ASSESSING THE IMPACT OF HIGH-SPEED RAIL ON DOMESTIC AVIATION CO_2 EMISSIONS IN CHINA

Bojun Wang, Corresponding Author
Air Transportation Systems Lab, UCL Energy Institute, University College London
Central House, 14 Upper Woburn Place, London, WC1H 0NN
Tel: 44 (0) 20-7679-2000; Fax: 020-7679-2000; Email: bojun.wang.13@ucl.ac.uk

Aidan O'Sullivan
Air Transportation Systems Lab, UCL Energy Institute, University College London
Central House, 14 Upper Woburn Place, London, WC1H 0NN
Tel: 44 (0) 20-7679-2000; Fax: 020-7679-2000; Email: aidan.osullivan@ucl.ac.uk

Andreas W. Schäfer,
Air Transportation Systems Lab, UCL Energy Institute, University College London
Central House, 14 Upper Woburn Place, London, WC1H 0NN
Tel: 44 (0) 20-7679-2000; Fax: 020-7679-2000; Email: a.schafer@ucl.ac.uk

Word count: 6,960 words text + 2 tables x 250 words (each) = 7,460 words

Submission Date: 1st August 2018 to the 98th TRB Annual Meeting.

ABSTRACT

This paper examines the beneficial impact of high-speed rail (HSR) on reducing aviation CO_2 emissions in China. As a fast-growing economy and the world's largest CO_2 emitter, China has made massive infrastructure investments but has also committed to reducing emissions across all sectors. In this study we demonstrate that investments in China's HSR can effectively contribute to emissions reduction from domestic aviation, a sector that is particularly challenging to decarbonize. Although a wide body of literature has assessed the competition between HSR and air transport, little attention has been paid to the climate implications of such phenomenon. From our estimation, through mode substitution for air transport, HSR generates a cumulative net CO_2 savings of between 1.76 and 2.76 million tons from 2012 to 2015. This was equivalent to 3.2-5.1% of 2015 domestic aviation emissions. Importantly, we also demonstrate that by not taking into account the electricity consumption of HSR, the environmental benefits of HSR would be overestimated. Lastly, through analysis on future energy mix scenarios this study highlights that HSR has a great potential to reduce CO_2 emissions even further if China achieved its climate pledge in the Paris Agreement in terms of decarbonizing its electricity generation sector by 2030.

Keywords: High-speed rail, Air transportation, Substitution, Net CO_2 savings, China

INTRODUCTION

In 2015, the transport sector in China accounted for 10.6% of its energy related CO_2 emissions and for 15.7% of final energy demand *(1)*. This was the third largest source of GHG emissions of the country. China has announced an ambitious climate target in the Paris Agreement to cut its CO_2 emissions per unit of GDP by 60-65% from the 2005 level by 2030 *(2)*. This would require significant reductions of carbon intensity from all industries, including the transport sector. Since the early 2000s, China has rapidly developed the world's largest high-speed rail (HSR) network: by the end of 2015, its total HSR track length reached to 19838 km, which accounts for 51% of the world's total HSR track length *(3)*. This expansion of infrastructure has led to a remarkable increase in ridership in the last decade from 7.34 million passengers carried in 2008 to 961.4 million total passengers in 2015 *(4)*. This indicates that HSR has been a major success in the development of the Chinese transport system. In 2016, a further HSR development plan was announced, which aims to expand the HSR network from the current 'Four-vertical and Four-horizontal lines' structure to an 'Eight-vertical and Eight-horizontal lines' structure by 2025, with the total track length of 38000 km *(5)*.

Domestic air transport in China has also experienced a rapid growth in recent years and accounted for 5.6% of the total CO_2 emissions from the transport sector in 2015 *(1)*. Despite its relatively small share in the current total transport emissions, the air traffic flow of the domestic China is projected to almost quadruple from 2016 to 2036, and to become the world's largest air transport market with about 1900 billion revenue passenger kilometers (RPK) *(6)*. Driven by the expected significant growth, the total CO_2 emissions from air transport will increase considerably. As a result, reducing emissions from the aviation sector becomes an increasingly important issue in China. However, possible solutions for cutting air transport emissions are limited *(7)*. Given that the technology of electric aircraft is currently in the research and development phase, and that biofuel utilization is focused on international aviation, it is much more challenging to efficiently reduce emissions from the aviation sector than other transport modes such as road transport, which is planned to be decarbonized through the mass deployment of electric vehicles. Substitution of flights with HSR is therefore an important potential solution for reducing aviation emissions.

