently high by passengers. Part (3) shows that HSR helps relieve hub airport capacity constraint by providing rail and air-rail services.

Recall that air-rail passengers buy separate tickets from airline and HSR under competition scenario, while they buy integrated air-rail tickets under cooperation scenario. A comparison of Equation (7a), (7c) and (7e) and equations in Table 3-8 gives rise to Proposition 4.

***Proposition 4:*** Under cooperation scenario, when all markets can be covered by airline,  $P_1^{A*} + P_2^{R*} - P_3^{AR*} = \frac{1}{2}(S_1^A + S_2^R - S_3^{AR})$  always holds.

The implication of Proposition 4 is that under cooperation scenario, the integrated ticket of air-rail transfer service may not always be cheaper than buying the ticket separately, as it depends on

the net travel benefits in the three markets. If  $S_3^{AR}$  is smaller than  $S_1^A + S_2^R$ , airline and HSR will offer a discount for the integrated air-rail ticket. If this is not the case, the integrated ticket will even be higher than buying the tickets separately. In fact, the difference between  $S_3^{AR}$  and  $S_1^A + S_2^R$  measures how connecting passengers value the integrated service provided by airline and HSR jointly to facilitate air-rail transfer under cooperation scenario. In reality, buying two separate items can be more expensive than buying a combined one, because otherwise the pricing of the combined item would be invalid. For example, booking flight and hotel together can be much cheaper than booking them separately. However, the main point here is that if the quality of an integrated trip is perceived higher than the quality of two separate trips, the integrated ticket can be more costly. For instance, non-stop flights are usually more expensive than flights with one or more stops. Although this example does not fit into the setting of the model, it illustrates the main point of Proposition 4.

## Chapter 4: Social Welfare Comparison

Since comparing social welfare between competition and cooperation scenarios analytically is very complicated when airport capacity comes into play, we do it numerically. We consider two cases. One is long-haul case in which air travel is preferred in all markets, the other is medium-haul case in which air-air travel is preferred in market 3, but HSR is preferred in market 2.

### 4.1 Long-haul case

First of all, we compute social welfare in the three markets.

$$SW_1 = \pi_1^A + CS_1 = P_1^{A*} q_1^{A*} + \int_{\frac{P_1^{A*}}{S_1^A}}^1 (\theta S_1^A - P_1^{A*}) d\theta = P_1^{A*} q_1^{A*} + \frac{1}{2} S_1^A (q_1^{A*})^2 \quad (9a)$$

$$\begin{aligned} SW_2 &= \pi_2^A + \pi_2^R + CS_2 \\ &= P_2^{A*} q_2^{A*} + P_2^{R*} q_2^{R*} + \int_{\frac{P_2^{A*}-P_2^{R*}}{S_2^A-S_2^R}}^1 (\theta S_2^A - P_2^{A*}) d\theta + \int_{\frac{P_2^{R*}}{S_2^R}}^{\frac{P_2^{A*}-P_2^{R*}}{S_2^A-S_2^R}} (\theta S_2^R - P_2^{R*}) d\theta \\ &= P_2^{A*} q_2^{A*} + P_2^{R*} q_2^{R*} + \frac{1}{2} q_2^{A*} (S_2^A - P_2^{A*}) + \frac{1}{2} q_2^{R*} (S_2^R - P_2^{R*}) \end{aligned} \quad (9b)$$

$$\begin{aligned} SW_3 &= \pi_3^{AA} + \pi_3^{AR} + CS_3 \\ &= \pi_3^{AA} + \pi_3^{AR} + \int_{\frac{P_3^{AA*}-P_3^{AR*}}{S_3^{AA}-S_3^{AR}}}^1 (\theta S_3^{AA} - P_3^{AA*}) d\theta + \int_{\frac{P_3^{AR*}}{S_3^{AR}}}^{\frac{P_3^{AA*}-P_3^{AR*}}{S_3^{AA}-S_3^{AR}}} (\theta S_3^{AR} - P_3^{AR*}) d\theta \\ &= P_3^{AA*} q_3^{AA*} + P_3^{AR*} q_3^{AR*} + \frac{1}{2} q_3^{AA*} (S_3^{AA} - P_3^{AA*}) + \frac{1}{2} q_3^{AR*} (S_3^{AR} - P_3^{AR*}) \end{aligned} \quad (9c)$$

$$SW = SW_1 + SW_2 + SW_3 \quad (9d)$$

Recall that we break down total travel time into access, egress and terminal time, in-vehicle time and connecting time in Table 3-1. Details of parameter values used for social welfare analysis are shown in Table 4-1. Although trip times and gross travel benefits summarized in Table 4-1 may be somewhat arbitrary, they reflect the characteristics that (1) access, egress and terminal time by rail is shorter than by air, (2) airline-HSR cooperation benefits air-rail connecting passengers in reducing connecting time, and (3) air travel is always preferred in all markets if air travel distance in market 2 is sufficiently long. We did many numerical tests with different sets of parameters that satisfy the above characteristics. The results are similar. One of the tests is presented in Appendix B to show that the results of social welfare comparison are robust.

**Table 4-1: Parameter values for social welfare analysis in long-haul case**

	Total travel time	Gross travel benefit
Market 1 (air only)	$T_1^A = 3h + \frac{7500km}{740km/h} \approx 13h$	$b_1 = 25h$
Market 2 (air)	$T_2^A = 3h + \frac{1000km}{740km/h} \approx 4.5h$	$b_2 = 10h$
Market 2 (HSR)	$T_2^R = 1h + \frac{1100km}{250km/h} \approx 5.5h$	
Market 3 (air-air)	$T_3^{AA} = 3h + \frac{8500km}{740km/h} + 2h \approx 16.5h$	$b_3 = 35h$
Market 3 (air-rail)	$T_3^{AR-comp} = 2h + \frac{7500km}{740km/h} + \frac{1100km}{250km/h} + 3h \approx 19.5h$	
	$T_3^{AR-coop} = 2h + \frac{7500km}{740km/h} + \frac{1100km}{250km/h} + 2h \approx 18.5h$	

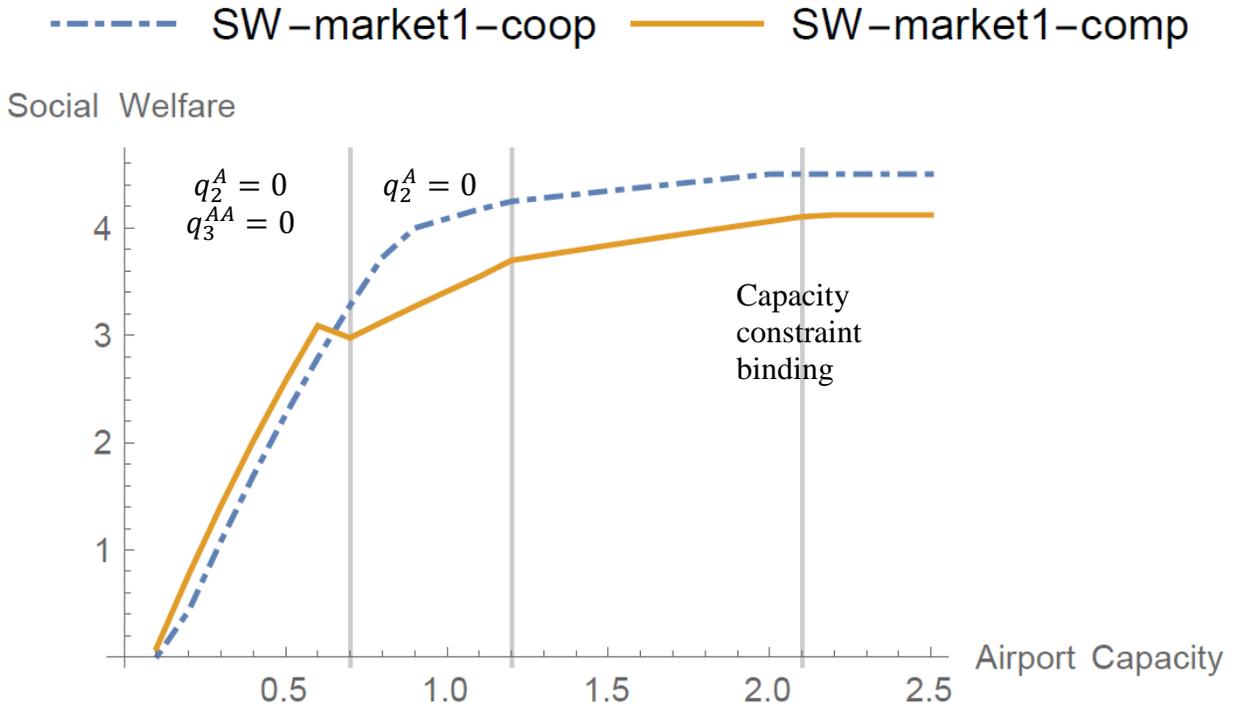
The speed of HSR that we use in the numerical analysis is 250 km/h, which is usually considered as a benchmark speed. For instance, International Union of Railways (UIC) defines a rail service as high-speed if it reaches over 250 km/h on some parts of the route. Furthermore, when we take into account intermediate stops, acceleration and deceleration time, 250 km/h is a reasonable average speed for the whole HSR journey. The speed of aircraft is close to the speed of sound and stays relatively stable.

We compute social welfare under both competition and cooperation scenarios for different values of airport capacity. We first compare social welfare in each market, and then compare overall social welfare in the network. The results are presented from Figure 4-1 to Figure 4-4. For better explanation, we draw three vertical lines in the figures. The vertical lines indicate the airport capacity ranges within which airline is subjected to capacity constraint or has to abandon certain market(s). Note that the capacity ranges under competition scenario are slightly different from the ranges under cooperation scenario. In the figures, we show the capacity ranges under competition scenario.

Figure 4-1 shows social welfare comparison in market 1 for long-haul case. The solid line represents social welfare under competition scenario, while the dotted line represents social welfare under cooperation scenario. When there is excess capacity, social welfare remains unchanged for both competition and cooperation scenarios. When capacity constraint becomes binding, social welfare in both scenarios decreases first gradually then drastically with the decrease of airport capacity. Figure 4-1 also shows that cooperation generates larger social welfare than competition in market 1 until runway capacity becomes sufficiently small. A

comparison of  $P_1^A$  under competition scenario (Equation 5a) and  $P_1^A$  under cooperation scenario (Table 3-8) gives rise to Proposition 5.

Figure 4-1: Social welfare comparison in market 1 for long-haul case



**Proposition 5:** When hub airport is not subjected to capacity constraint, airline charges higher air fare under competition scenario than under cooperation scenario in the market where HSR is not present.