Given its substantial growth, fast speed, and better safety and reliability, high speed rail has become a competitive alternative for travel in China, and significantly challenges air transport in the domestic market. Competition from HSR has directly resulted in cancellations of some short-haul airline routes, examples include Zhengzhou-Xi'an, Changsha-Guangzhou, and Zhengzhou-Changsha *(8)*. As a result, there has been growing research interests on the HSR-Air competition effects. Previous literature on HSR-Air competition has mainly focused on three aspects.

One strand uses econometric models to assess the HSR-aviation competition, with HSR entry as a dummy variable. Chen *(9)* conclude that after the introduction of China's two major HSR corridors, there has been a 28.2% reduction in passengers and 26.4% reduction in flights from inter-city travel on these two HSR lines specifically; Wan et al *(10)* found that HSR entries lead to a more significant drop in airline seat capacity in China than in Japan and Korea; and Jimenez and Betancor *(11)* demonstrates that in Spain HSR leads to reduction of 17% in flight frequencies on four HSR routes connecting Madrid to other cities. A second strand of research has focused on discrete choice models using surveys data that predict transport modal split and future market shares of different transport modes *(12-15)*. This method is more widely used in studies assessing the HSR impacts in Europe. From a nested logit model estimation, Roman et al. *(12)* predict that HSR in Spain will obtain only less than 35% market share when competing with air. Pagliara et al *(15)* have similar findings that on the Madrid-Barcelona HSR corridor, market share taken by HSR was lower than expected. Finally, there are also theoretical models examining the socio-economic outcomes of HSR and air competition on traffic, price, and profits *(8, 16-18)*. These studies assessed the HSR-Air competition effects from different aspects, however the environmental consequences from substitution of HSR for aviation have been largely overlooked.

A wide body of literature has also evaluated the climate impacts and potential mitigation options for aviation. Examples include Schäfer et al *(7)*, Dray et al *(19)*; Dessens et al *(20)*, and Krammer et al *(21)*. Key findings from this work show that the expected growth in demand for air transport passenger travel if left unchecked could lead to aviation being responsible for 25% of global CO_2 emissions by 2050. Research into the climate impacts of HSR has been primarily drawn to the life cycle assessment of HSR in different world regions, such as in the U.S. *(22-24)*, in China *(25)*, and in Europe *(26, 27)*. While the above studies have addressed the climate impacts of the two transport modes separately, little is known about the net climate impacts of transitioning intercity travel from air transport to HSR. Substituting HSR travel for aviation is considered to be one possible solution of reducing air transport emissions. However, the success of this requires an understanding of a number of factors including the carbon intensity of the electricity mix used to power the HSR. This is an under explored issue especially in the Chinese context, and as the first step of filling this gap, this work provides an empirical evaluation of net CO_2 savings from the HSR-Air substitution in China.

The main contributions of our study to the existing literature are threefold: (1) a comparative analysis of the network development in China for HSR and air transport during the HSR-era (2010-2015); (2) empirically estimating the HSR substitution effects on air transport using panel data over the period of 2000-2015; (3) providing important insights on the potential contribution of HSR in decarbonizing China's transport sector by estimating the net CO_2 emissions savings resulting from HSR substitution for air transport, together with analysis on future energy mix scenarios.

The next section of this paper describes the data underlying this work, upon which a comparison of network development of HSR and aviation in China is described. The methodology is then discussed in Section 3. Based on the methodology, Section 4 empirically analyzes changes in airline supply due to the HSR competition and estimates the CO_2 emissions impacts from HSR substation for air transport. The carbon intensity of the electricity generation mix has a significant impact on our results, and given China's rapid progress in decarbonizing this sector, we consider a future scenario utilizing the forecast carbon intensity of the electricity mix based on China's climate pledge in the Paris Agreement, and compare the results with the present day. Section 5 offers conclusions.

DATA

We construct a dataset comprising domestic city pairs using both air transport and HSR-related data over the period of 2000-2015. In total, 78 Chinese cities with access to air transport are selected in this study. The inter-city air travel between these cities account for more than 90% of total RPK of the domestic Chinese aviation market in 2015. We define a market as a non-stop city pair connected by air transport. Air transport supply data is obtained from Sabre Market Intelligence database *(28)*, which contains information on flight frequency, seats available, and fleet types by flight segment for each year. For HSR, we collect information of all HSR corridors in China that are in operation by the end of 2015. The collected information includes these corridors' specific opening dates, passing-by cities, and the HSR track length between each city pair *(3)*.

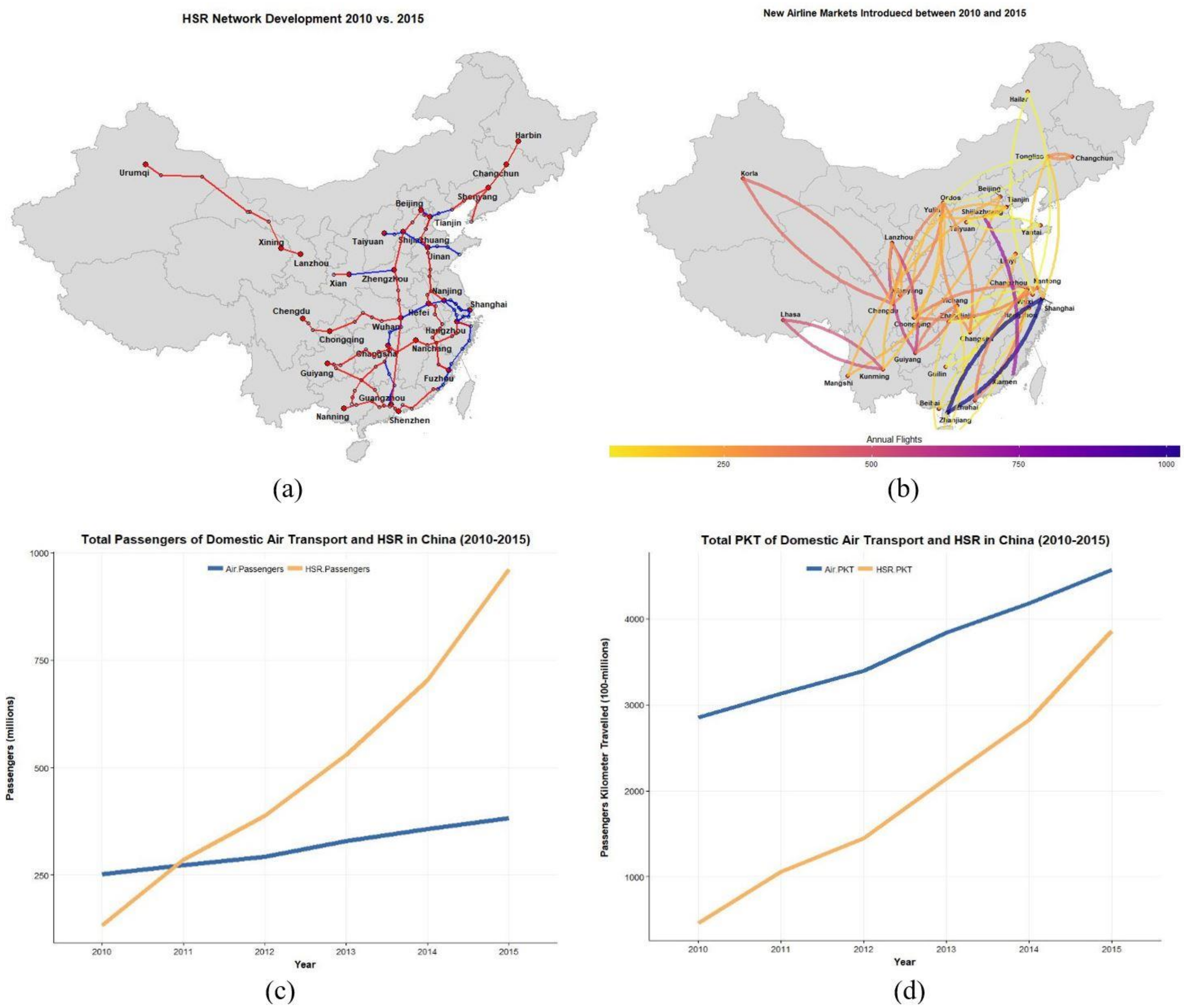

FIGURE 1 Comparison between HSR and Domestic Air Transport networks 2010-2015.