**Proof:**

When airport is not subjected to capacity constraint, we have derived equilibrium results under competition and cooperation scenarios in Equation (5)-(6) and Table 3-8:

$$P_1^{A^*-comp} = \frac{S_1^A S_3^{AR} (3S_2^R S_3^{AA} (S_2^A - S_2^R) + S_3^{AR} (4S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}))}{3S_1^A S_2^R S_3^{AA} (S_2^A - S_2^R) + S_3^{AR} (4S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) (S_1^A + S_3^{AR}) + S_2^R S_3^{AR} (S_2^A - S_2^R) (4S_3^{AA} - S_3^{AR})}$$

$$P_1^{A^*-coop} = \frac{S_1^A}{2}$$

Thus,  $P_1^{A^*-comp} - P_1^{A^*-coop} = S_1^A q_3^{AR^*-comp} + \gamma$ , where

$$\gamma = \frac{S_2^R (S_2^A - S_2^R) S_3^{AA} S_3^{AR}}{3S_1^A S_2^R S_3^{AA} (S_2^A - S_2^R) + S_3^{AR} (4S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) (S_1^A + S_3^{AR}) + S_2^R S_3^{AR} (S_2^A - S_2^R) (4S_3^{AA} - S_3^{AR})}$$

$$q_3^{AR^*-comp} = \frac{S_2^R (S_2^A - S_2^R) ((S_3^{AR})^2 - 3S_1^A S_3^{AA}) + S_3^{AR} (4S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) (S_3^{AR} - S_1^A)}{2(3S_1^A S_2^R S_3^{AA} (S_2^A - S_2^R) + S_3^{AR} (4S_2^A - S_2^R) (S_3^{AA} - S_3^{AR}) (S_1^A + S_3^{AR}) + S_2^R S_3^{AR} (S_2^A - S_2^R) (4S_3^{AA} - S_3^{AR}))}$$

It can be shown that  $\gamma > 0$ , because we assume  $S_1^A > 0$ ,  $S_2^A > S_2^R > 0$  and  $S_3^{AA} > S_3^{AR} > 0$ .

Since  $q_3^{AR^*} > 0$  and  $\gamma > 0$ , it turns out that  $P_1^{A^*-comp} > P_1^{A^*-coop}$ .

*Q.E.D.*

Proposition 5 shows that the inequality  $P_1^{A^*-comp} > P_1^{A^*-coop}$  always holds when airport capacity is not constrained. Although competition is generally believed to be more socially beneficial than cooperation, Proposition 5 implies that even under competition scenario and with sufficient airport capacity, airline charges higher-than-monopoly price in market 1.

The reason is that under competition scenario, airline is competing with HSR not only for non-stop passengers but also for connecting passengers. Hence, under competition scenario, airline's pricing strategy in market 1 will affect connecting passengers' mode choice, as they buy air-rail tickets from the two operators separately. The situation is different for cooperation scenario, in which connecting passengers' behavior will not be affected by air fare in market 1, because an integrated ticket is provided for air-rail transfer passengers. Since airline, when competing with HSR, wants to make air-air connecting service more appealing, its strategy is to increase air fare

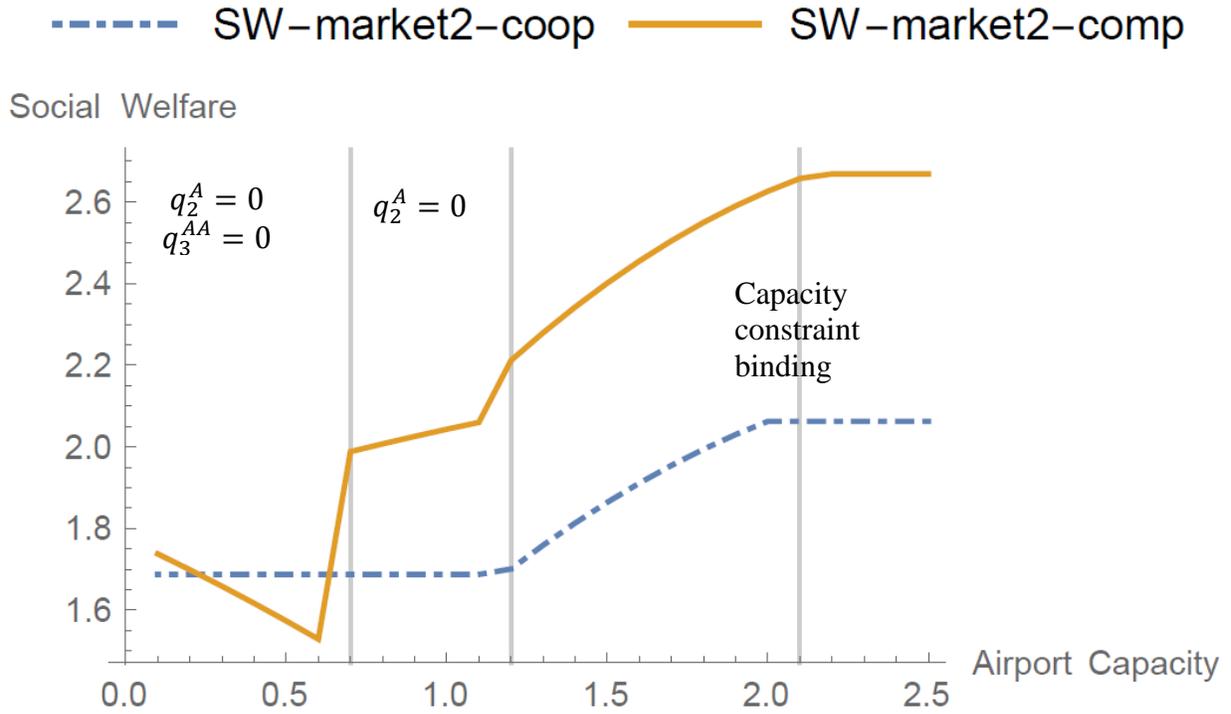
in market 1 so as to make air-rail connecting service more expensive, thus less attractive.

However, this strategy harms passengers and social welfare in market 1. As a result, competition may lead to a lower social welfare in market 1 than cooperation does.

In the numerical analysis, when airline can still serve market 3, air fare under competition scenario is strictly higher than under cooperation scenario in market 1. The higher air fare contributed to the lower social welfare under competition scenario. When airline becomes just unable to serve air-air passengers,  $P_1^{A^*-\text{comp}}$  becomes lower than  $P_1^{A^*-\text{coop}}$ , because airline no longer needs to intentionally make air-rail service unattractive by increasing air fare in market 1. This explains the slight increase of social welfare under competition scenario. Consequently, competition becomes socially desirable in market 1 when capacity is sufficiently small.

Proposition 5 may not work when entry is possible. In fact, by increasing air price in market 1, airline trades off the loss of revenue in market 1 and the gain in market 3. When entry is possible, the loss in market 1 may not be offset by the gain in market 3. However, if the incumbent airline has some market power in market 1 so that the entrant airline can only gain an exogenous amount of market share in market 1, Proposition 5 may still work. The market power may be due to frequent flyer program, service quality, brand loyalty, a strong safety record, etc.

Figure 4-2: Social welfare comparison in market 2 for long-haul case



Market 2 is the non-stop market where airline is subjected to direct competition from HSR. Intuitively, competition should be encouraged in market 2 from a social welfare perspective. Figure 4-2 shows social welfare comparison in market 2. Social welfare in market 2 under competition scenario is higher than under cooperation scenario except when airport capacity is sufficiently small.

When airport is not capacity constrained, only airline serves market 2 and charges monopoly price under cooperation scenario, as shown in Proposition 2. The competition between airline and HSR generates larger social welfare, when airport is not capacity constrained. When hub airport is subjected to capacity constraint but airline can still cover all markets, social welfare of both scenarios falls gradually, but social welfare under competition scenario is still larger. When

airline can no longer serve market 2, passengers in market 2 can only travel by HSR. Under cooperation scenario, social welfare remains unchanged, as passengers bear monopoly rail price. Under competition scenario, although HSR also becomes the monopoly in market 2, it will charge lower-than-monopoly price due to the consideration of air-rail transfer passengers. Two sharp decreases of social welfare occur under competition scenario as soon as airline cannot support market 2 or market 3. The reason is the sudden increase of rail price, as HSR gains market power each time airline withdraws from a market. The second sharp decrease of social welfare under competition scenario renders cooperation socially more desirable. Since then, social welfare increases with the decrease of airport capacity, because, in order to capture air-rail transfer passengers, rail price starts to decrease to mitigate the fast increase of air fare in market 1, thus benefiting market 2.