Figure 1 provides an overview of China's air transport and HSR development over the sample period. As can be seen in (a), China's HSR network saw a considerable development between 2010-2015, increased from a total track length of 5100km in 2010 (in blue lines) to 19838km in 2015 (in red lines). By the end of 2015, a HSR network that connects the North China with the South China and the East China with the West China has been completed. During the same time period, the domestic air transport network had less significant expansion, as shown in (b). Only a few new city pair markets were introduced, from which Shanghai-Zhanjiang, Shijiazhuang-Xiamen, and Lanzhou-Guiyang have a relatively heavy traffic with annual average flights between 500 and 1000. With respect to the growth of passenger demand of the two transport modes, (c) and (d) depict the annual total ridership and the total passenger-kilometer-travelled (PKT) over the period of 2010-2015, respectively. As can be seen in (c), the total number of passengers taking HSR has increased considerably, and surpassed passengers of domestic air transport since 2011 (interestingly, 2011 is also the year when China's busiest HSR corridor linking Beijing and Shanghai started its operation). However, in terms of total passenger kilometers, air transport still leads the way due to its advantages in long-haul travel, albeit with slower growth than that of HSR (d).

METHODOLOGY

This section discusses the methodology employed in this study. Firstly, the data-preprocessing method used to allow comparison of groups with and without direct HSR competition is described. The two groups are matched to estimate the empirical changes of airline supply due to the introduction of HSR. Following this, we describe our method for calculating energy use and CO_2 emissions for both air transport and HSR. This allows us to estimate the net CO_2 emissions resulting from the HSR substitution for air transport.

HSR-Air Routes Treatment

To start the analysis, we firstly divide the entire city-pairs sample into two groups, i.e. the Treated Group and the Control Group. Similar to previous studies *(10)*, we consider city pairs in the 'Treated Group' as those that saw a direct entry of HSR service during the sample period of 2000-2015, while those not facing HSR entries within the sampling period belong to the 'Control (or untreated) Group'. Unlike earlier research that only account for HSR entries to 'online' city pairs (city pairs that are directly linked by a single HSR corridor), one novelty of this work is that we identify both online and cross-line city pairs with HSR connections, which makes our sample size of the Treated Group significantly larger than those of the previous studies. In addition, existing literature have found that HSR is the most competitive in short-range distance markets (less than 500km), and its competitiveness declines as travel distance increases. Thus, we also split the sample by distance range, i.e. D1 contains city pairs with greater circle distance less than 500 km, D2 covers city pairs with distance between 500 and 1000 km, and D3 includes city pairs with distance greater than 1000 km.

In total, there are 675 inter-city markets and 10800 observations throughout the sample period. Among all city pairs in the sample, 322 belong to the Control Group (5152 total observations) and 353 belong to the Treated Group (5648 total observations). In terms of distance range category, there are 80 city pairs in the D1 (less than 500 km) group, 344 city pairs in the D2 (500-1000 km) group, and 251city pairs in the D3 (greater than 1000km) group. After identifying city pairs in the treated group and the control group, we match the growth trend of both groups in terms of airline supply over the period of 2000-2015. An observable change in the aviation supply growth trends between the two groups is expected. Specifically, city pairs that do not face direct HSR competition should follow similar growth of the pre-HSR era. While city pairs in the treated group may show evidence of an explicit decline in the air transport supply, depending on the distance range.

Energy Use and CO_2 Emissions Calculation

As described in the Introduction, the primary interest of this paper is to empirically measure the net CO_2 emissions savings of the mode shift from air transport to HSR in intercity travel. This requires us to calculate both the reduced emissions from air transport and the emissions of HSR for carrying the shifted demand.

Air transport

Total aircraft fuel burn on a given segment is determined by fleet size, load factor, stage length, and total number of flights for each aircraft type operated. In this study, fuel burn is calculated based on the PIANO-X aircraft performance model *(29)* for climb, cruise, and descent. We use nine aircraft size classes adapted from the Sustainable Aviation aircraft size classes *(30)*. Additionally, in order to capture the differences of airline load factors in different city pair markets, we calculate the average annual load factors for all flight segments covered in our sample. As such, the potential changes of fleet mix by segment over the sample period are addressed, and the annual aircraft fleet CO_2 emissions can be as close to actual values as possible.

HSR

In this study, HSR emissions are estimated just for the estimated shifted traffic from air transport. Thus, any induced demand or transitioning inter-city travels from other transport modes are not included in our calculation. When calculate the HSR emissions, we take into account shares of different fuel sources for electricity generation in China for each year. Combing the methods used by Chester and Horvath *(24)* and Clewlow *(31)*, the CO_2 emissions of HSR for transporting the shifted demand during operation is computed based on Equation 1:

$$\begin{cases} ElectricityUse_{HSR} = Electricity.Intensity_{HSR} \times Seat.km_{od} \times Trains_{od} \\ ElectricityUse_{S.HSR} = ElectricityUse_{HSR} \times \left(\frac{Gen_S}{Gen_T}\right)_Y \\ CO_{2HSR} = \sum (EF_{S,Y} \times ElectirictyUse_{S.HSR}) \end{cases} \quad \text{Eq. (1)}$$

Where:

- $ElectricityUse_{HSR}$: kWh, yearly total electricity consumption of HSR operating between origin city *o* and destination city *d*;
- $Electiricty.Intensity_{HSR}$: kWh/seat-km per train, electricity consumed per seat-kilometre travelled by HSR;
- $Trains_{od}$: total number of trains operated between origin city *o* and destination city *d* in the given year;
- $ElectricityUse_{S.HSR}$: HSR electricity consumption that is generated by source *S*;
- $\left(\frac{Gen_S}{Gen_T}\right)_Y$: Share of source *S* in the electricity generation in China in year Y. Gen_S is the total electricity generation (GWh) from source *S*, and Gen_T is the total generation of electricity (GWh) from all sources.
- $CO_{2\,HSR}$: Total CO_2 emissions from HSR for transporting the shifted demand from air transport.
- $EF_{S,Y}$: Emission Factors of source *S* in the fuel mix of electricity generation in year *Y*.

This paper computes HSR emissions specifically in China’s HSR context. Comparing with the studies of Chester and Horvath *(24)* and Clewlow *(31)*, which preliminarily focus on the U.S. market, we stress that HSR in China has significantly different vehicle types, load factors, and fuel mix for electricity generation. There are four main types of high speed vehicles used in the Chinese HSR system, namely CRH2, CRH2-300, and CRH3C, and CRH380. Zhou *(32)* provides a comprehensive review for these CHR series vehicles. In addition, although there are currently no data for the electricity intensity of China’s HSR vehicles, such data is available for their prototypes *(24, SI)*, from which the CRH inherits mostly same structure and vehicle material. Thus, we use the electricity intensity values of these prototypes to compute the energy use of China’s HSR. In order to minimize impacts to our calculation of the potential variation in energy efficiency of these derivatives from their prototypes, we also include a generic model that has an electricity intensity value averaged across a range of HSR electricity intensity values summarized by Chester and Horvath *(24)*. Table 1 summarizes the key features of the CRH vehicles based on Zhou *(32)* and Chester and Horvath *(24)*:

TABLE 1 Key parameters of China's CRH series vehicles.

Vehicle Type	Prototype	Electricity Intensity (kWh/seat-km)	Seat capacity	Max speed (km/h)	Train length(m)	Weight (ton)	Train sets
CRH2	Shinkansen E2-1000	0.037	610	250	201.4	359.7	8
CRH2-300	Shinkansen E2-1000	0.037	600	300	201.4	370.8	8
CRH3C	Siemens Bahn ICE-3	0.058	556	350	200	447	8
CRH380	Siemens Bahn ICE-3	0.058	1005	350	399.27	980	16
Generic Model	Average of all HSR vehicles from *(24)*	0.043	N/A	N/A	N/A	N/A	N/A

For China's electricity generation by energy sources, we use data between 2000 and 2015 from IEA *(36)*. From Figure 2, coal still plays a dominate role in China's electricity production, despite its slowly decreasing proportion which is being replaced by nuclear and renewable sources such as hydro, wind, and solar. The emission factors of in Figure 2 are obtained from IEA *(33)*. With this information, the total HSR emissions are calculated for transporting the shifted demand from air transport.