Figure 4-3: Social welfare comparison in market 3 for long-haul case

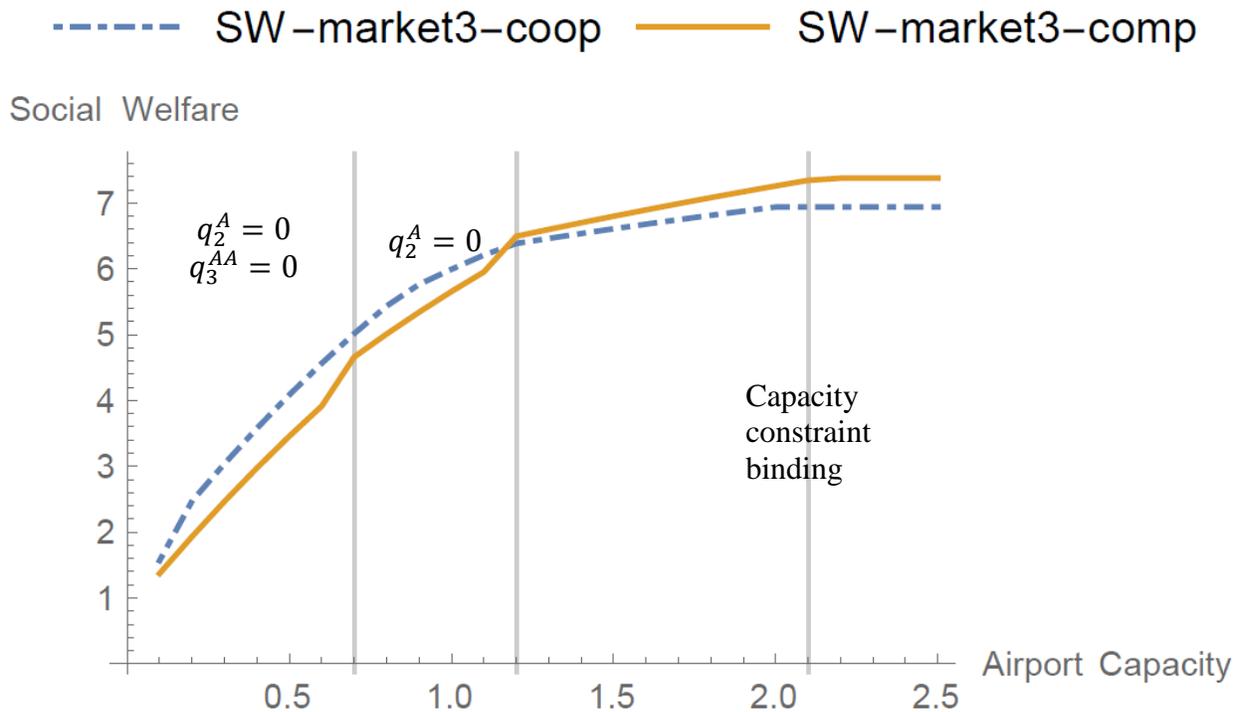


Figure 4-3 illustrates social welfare comparison in market 3. When airport capacity constraint is not binding, air-air is the only available mode under cooperation scenario. Thus, competition is socially preferred to cooperation in market 3 for sufficiently large airport capacity. However, as airport capacity shrinks, the gap is narrowed. When airport capacity passes the point where airline cannot serve all markets, cooperation becomes socially more desirable than competition. The reason is that when airline cannot support market 2, HSR becomes the monopoly in market 2 and a jump of rail price is expected under competition scenario. Hence, passengers traveling by air-rail in market 3 will be negatively affected. HSR will again raise its price under competition scenario when  $q_3^{AA}$  goes to zero. We can see that the gap between cooperation and competition is widened. The gap gets closer when airport capacity is very small, but still cooperation is preferable in market 3.

Figure 4-4: Overall social welfare comparison for long-haul case

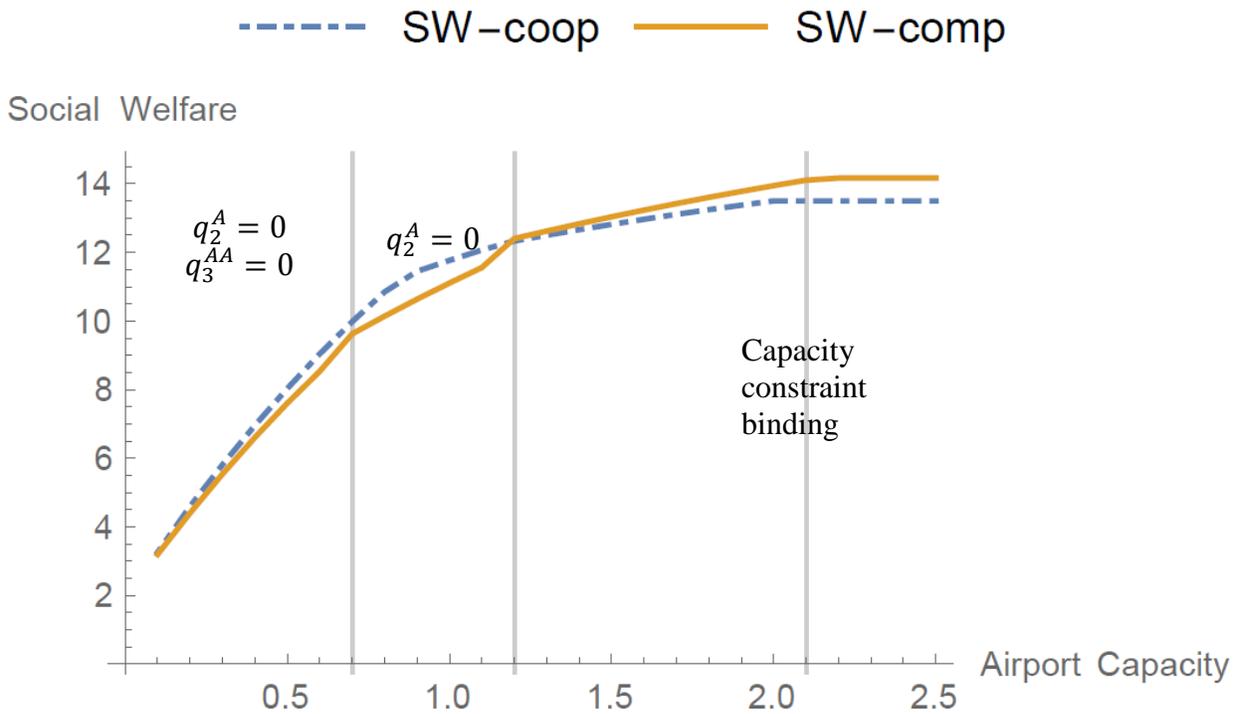


Figure 4-4 depicts the comparison of overall social welfare, which is the sum of social welfare in all three markets. When airport capacity is sufficient, competition is socially desirable. As airport capacity becomes smaller, the difference of overall social welfare between competition and cooperation is narrowed. When airline cannot serve all markets, cooperation becomes socially preferred. As airport capacity gets even smaller, the gap is again narrowed.

#### 4.2 Medium-haul case

When market 2 is a medium-haul market, HSR becomes the preferred mode. However, in market 3, air-air connection is still preferred. The demand functions of medium-haul case are expressed in Table 4-2. Note that compared with long-haul case in Table 3-2, the only difference is in market 2.

**Table 4-2: Traffic volumes of all markets in medium-haul case**

Market	Traffic Volume
Market 1(Only air)	$q_1^A = \min\left\{\left[1 - \frac{P_1^A}{S_1^A}\right]^+, 1\right\}$
Market 2 (Air)	$q_2^A = \min\left\{\left[\frac{P_2^R - P_2^A}{S_2^R - S_2^A} - \frac{P_2^A}{S_2^A}\right]^+, 1\right\}$
Market 2 (HSR)	$q_2^R = \min\left\{\left[1 - \frac{P_2^R - P_2^A}{S_2^R - S_2^A}\right]^+, 1\right\}$
Market 3 (Air-Air)	$q_3^{AA} = \min\left\{\left[1 - \frac{P_3^{AA} - P_3^{AR}}{S_3^{AA} - S_3^{AR}}\right]^+, 1\right\}$
Market 3 (Air-HSR)	$q_3^{AR} = \min\left\{\left[\frac{P_3^{AA} - P_3^{AR}}{S_3^{AA} - S_3^{AR}} - \frac{P_3^{AR}}{S_3^{AR}}\right]^+, 1\right\}$

For medium-haul case, the computation of social welfare in market 1 and market 3 is the same as Equation (9a) and Equation (9c) in long-haul case. Social welfare computation in market 2 is expressed in Equation (10). Although the integral is different from Equation (9b) in long-haul case, the result turns out to be the same.

$$\begin{aligned}
SW_2 &= \pi_2^A + \pi_2^R + CS_2 \\
&= P_2^{A*} q_2^{A*} + P_2^{R*} q_2^{R*} + \int_{\frac{P_2^{R*} - P_2^{A*}}{S_2^R - S_2^A}}^1 (\theta S_2^R - P_2^{R*}) d\theta + \int_{\frac{P_2^{A*}}{S_2^A}}^{\frac{P_2^{R*} - P_2^{A*}}{S_2^R - S_2^A}} (\theta S_2^A - P_2^{A*}) d\theta \\
&= P_2^{A*} q_2^{A*} + P_2^{R*} q_2^{R*} + \frac{1}{2} q_2^{R*} (S_2^R - P_2^{R*}) + \frac{1}{2} q_2^{A*} (S_2^A - P_2^{A*}) \tag{10}
\end{aligned}$$

We adjust down travel distance in market 2 so that traveling in market 2 by HSR takes less door-to-door time than by air transport. The parameter values used for numerical analysis are presented in Table 4-3.

**Table 4-3: Parameter values for social welfare analysis in medium-haul case**

	Total travel time	Gross travel benefit
Market 1 (air only)	$T_1^A = 3h + \frac{7500km}{740km/h} \approx 13h$	$b_1 = 25h$
Market 2 (air)	$T_2^A = 3h + \frac{450km}{740km/h} \approx 3.5h$	$b_2 = 10h$
Market 2 (HSR)	$T_2^R = 1h + \frac{500km}{250km/h} = 3h$	
Market 3 (air-air)	$T_3^{AA} = 3h + \frac{7500km + 450km}{740km/h} + 2h \approx 15.5h$	
	$T_3^{AR-comp} = 2h + \frac{7500km}{740km/h} + \frac{500km}{250km/h} + 3h \approx 17h$	$b_3 = 35h$
Market 3 (air-rail)	$T_3^{AR-coop} = 2h + \frac{7500km}{740km/h} + \frac{500km}{250km/h} + 2h \approx 16h$	

Social welfare comparison for medium-haul case is depicted from Figure 4-5 to Figure 4-8. We compare social welfare first in each market, then in the overall network. As in the long-haul case, we also draw three vertical lines in the figures to divide hub airport capacity into several ranges under competition scenario. The capacity ranges under competition scenario are different from those under cooperation scenario. Under cooperation scenario, airline does not serve market 2 no matter how large airport capacity is, because HSR is always the preferred mode. When  $K < 1.5$ , airport capacity constraint becomes binding<sup>10</sup>. Thus, social welfare remains unchanged for  $K \geq 1.5$ . With the selected parameter values, it turns out that, for  $0.97 \leq K < 1.5$ , airline can still serve all markets except market 2 which is always left to HSR under cooperation scenario. For  $0.18 \leq K < 0.97$ , airline is not able to serve market 3. For  $0 < K < 0.18$ , airline is not able to serve market 1. The three vertical lines for cooperation scenario are  $K = 1.5$ ,  $K = 0.97$  and  $K = 0.18$ , which are not depicted in the figures for the reason of clear illustration.

Figure 4-5 illustrates social welfare comparison in market 1 for medium-haul case. Cooperation is socially preferred in market 1 until airline can no longer support market 3 due to insufficient airport capacity. In fact, Proposition 5 also applies for medium-haul case. Airline charges higher-than-monopoly price in market 1 under competition scenario when hub airport capacity is not constrained. The aim of airline's excessive pricing in market 1 is to facilitate its competition against HSR for connecting passengers in market 3, but it negatively affects passengers in market 1. When airline withdraws from market 3, the excessive pricing becomes unnecessary.

---

<sup>10</sup> This is different from long-haul case, in which airport capacity becomes binding when  $K < 2$  under cooperation scenario. In long-haul case, we do not explain in detail the difference of capacity ranges between competition and cooperation scenarios, because the difference is almost negligible.

The overall trend shown in Figure 4-5 is similar to the long-haul case in Figure 4-1, but the negative impact of airline's excessive pricing in market 1 seems to be larger in the medium-haul case.

Figure 4-5: Social welfare comparison in market 1 for medium-haul case

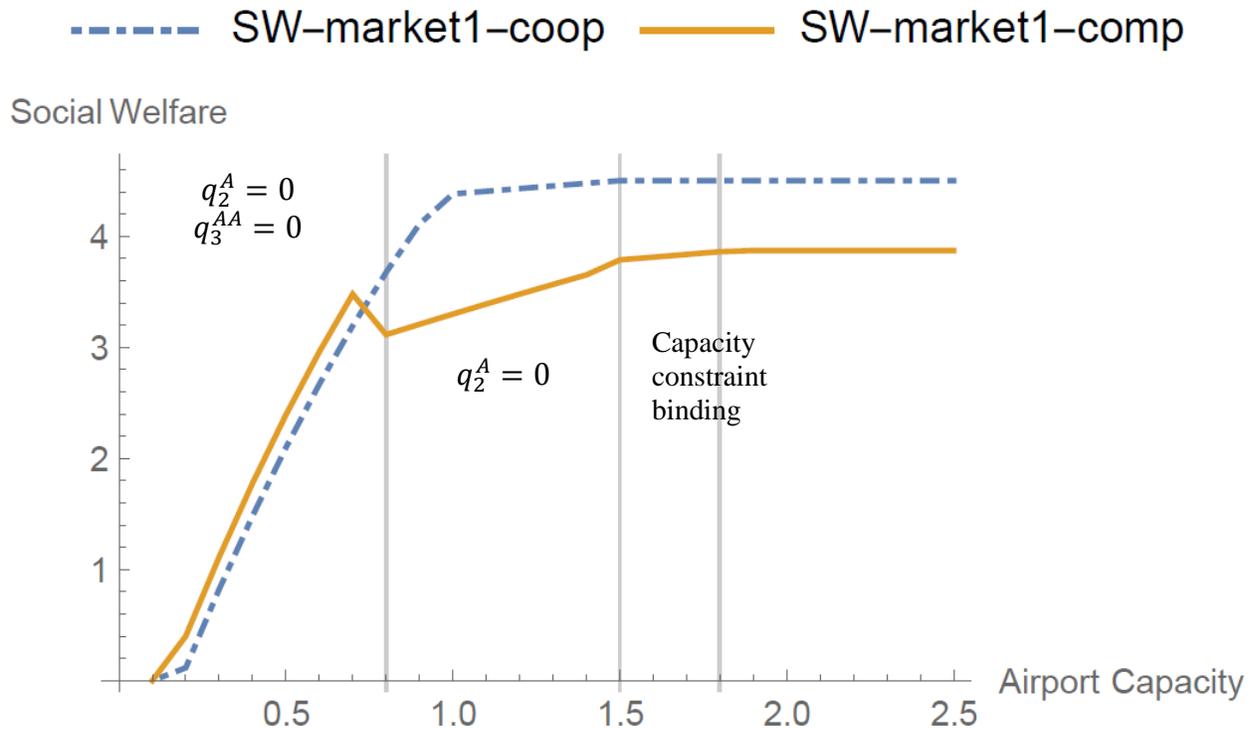
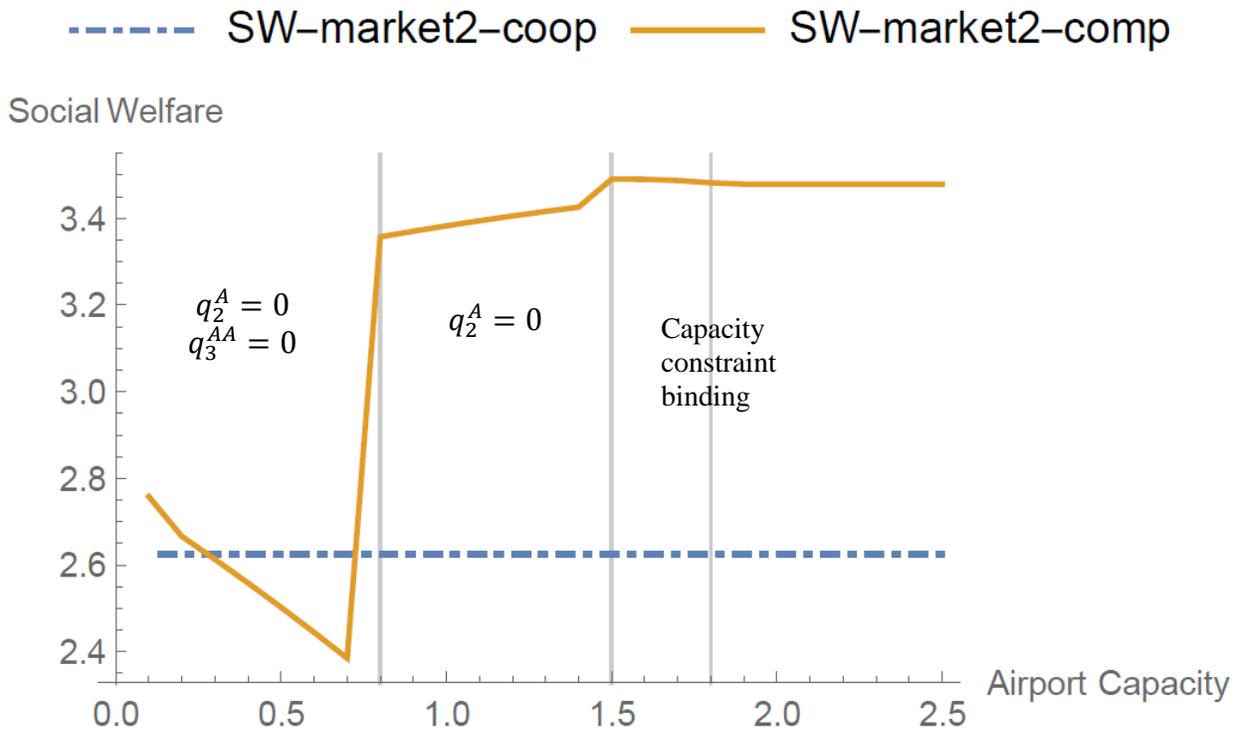


Figure 4-6 shows social welfare comparison in market 2. As mentioned earlier, under cooperation scenario, HSR is the only transport mode in market 2 and charges monopoly price. Consequently, social welfare under cooperation scenario is a constant independent of airport capacity. When airline is subjected to capacity constraint but can still serve all markets, there is a slight increase of social welfare in market 2 under competition scenario. This is different from the long-haul case where social welfare decreases gradually within this capacity range. The reason is that when airport is capacity constrained, air fare in market 2 increases to a greater

extent than rail fare does. As a result, more (less, respectively) passengers travel by HSR (air, respectively) than when capacity constraint is not binding, despite that the overall traffic volume is smaller. Since HSR is preferred in medium-haul market, the increase of HSR passengers brings about a slight increase in social welfare in market 2. When airline cannot support all markets, social welfare changes in a similar pattern as long-haul case for the same reasons explained earlier. In summary, no matter market 2 is a medium-haul or long-haul market, competition always benefit market 2 until airport capacity is very small. The negative impact of cooperation in market 2 seems to be larger in the medium-haul case.

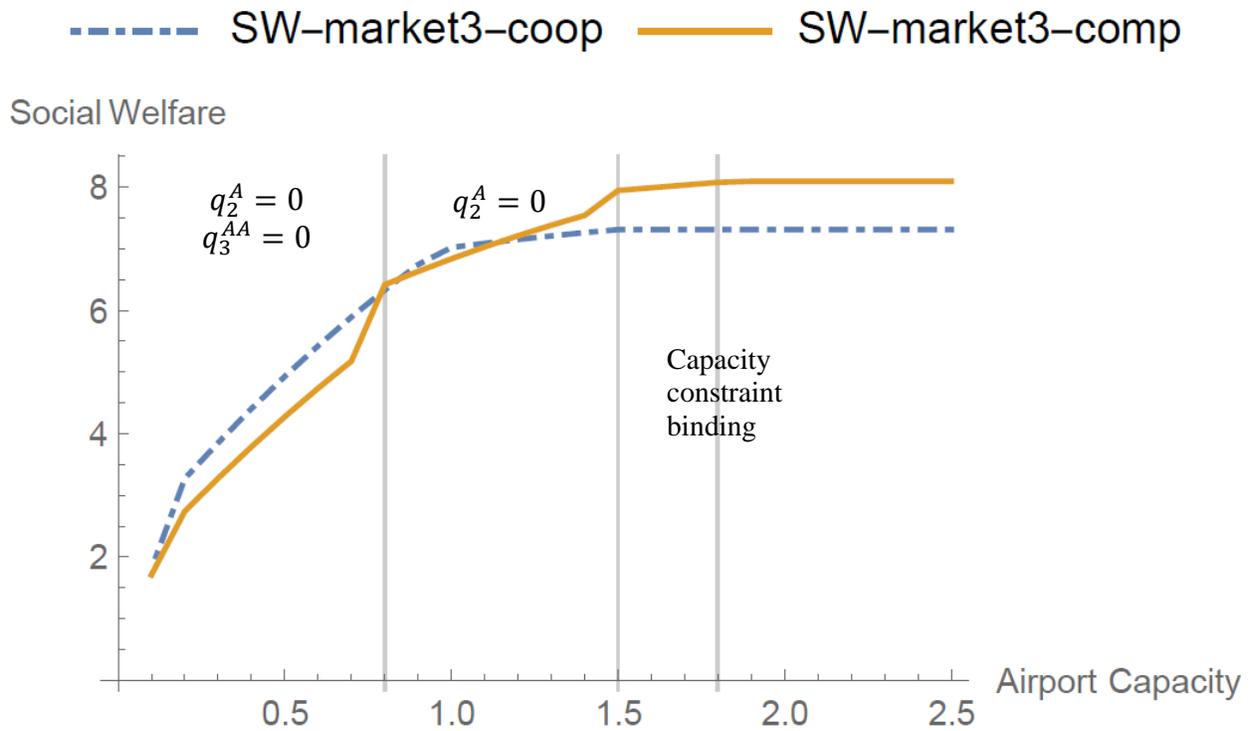
Figure 4-6: Social welfare comparison in market 2 for medium-haul case



Social welfare comparison in market 3 is depicted in Figure 4-7. When airline and HSR cooperate, they will not serve air-rail connecting market until  $K < 1.5$ . For  $K \geq 1.5$ , social welfare in market 3 is a constant. Introducing competition will undoubtedly improve social