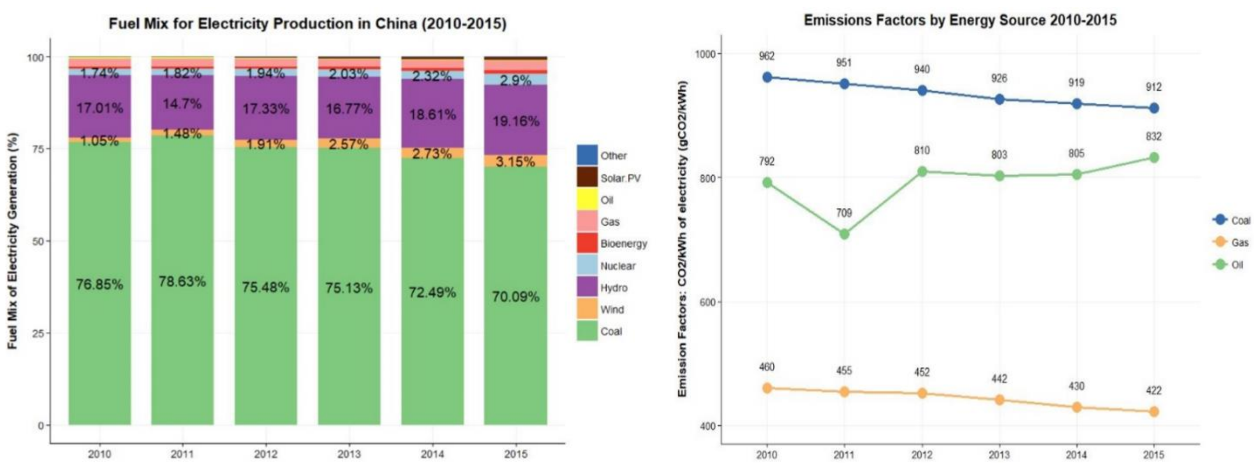

FIGURE 2 China's electricity generation mix and corresponding emission factors 2010-2015.

RESULTS AND DISCUSSION

In this section, results are discussed in the following orders: 1) empirical evidence of the airline supply diversion after HSR entries; 2) estimation of the shifted demand from air transport to HSR; 3) net CO_2 emissions of the HSR substitution for air transport; 4) Future electricity mix scenario.