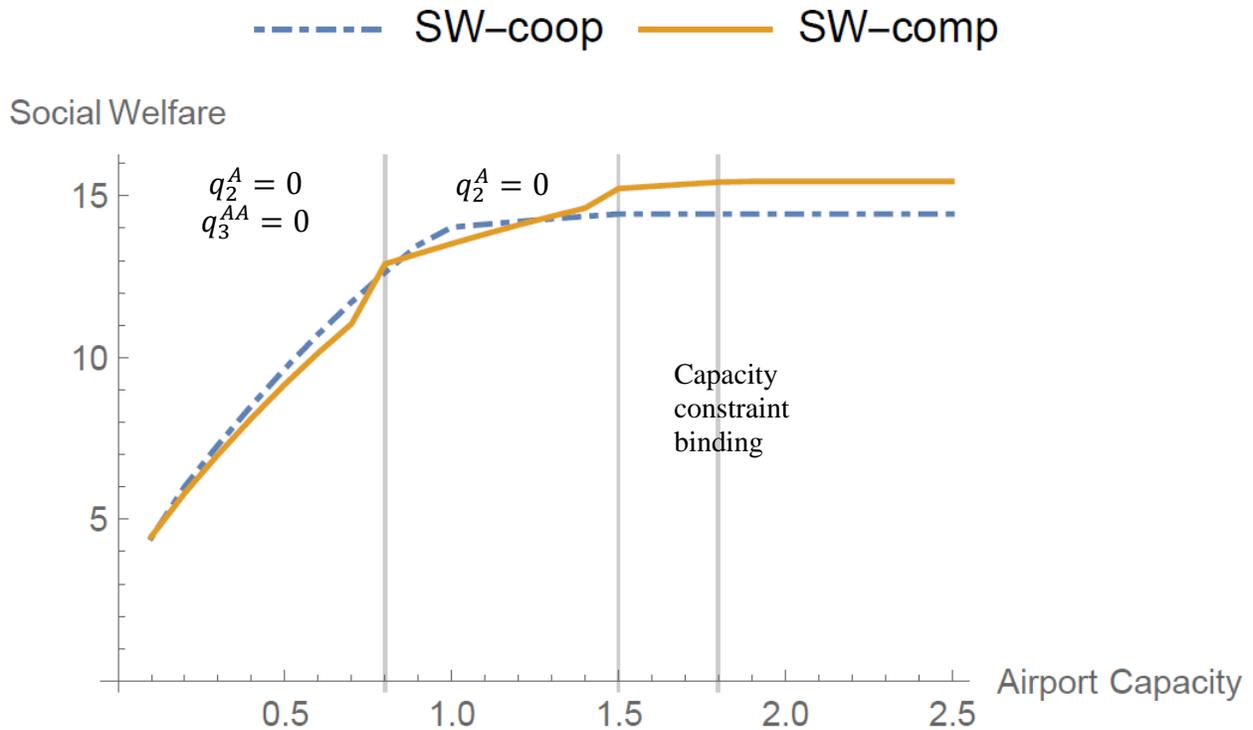
welfare when airport is not subjected to capacity constraint. As social welfare decreases with the decrease of airport capacity, cooperation becomes socially better than competition when airline cannot serve air-air passengers. As air-rail becomes the only transport mode in market 3, the fares of air-rail service in both scenarios are nearly the same. However, air-rail service under cooperation scenario is perceived of higher quality than under competition scenario, because of the integrated services provided jointly by HSR and airline when they cooperate. As a result, social welfare under cooperation scenario turns out to be higher for insufficient airport capacity. In summary, competition generates higher social welfare than cooperation does in market 3 when airport capacity is sufficient for airline to serve all markets. Otherwise, intermodal cooperation is socially desirable in market 3.

Figure 4-7: Social welfare comparison in market 3 for medium-haul case



The overall social welfare comparison of medium-haul case is presented in Figure 4-8. Competition is socially desirable when airline can serve all markets. Otherwise cooperation is found to be socially preferred.

Figure 4-8: Overall social welfare comparison for medium-haul case



Based on welfare analysis in the long-haul and medium-haul cases, the conditions under which intermodal competition or cooperation should be encouraged in both cases are similar. Intermodal cooperation (competition, respectively) should be encouraged in market 1 (market 2, respectively) until airport capacity is so small that airline can only support one market. In market 3, intermodal competition should be encouraged when airline can serve all markets. However, as the case that airline can only serve one market due to heavily constrained airport capacity is

uncommon in practice, we can conclude that intermodal cooperation benefits market 1 but harms market 2 from social welfare perspective. In terms of overall social welfare, intermodal cooperation should be encouraged when airline cannot serve all markets in its competition with HSR.

However, the results are based on the assumption that the sizes of all markets are the same. Different market sizes will not change welfare comparison results in a single market, but will affect the results of overall social welfare in the network. If market 1 is much larger than the other two markets, intermodal cooperation should be encouraged, since the negative impact of competition in market 1 may dominate the positive impacts of competition in market 2 and 3. In contrast, if market 2 is much larger than the other two markets, intermodal competition should be encouraged. In addition, if market 3 is much larger than the other two markets, intermodal cooperation should be encouraged only when airline cannot serve all markets in its competition with HSR.

Policy makers of one country may not place equal weights on all markets in the network. They may consider domestic markets to be more important than international ones. If market 2 is considered to be more important, intermodal competition should be encouraged, while if market 1 is considered to be more important, intermodal cooperation should be encouraged.

## **Chapter 5: Conclusion and future research**

### **5.1 Conclusion**

This thesis contributes to the literature on intermodal competition and cooperation between HSR and airline with vertical differentiation by developing a theoretical model which incorporates different segments of total travel time and aims to analyze under what circumstances intermodal cooperation or competition between HSR and airline would be socially beneficial.

The merits of the theoretical model developed in this thesis are twofold. First, it provides a first attempt to consider vertical differentiation between airline and HSR theoretically. Second, the model developed in this paper can offer some policy implications for evaluating the potential effects of airline and HSR cooperation.

Our model shows that HSR (air travel, respectively) is preferred in short-to-medium-haul (long-haul, respectively) markets, while, in connecting markets, air-air is preferred for connecting travel when one leg of the journey is medium-to-long-haul markets. By deriving equilibrium outcomes under both competition and cooperation scenarios with the consideration of potential hub airport runway congestion, we have the following findings.

1. An improvement of rail speed or air-rail connecting time will lead to a decrease of air fare on the routes that HSR and airline compete;
2. When the willingness to travel in a market increases, it will boost both the fares and traffic volumes in this market;
3. When airline cannot serve all markets due to limited hub airport capacity, it will not necessarily withdraw first from the connecting market which occupies more airport

capacity. Instead, airline will withdraw from the market in which it has less competitive advantage over HSR;

4. The integrated ticket offered by airline and HSR for air-rail connecting service may not always be cheaper than buying the tickets separately from the two operators. It depends on passengers' valuation of the service provided by airline and HSR jointly to facilitate the air-rail transfer;
5. HSR-airline competition in the connecting market may result in airline charging higher-than-monopoly price in the market where HSR is not present. Although HSR-airline cooperation can eliminate this kind of negative impacts, cooperation harms social welfare in the markets where HSR and airline are both present;
6. From a social welfare perspective, intermodal cooperation benefits the non-stop market where only airline is present, but it harms the non-stop market where both airline and HSR are present. In the connecting market, intermodal competition should be encouraged only when airport capacity is sufficient for airline to serve all markets in the network.

Intermodal cooperation benefits some markets while disadvantaging others. Different market sizes or different weights placed by policy makers in different markets affect the final result of the overall social welfare in the network. We suggest that intermodal cooperation should be encouraged if (1) the market, where only air transport is present, is much larger than the other markets; or (2) the connecting market is much larger than the other markets and airline cannot serve all markets in the network due to insufficient airport capacity. Otherwise, intermodal competition should be encouraged.

## 5.2 Future research

This thesis has several limitations that may suggest directions for future research.

1. We do not consider marginal costs of airline and HSR in the analytical part of this study mainly due to the tractability of the model, although in Appendix B we numerically test the effects of constant marginal costs, which do not alter the main results. Since economies of traffic density are an important feature for both airline and railroad industries (Brueckner and Spiller 1994; Harris 1977; Graham et al. 2003), further efforts are still needed on examining the effects of economies of traffic density on the model results.
2. We assume hub airport capacity is exogenous. An interesting extension of our model is to incorporate airport congestion pricing so that air traffic is determined endogenously. In order to incorporate the behavior of the hub airport, our model has to be simplified in one way or another. One possible approach is to treat access time, distance, and travel speed as given, but retain connecting time as an aspect of vertical differentiation.
3. Two players (one airline, one rail operator) are assumed and analyzed in our model. In practice, more players may be present in the network. Introducing a third player, for example a FSC or a LCC, in market 1 would be an interesting direction for future research.
4. Further empirical studies can be conducted to find evidence of the results predicted by the model, especially whether the airline does engage in excessive pricing in its international market to facilitate its competition with HSR in the connecting market.
5. The social welfare analysis in this thesis excludes any climate change effects. As the demand for air travel is predicted to grow continuously, HSR has been proposed to

substitute air travel in many parts of the world, including Europe and Japan, for the (claimed) rationale that HSR is more energy efficient and produces less greenhouse gas emissions. Thus, it is interesting to further explore how the consideration of the climate impacts of the two modes would affect the results of this study.

6. We do not incorporate schedule delays in the model. As HSR and airlines are also likely to engage in service frequency competition, not merely price competition, future work is needed to treat frequency as a decision variable. Although we have studied the impacts of improved rail speed on equilibrium prices and traffic volumes, rail speed can also be a decision variable by the rail operator for future consideration in order to examine the long-term impacts on airlines and the market.

## Bibliography

- Adler, N., Pels, E. & Nash, C., 2010. High-speed rail and air transport competition: Game engineering as tool for cost-benefit analysis. *Transportation Research Part B: Methodological*, 44(7), pp.812–833.
- Albalade, D. & Bel, G., 2012. High-speed rail: Lessons for policy makers from experiences abroad. *Public Administration Review*, 72(3), pp.336–349.
- Albalade, D., Bel, G. & Fageda, X., 2015. Competition and cooperation between high-speed rail and air transportation services in Europe. *Journal of Transport Geography*, 42, pp.166–174.
- Behrens, C. & Pels, E., 2012. Intermodal competition in the London-Paris passenger market: High-Speed Rail and air transport. *Journal of Urban Economics*, 71(3), pp.278–288.
- Bhat, C.R., 1997. Covariance heterogeneity in nested logit models: Econometric structure and application to intercity travel. *Transportation Research Part B: Methodological*, 31(1), pp.11–21.
- Braeutigam, R. R., Daughety, A. F., & Turnquist, M. A., 1984. A firm specific analysis of economies of density in the US railroad industry. *The Journal of Industrial Economics*, pp.3-20.
- Brueckner, J. K., & Spiller, P. T., 1994. Economies of traffic density in the deregulated airline industry. *Journal of Law and Economics*, pp. 379-415.
- Cheng, Y.H., 2010. High-speed rail in Taiwan: New experience and issues for future development. *Transport Policy*, 17(2), pp.51–63.
- 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 Policy*, 33, pp.136–143.
- D'Alfonso, T., Jiang, C. & Bracaglia, V., 2015. Would competition between air transport and high-speed rail benefit environment and social welfare? *Transportation Research Part B*, 74, pp.118–137.
- Dobruszkes, F., 2011. High-speed rail and air transport competition in Western Europe: A supply-oriented perspective. *Transport Policy*, 18(6), pp.870–879.
- European Commission, 1998. *Interactions Between High-speed Rail and Air Passenger Transport-Final Report of the Action*, Luxembourg.

- European Commission, 2001. *WHITE PAPER: European transport policy for 2010: time to decide*, Brussels. Available at:  
[http://ec.europa.eu/transport/white\\_paper/documents/doc/lb\\_com\\_2001\\_0370\\_en.pdf](http://ec.europa.eu/transport/white_paper/documents/doc/lb_com_2001_0370_en.pdf).
- Fu, H., Nie, L., Meng, L., Sperry, B.R. & He, Z., 2015. A hierarchical line planning approach for a large-scale high speed rail network: The China case. *Transportation Research Part A: Policy and Practice*, 75, pp.61–83.
- Fu, X., Dresner, M. & Oum, T.H., 2011. Effects of transport service differentiation in the US domestic airline market. *Transportation Research Part E: Logistics and Transportation Review*, 47(3), pp.297–305.
- Fu, X., Oum, T.H. & Yan, J., 2014. An analysis of travel demand in Japan's intercity market: Empirical estimation and policy simulation. *Journal of Transport Economics and Policy*, 48(PART 1), pp.97–113.
- Fu, X., Zhang, A. & Lei, Z., 2012. Will China's airline industry survive the entry of high-speed rail? *Research in Transportation Economics*, 35(1), pp.13–25.
- GAO, 2009. *High Speed Passenger Rail: Future Development Will Depend on Addressing Financial and Other Challenges and Establishing a Clear Federal Role*, Washington, D.C.
- Givoni, M., 2006. Development and impact of the modern high-speed train: A review. *Transport Reviews*, 26(5), pp.593–611.
- Givoni, M. & Banister, D., 2006. Airline and railway integration. *Transport Policy*, 13(5), pp.386–397.
- Givoni, M. & Dobruszkes, F., 2013. A review of ex-post evidence for mode substitution and induced demand following the introduction of high-speed rail. *Transport Reviews*, 33(6), pp.720–742.
- González-Savignat, M., 2004. Competition in air transport - The case of the high speed train. *Journal of Transport Economics and Policy*, 38(1), pp.77–107.
- Graham, D. J., Couto, A., Adeney, W. E., & Glaister, S., 2003. Economies of scale and density in urban rail transport: effects on productivity. *Transportation Research Part E: Logistics and Transportation Review*, 39(6), pp. 443-458.
- Grimme, W., 2007. Experiences with advanced air-rail passenger intermodality—the case of Germany. *Air Transport Research Society World Conference*.
- Harris, R. G., 1977. Economies of traffic density in the rail freight industry. *The Bell Journal of Economics*, pp. 556-564.

- Hensher, D. A., 1997. A practical approach to identifying the market potential for high speed rail: A case study in the Sydney-Canberra Corridor. *Transportation Research Part A: Policy and Practice*, 31(6), pp.431–446.
- IATA, 2003. *Air/ Rail Intermodality Study*, Hounslow. Available at: [http://ec.europa.eu/transport/modes/rail/studies/doc/2003\\_air\\_rail.pdf](http://ec.europa.eu/transport/modes/rail/studies/doc/2003_air_rail.pdf).
- Janic, M., 1993. A model of competition between high speed rail and air transport. *Transportation Planning and Technology*, 17(1), pp.1–23.
- Janic, M., 2003. The potential for modal substitution. In *Towards Sustainable Aviation*. pp. 131–148.
- Jiang, C. & Zhang, A., 2014a. Effects of high-speed rail and airline cooperation under hub airport capacity constraint. *Transportation Research Part B: Methodological*, 60, pp.33–49.
- Jiang, C. & Zhang, A., 2014b. High-speed rail competition: Long-term impacts on airline network, market coverage and social welfare. Unpublished manuscript, University of Manitoba.
- Koppelman, F.S. & Wen, C.-H., 2000. The paired combinatorial logit model: properties, estimation and application. *Transportation Research Part B: Methodological*, 34(2), pp.75–89.
- Levinson, D., Mathieu J.M., Gillen, D. & Kanafani, A., 1997. The full cost of high-speed rail: an engineering approach. *The Annals of Regional Science*, 31(2), pp.189–215.
- McGeehan, H., 1993. Railway costs and productivity growth: The case of the republic of Ireland, 1973-1983. *Journal of Transport Economics and Policy*, pp.19-32.
- Ortúzar, J.D.D. & Simonetti, C., 2008. Modelling the demand for medium distance air travel with the mixed data estimation method. *Journal of Air Transport Management*, 14(6), pp.297–303.
- Park, Y. & Ha, H.K., 2006. Analysis of the impact of high-speed railroad service on air transport demand. *Transportation Research Part E: Logistics and Transportation Review*, 42(2), pp.95–104.
- Reisinger, M., 2005. Why do low cost carriers arise and how can they survive the competitive responses of established airlines?: A theoretical explanation. In F. Peter et al., eds. *Competition versus predation in aviation markets : a survey of experience in North America, Europe and Australia*.
- Román, C., Espino, R. & Martín, J.C., 2007. Competition of high-speed train with air transport: The case of Madrid-Barcelona. *Journal of Air Transport Management*, 13(5), pp.277–284.

- Román, C. & Martín, J.C., 2014. Integration of HSR and air transport: Understanding passengers' preferences. *Transportation Research Part E: Logistics and Transportation Review*, 71, pp.129–141.
- Singh, N. & Vives, X., 1984. Price and quantity competition in a differentiated duopoly. *The RAND Journal of Economics*, pp. 546-554.
- Socorro, M.P. & Vicens, M.F., 2013. The effects of airline and high speed train integration. *Transportation Research Part A: Policy and Practice*, 49, pp.160–177.
- Steer Davies Gleave, 2006. *Air and rail competition and complementarity. Case study report prepared for European Commission DG Energy and Transport.*, London.
- Takebayashi, M., 2015. Multiple hub network and high-speed railway: Connectivity, gateway, and airport leakage. *Transportation Research Part A: Policy and Practice*.
- Taniguchi, M., 1992. *High speed rail in Japan: a review and evaluation of the Shinkansen train (Working Paper UCTC No.103)*, Berkeley, CA. Available at: <http://www.uctc.net/papers/103.pdf>.
- Tirole, J., 1988. *The Theory of Industrial Organization*, The MIT Press.
- UIC, 2014. *High Speed Lines in The World*, Available at: [http://www.uic.org/IMG/pdf/20140901\\_high\\_speed\\_lines\\_in\\_the\\_world.pdf](http://www.uic.org/IMG/pdf/20140901_high_speed_lines_in_the_world.pdf).
- Wei, F., Chen, J. & Zhang, L., 2014. *The Pricing Effects of Competition from High-Speed Rails : Evidence from the Chinese Airline Market (Working Paper)*, Available at: [http://economics.illinoisstate.edu/jchen4/files/docs/demandshock\\_nov112014.pdf](http://economics.illinoisstate.edu/jchen4/files/docs/demandshock_nov112014.pdf).
- Yamaguchi, K., Ohashi, H. & Hihara, K., 2008. *Competitive analysis of airfare in Japan: competition among air carriers and rivalry with the high-speed railway system*, Tokyo.
- Yang, H. & Zhang, A., 2012. Effects of high-speed rail and air transport competition on prices, profits and welfare. *Transportation Research Part B: Methodological*, 46(10), pp.1322–1333.

## Appendix A: Competitive equilibrium with hub airport capacity constraint

The closed-form solution under competition scenario and with constrained hub airport runway

capacity is expressed below. Note, to save notations, we use  $B_2 = S_2^A - S_2^R$  and  $B_3 = S_3^{AA} - S_3^{AR}$ .

Equilibrium prices:

$$P_1^{A*} = S_1^A S_3^{AR} \left( 2B_2^2 B_3^2 (S_1^A + S_3^{AR}) (5S_2^R + 6S_3^{AR}) + 2(B_2 + B_3)^2 S_1^A S_2^R S_3^{AR^2} + 2B_2 B_3 (B_2 + B_3) S_3^{AR} (6S_1^A S_2^R + 2S_1^A S_3^{AR} + 5S_2^R S_3^{AR}) - KB_2 B_3 (4B_2 B_3 (S_1^A + S_3^{AR}) (S_2^R + S_3^{AR}) + (B_2 + B_3) S_2^R S_3^{AR} (2S_1^A + 3S_3^{AR})) \right) / (2B_2^2 B_3^2 (S_1^A + S_3^{AR}) ((S_1^A + S_3^{AR}) (S_2^R + 2S_3^{AR}) + S_2^R S_3^{AR}) + B_2 B_3 (B_2 + B_3) S_3^{AR} (4S_1^A (S_1^A + S_3^{AR}) (2S_2^R + S_3^{AR}) + (4S_1^A + 3S_3^{AR}) S_2^R S_3^{AR}) + 2(B_2 + B_3)^2 (S_1^A + S_3^{AR}) S_1^A S_2^R S_3^{AR^2})$$

$$P_2^{A*} = B_2 (B_2 B_3 (2B_2 B_3 (S_1^A + S_3^{AR}) ((S_1^A + S_3^{AR}) (S_2^R + 2S_3^{AR}) + S_2^R S_3^{AR}) + S_3^{AR} (4(B_2 + 2B_3) (2S_1^A + 3S_3^{AR}) S_1^A S_2^R + 4(B_2 + 5B_3) (S_1^A + S_3^{AR}) S_1^A S_3^{AR} + (3B_2 + 5B_3) S_2^R S_3^{AR^2})) + 2(B_2 + B_3) S_1^A S_2^R S_3^{AR^2} ((B_2 + 9B_3) (S_1^A + S_3^{AR}) + 2B_3 S_3^{AR}) - 2KB_3 S_1^A S_3^{AR} (B_2 B_3 (2(S_1^A + S_3^{AR}) (S_2^R + 2S_3^{AR}) + S_2^R S_3^{AR}) + 4(B_2 + B_3) (S_1^A + S_3^{AR}) S_2^R S_3^{AR})) / (2 (2B_2^2 B_3^2 (S_1^A + S_3^{AR}) ((S_1^A + S_3^{AR}) (S_2^R + 2S_3^{AR}) + S_2^R S_3^{AR}) + B_2 B_3 (B_2 + B_3) S_3^{AR} (4S_1^A (S_1^A + S_3^{AR}) (2S_2^R + S_3^{AR}) + (4S_1^A + 3S_3^{AR}) S_2^R S_3^{AR}) + 2(B_2 + B_3)^2 (S_1^A + S_3^{AR}) S_1^A S_2^R S_3^{AR^2}))$$

$$P_2^{R*} = (2B_2 B_3 S_2^R S_3^{AR}) (B_2 B_3 (S_1^A + S_3^{AR}) (S_3^{AR} - 2S_1^A) + (B_2 + B_3) (2S_1^A + 3S_3^{AR}) S_1^A S_3^{AR} + K (B_2 B_3 S_1^A (S_1^A + S_3^{AR}) - (B_2 + B_3) S_1^A S_3^{AR} (S_1^A + S_3^{AR}))) / (2B_2^2 B_3^2 (S_1^A + S_3^{AR}) ((S_1^A + S_3^{AR}) (S_2^R + 2S_3^{AR}) + S_2^R S_3^{AR}) + B_2 B_3 (B_2 + B_3) S_3^{AR} (4S_1^A (S_1^A + S_3^{AR}) (2S_2^R + S_3^{AR}) + (4S_1^A + 3S_3^{AR}) S_2^R S_3^{AR}) + 2(B_2 + B_3)^2 (S_1^A + S_3^{AR}) S_1^A S_2^R S_3^{AR^2})$$

$$P_3^{AA*} = (2(B_2 + B_3) S_1^A S_3^{AR^2} (2S_1^A S_3^{AR} ((B_2 + B_3) S_2^R + 2B_2 B_3) + B_3 (21B_2 + B_3) (S_1^A + S_3^{AR}) S_2^R) + B_2 B_3^2 (3B_2 + B_3) S_1^A S_2^R S_3^{AR^2} + (S_1^A + S_3^{AR}) S_3^{AR} B_2 B_3^2 (B_2 (36S_1^A S_2^R + 44S_1^A S_3^{AR} + 5S_2^R S_3^{AR}) + B_3 (8S_1^A S_2^R + 4S_1^A S_3^{AR} + 3S_2^R S_3^{AR})) + 2B_2^2 B_3^3 ((S_1^A + 2S_3^{AR}) (S_1^A S_2^R + 2S_1^A S_3^{AR} + S_2^R S_3^{AR}) + 2S_3^{AR^3}) - KB_2 B_3 S_1^A S_3^{AR} (2B_2 B_3 (2(S_1^A + S_3^{AR}) (3S_2^R + 4S_3^{AR}) + S_2^R S_3^{AR}) + 2(B_2 + B_3) S_2^R S_3^{AR} (6S_1^A + 7S_3^{AR}))) / (2(2B_2^2 B_3^2 (S_1^A + S_3^{AR}) ((S_1^A + S_3^{AR}) (S_2^R + 2S_3^{AR}) + S_2^R S_3^{AR}) + B_2 B_3 (B_2 + B_3) S_3^{AR} (4S_1^A (S_1^A + S_3^{AR}) (2S_2^R + S_3^{AR}) + (4S_1^A + 3S_3^{AR}) S_2^R S_3^{AR}) + 2(B_2 + B_3)^2 (S_1^A + S_3^{AR}) S_1^A S_2^R S_3^{AR^2}))$$

$$P_3^{AR*} = P_1^{A*} + P_2^{R*}$$

Equilibrium quantities:

$$q_1^{A*} = (2(B_2 + B_3)^2 S_1^A S_2^R S_3^{AR^2} + 2B_2^2 B_3^2 (S_1^A + S_3^{AR}) \left( (S_2^R + S_3^{AR})(S_1^A - 3S_3^{AR}) + S_3^{AR}(S_1^A - S_3^{AR}) \right) + B_2 B_3 (B_2 + B_3) S_3^{AR} \left( 4S_1^A (2S_2^R + S_3^{AR}) - 7S_2^R S_3^{AR^2} \right) + K B_2 B_3 S_3^{AR} (4B_2 B_3 (S_1^A + S_3^{AR})(S_2^R + S_3^{AR}) + (B_2 + B_3)(2S_1^A + 3S_3^{AR}) S_2^R S_3^{AR})) / (2B_2^2 B_3^2 (S_1^A + S_3^{AR}) \left( (S_1^A + S_3^{AR})(S_2^R + 2S_3^{AR}) + S_2^R S_3^{AR} \right) + B_2 B_3 (B_2 + B_3) S_3^{AR} (4S_1^A (S_1^A + S_3^{AR})(2S_2^R + S_3^{AR}) + (4S_1^A + 3S_3^{AR}) S_2^R S_3^{AR}) + 2(B_2 + B_3)^2 (S_1^A + S_3^{AR}) S_1^A S_2^R S_3^{AR^2})$$

$$q_2^{A*} = (2B_2^2 B_3^2 (S_1^A + S_3^{AR}) \left( (S_2^R + S_3^{AR})(S_1^A + 2S_3^{AR}) + S_1^A S_3^{AR} \right) + B_2 B_3 S_3^{AR} \left( B_2 (4(2S_2^R + S_3^{AR})(S_1^A + S_3^{AR}) S_1^A + (4S_1^A + 3S_3^{AR}) S_2^R S_3^{AR}) - B_3 \left( 4(S_1^A + S_3^{AR}) \left( S_1^A (S_2^R + 3S_3^{AR}) + S_2^R (S_1^A - S_3^{AR}) \right) - S_2^R S_3^{AR^2} \right) \right) + 2(B_2 - 3B_3)(B_2 + B_3) S_1^A S_2^R S_3^{AR^2} (S_1^A + S_3^{AR}) + 2K \left( B_2 B_3^2 S_1^A S_3^{AR} (4S_1^A (S_2^R + S_3^{AR}) + (5S_2^R + 4S_3^{AR}) S_3^{AR}) + 2B_3 (B_2 + B_3) (S_1^A + S_3^{AR}) S_1^A S_2^R S_3^{AR^2} \right) / (2 \left( 2B_2^2 B_3^2 (S_1^A + S_3^{AR}) \left( (S_1^A + S_3^{AR})(S_2^R + 2S_3^{AR}) + S_2^R S_3^{AR} \right) + B_2 B_3 (B_2 + B_3) S_3^{AR} (4S_1^A (S_1^A + S_3^{AR})(2S_2^R + S_3^{AR}) + (4S_1^A + 3S_3^{AR}) S_2^R S_3^{AR}) + 2(B_2 + B_3)^2 (S_1^A + S_3^{AR}) S_1^A S_2^R S_3^{AR^2} \right))$$

$$q_2^{R*} = (2B_2^2 B_3^2 (S_1^A + S_3^{AR}) (S_1^A S_2^R + 2S_2^R S_3^{AR} + 6S_1^A S_3^{AR}) + B_2 B_3 S_3^{AR} \left( B_3 \left( 8(S_1^A + S_3^{AR})(3S_2^R + S_3^{AR}) S_1^A + 4(S_1^A + S_2^R) S_1^A S_3^{AR} + S_2^R S_3^{AR^2} \right) + B_2 \left( 4(S_1^A + S_3^{AR})(2S_2^R - S_3^{AR}) S_1^A + 4S_1^A S_3^{AR} (S_2^R - S_3^{AR}) + 3S_2^R S_3^{AR^2} \right) \right) + 2(B_2 + 5B_3)(B_2 + B_3) S_1^A S_2^R S_3^{AR^2} (S_1^A + S_3^{AR}) - 2K B_3 S_1^A S_3^{AR} \left( B_2 B_3 \left( 2B_2 (S_1^A + S_3^{AR}) + S_2^R (4S_1^A + 5S_3^{AR}) \right) + 2(S_1^A + S_3^{AR}) S_3^{AR} \left( B_2 (B_3 - B_2) + S_2^R (B_2 + B_3) \right) \right) / (2 \left( 2B_2^2 B_3^2 (S_1^A + S_3^{AR}) \left( (S_1^A + S_3^{AR})(S_2^R + 2S_3^{AR}) + S_2^R S_3^{AR} \right) + B_2 B_3 (B_2 + B_3) S_3^{AR} (4S_1^A (S_1^A + S_3^{AR})(2S_2^R + S_3^{AR}) + (4S_1^A + 3S_3^{AR}) S_2^R S_3^{AR}) + 2(B_2 + B_3)^2 (S_1^A + S_3^{AR}) S_1^A S_2^R S_3^{AR^2} \right))$$

$$q_3^{AA*} = (2B_2^2 B_3^2 (S_1^A + S_3^{AR}) \left( (S_2^R + 2S_3^{AR}) S_1^A + 2(S_2^R + S_3^{AR}) S_3^{AR} \right) + B_2 B_3 S_3^{AR} \left( B_3 \left( 4(S_1^A + S_3^{AR})(2S_2^R + S_3^{AR}) S_1^A + (4S_1^A + 3S_3^{AR}) S_2^R S_3^{AR} \right) - B_2 \left( 4(S_1^A + S_3^{AR}) \left( S_1^A (S_2^R + 3S_3^{AR}) + S_2^R (S_1^A - S_3^{AR}) \right) - S_2^R S_3^{AR^2} \right) \right) + 2(B_3 - 3B_2)(B_2 + B_3) (S_1^A + S_3^{AR}) S_1^A S_2^R S_3^{AR^2} + 2K B_2 S_3^{AR} \left( B_2 B_3 S_1^A (4(S_1^A + S_3^{AR})(S_2^R + S_3^{AR}) + S_2^R S_3^{AR}) + 2(B_2 + B_3) (S_1^A + S_3^{AR}) S_1^A S_2^R S_3^{AR} \right) / (2 \left( 2B_2^2 B_3^2 (S_1^A + S_3^{AR}) \left( (S_1^A + S_3^{AR})(S_2^R + 2S_3^{AR}) + S_2^R S_3^{AR} \right) + B_2 B_3 (B_2 + B_3) S_3^{AR} (4S_1^A (S_1^A + S_3^{AR})(2S_2^R + S_3^{AR}) + (4S_1^A + 3S_3^{AR}) S_2^R S_3^{AR}) + 2(B_2 + B_3)^2 (S_1^A + S_3^{AR}) S_1^A S_2^R S_3^{AR^2} \right))$$

$$q_3^{AR*} = \left( 2B_2^2 B_3^2 (S_1^A + S_3^{AR}) (2S_3^{AR} (S_3^{AR} - S_1^A) - (5S_2^R + 8S_3^{AR}) S_1^A) + B_2 B_3 S_3^{AR} \left( B_2 \left( 4S_1^A \left( (S_1^A + S_3^{AR}) (3S_3^{AR} - S_2^R) - S_1^A S_2^R \right) + (8S_1^A + S_2^R) S_3^{AR^2} \right) + B_3 \left( S_3^{AR} (4S_1^A (S_3^{AR} - S_1^A) + 3S_2^R S_3^{AR}) - 4S_1^A S_2^R (6S_1^A + 5S_3^{AR}) \right) \right) + 2(B_2 + B_3) S_1^A S_2^R S_3^{AR^2} \left( (3B_2 - B_3) S_1^A + (5B_2 + B_3) S_3^{AR} \right) + KB_2 S_1^A \left( 4(S_1^A + S_3^{AR}) \left( B_2 B_3^2 (S_2^R + 2S_3^{AR}) - (B_2 + B_3) S_2^R S_3^{AR^2} \right) + B_3 S_3^{AR} (B_3 (8S_1^A + 10S_3^{AR}) S_2^R - 8B_2 (S_1^A + S_3^{AR}) S_3^{AR}) \right) \right) / \left( 2 \left( 2B_2^2 B_3^2 (S_1^A + S_3^{AR}) \left( (S_1^A + S_3^{AR}) (S_2^R + 2S_3^{AR}) + S_2^R S_3^{AR} \right) + B_2 B_3 (B_2 + B_3) S_3^{AR} (4S_1^A (S_1^A + S_3^{AR}) (2S_2^R + S_3^{AR}) + (4S_1^A + 3S_3^{AR}) S_2^R S_3^{AR}) + 2(B_2 + B_3)^2 (S_1^A + S_3^{AR}) S_1^A S_2^R S_3^{AR^2} \right) \right)$$

This solution applies when airline can still serve all markets despite the constrained airport capacity. When airline has to withdraw from certain markets, this solution does not apply and the objective function should also be reformulated to drop the air traffic in the market that airline is not going to supply. The market that airline will withdraw first depends on service quality parameters.

## Appendix B: Robustness check

As proved in Proposition 2 and Proposition 5, HSR-airline cooperation improves social welfare in market 1 but harms social welfare in market 2 and market 3 when airport capacity is sufficient. Since the analytical results become very complicated when airport capacity comes into play, many numerical tests are conducted to assess how social welfare in each market changes with airport capacity. It appears that although the magnitudes of social welfare differ with different sets of parameters, the general trends are similar.

**Table B-1: A new set of parameters for robustness check**

	Total travel time	Gross travel benefit
Market 1 (air only)	$T_1^A = 4h + \frac{5600km}{700km/h} = 12h$	$b_1 = 32h$
Market 2 (air)	$T_2^A = 3h + \frac{1400km}{700km/h} = 5h$	$b_2 = 17h$
Market 2 (HSR)	$T_2^R = 2h + \frac{1500km}{300km/h} \approx 7h$	
Market 3 (air-air)	$T_3^{AA} = 4h + \frac{7000km}{700km/h} + 1h = 15h$	$b_3 = 45h$
Market 3 (air-rail)	$T_3^{AR-comp} = 3h + \frac{5600km}{700km/h} + \frac{1500km}{300km/h} + 3h \approx 19h$	
	$T_3^{AR-coop} = 3h + \frac{5600km}{700km/h} + \frac{1500km}{300km/h} + 2h \approx 18h$	

In this Appendix, we present one of the numerical tests to show that the results of social welfare comparison in Chapter 4 are robust. Table B-1 presents the new set of parameter values.

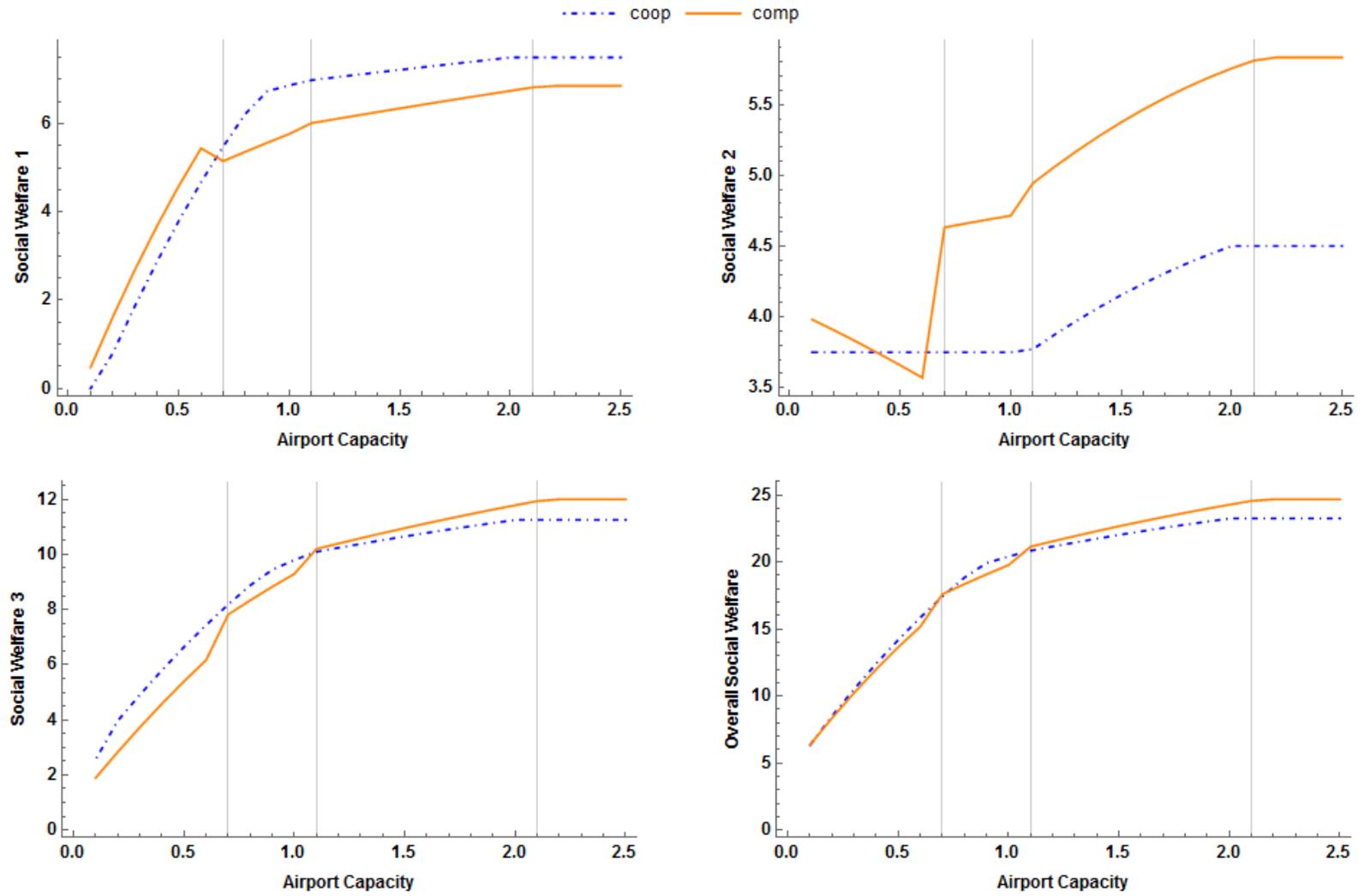
Compared with Table 4-1, the difference of total travel time between air and rail in market 2 and

market 3 becomes larger and the gross travel benefits of all three markets are increased in the new set of parameters. Figure B-1 presents social welfare comparison calculated by using these parameters in each market and in the overall market.

Figure B-1 presents similar trends as Figure 4-1 to Figure 4-4 in Chapter 4. Note that the scales of y-axis in the four plots are different from each other, because if we unify the scale of y-axis as the overall case, some parts of the trends will become difficult to discern. Therefore, for the purpose of better presentation, the scale of y-axis in each market differs.

Although the difference of social welfare between competition and cooperation scenarios seems to be smaller in market 3 and the overall market than in market 1 and market 2, it does not mean that intermodal cooperation has insignificant impacts on market 3 and the overall market. First, if the scales of y-axis in the four plots are unified, the magnitudes of the differences between the two scenarios in the four plots are similar. Second, total travel time and social welfare are both measured in hours. In practical sense, one mode can hardly be faster than the other mode in terms of total travel time for more than 5 hours or so. This also accounts for the seemingly slight differences of social welfare between the two scenarios. Third, relative differences are much more important than absolute differences. In our model, we normalize the population mass in each market to be 1. In practice, there could be millions of people in each market. If social welfare measured in hours is multiplied by the value of time, the differences of social welfare between the two scenarios in monetary value could be huge. Therefore, which scenario should be encouraged can be judged by which one generates relatively higher social welfare.

Figure B-1: Social welfare comparison for robustness check



Costs are important factors for both airlines and HSR. It is reasonable to assume that airlines incur higher constant marginal costs than HSR, because airlines have higher fuel consumption than HSR, especially during the take-off and landing (Steer Davies Gleave 2006). Using the parameters in Table B-1, we incorporate constant marginal costs for both airline and HSR, and calculate social welfare for both scenarios in each market.

We assume that airline incurs constant and identical marginal cost in market 1 and market 2 and HSR incurs half the constant marginal cost of airline. In market 3, the constant marginal cost of airline is the sum of its marginal costs in market 1 and market 2. Thus,  $C_1^A = C_2^A = C$ ,  $C_3^{AA} = 2C$  and  $C^R = \frac{1}{2}C$ . We use  $C = 1$  in the numerical test. The results of the effects of constant marginal costs are presented in Figure B-2. It shows that the overall trends of social welfare remain similar to Figure B-1, which did not incorporate constant marginal costs, although social welfare decreases in magnitudes due to the consideration of costs. Thus, it seems that constant marginal costs do not alter the main conclusion of this study.

However, an important feature in the transportation sector is economies of traffic density, which means that the marginal cost falls with the increase of traffic on the route. Both air and rail sectors have demonstrated economies of traffic density (Brueckner and Spiller 1994; Harris 1977; Graham et al. 2003). Thus, future research is needed to examine the effects of economies of traffic density on the results derived from our model.

Figure B-2: Social welfare comparison with constant marginal costs