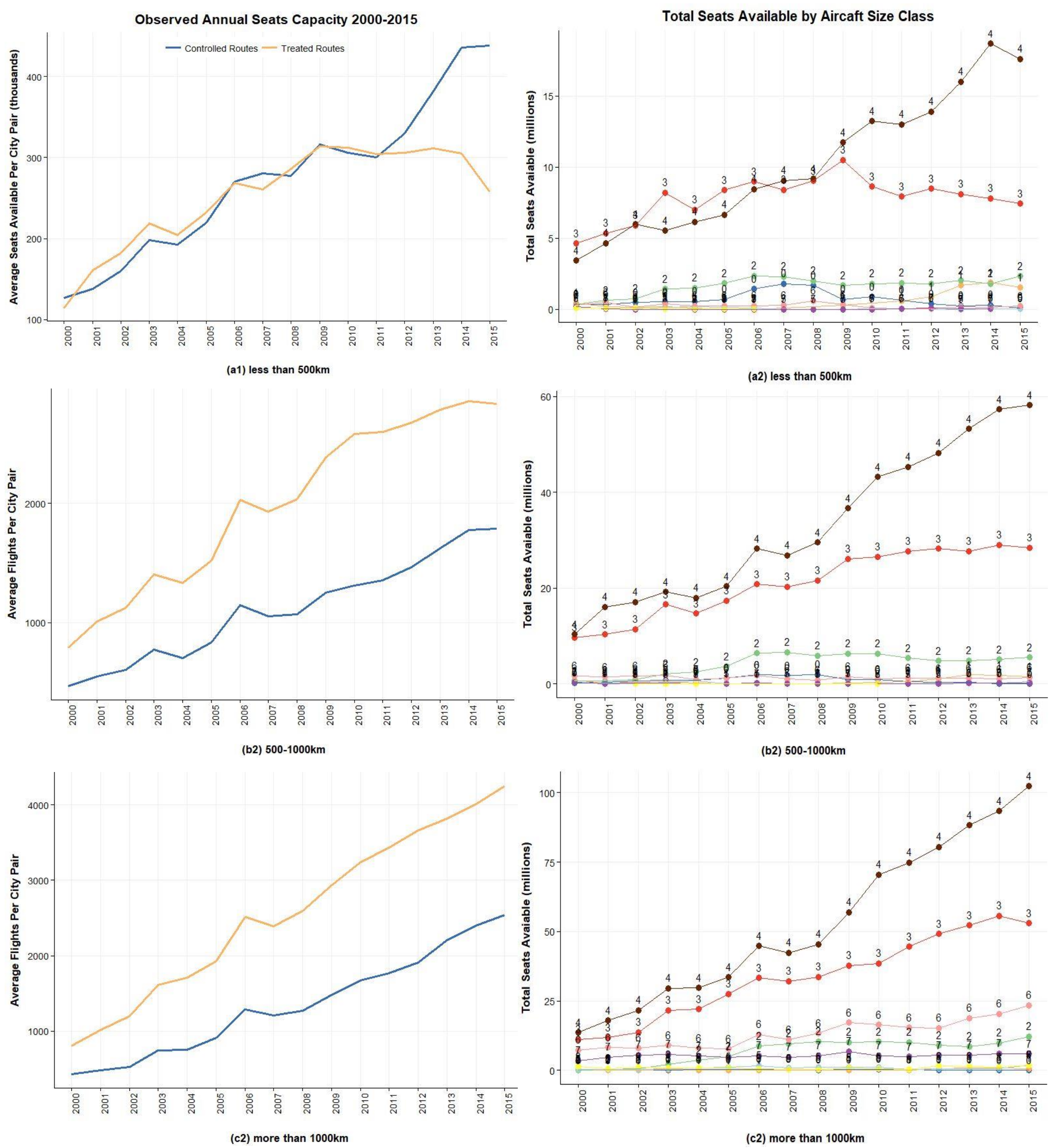

FIGURE 3 Air transport seats capacity of the treated routed and the controlled routes.

In Figure 3, the left-hand panel shows the annual average seat capacity per city pair of the controlled routes and the treated routes, between 2000 and 2015. The right-hand side depicts the total capacity growth by aircraft size over the time period by distance group. As expected, in the left side we found a clear deviation between the treated routes and the controlled routes in the short-range (D1) distance markets since about 2011. These distinctly different trends suggest that, although China's first HSR line started to operate since 2008 *(3)*, the HSR impacts on air transport market were not sufficiently significant until 2011. Note that from Figure 1.c, we already found the total ridership of HSR exceeded that of domestic aviation also since 2011 (the year when China's busiest HSR line between Beijing and Shanghai started operations). All of our empirical findings from the data imply that the year 2011 is an important turning point of the competition between HSR and air transport in China. In contrast, the impacts of HSR become less clear as distance increases in group D2 and D3, illustrating that there is less of an impact on air transport in medium- and long-haul travel.

From another perspective, during 2000-2010, the two groups roughly followed the same trend across all distance groups. There is no significant difference in terms of airline supply growth between the treated routes and the controlled routes over this period. While China's HSR did emerge from 2008, it was still in its infancy with only 730km track length and could hardly make any threats to air transport. However, since 2011, a number of major HSR corridors began operation, including China's busiest HSR line Beijing-Shanghai (introduced in 2011) and China's longest HSR line linking Beijing and Guangzhou (completed in 2012). The HSR lines introduced after 2011 effectively connect China's most developed mega cities with HSR, and this is when the HSR begins to challenge air transport on intercity travel.

Additionally, there are some other interesting findings from Figure 3. In medium and long-distance range markets, there are more seats available serving the treated routes than the controlled routes. This can be explained by the fact that HSR is generally introduced in densely populated areas with high GDP, such as Beijing, Shanghai, and Guangzhou, which also are regions that traditionally receive more services from air transport, compared with the less popular city pairs in the control group (the largest provincial capital city in the controlled group is Hohhot in Inner Mongolia, with total GDP of 309.05 billion yuan in 2015, compared to Beijing at 2.29 trillion yuan in the same year). Turning to the right-hand panel of Figure 3, we found that the capacity growth of domestic Chinese air transport mainly comes from the size class 4 aircraft, which is represented by the Boeing 737-800 *(30)*. The second largest share of the fleet is the size class 3 aircraft, represented by the Airbus 320-100/200 *(30)*, albeit with relatively flattened growth. The rest of air aircraft sizes only account for small shares with little growth in the domestic Chinese market over the sample period. From this observation, we could assume that the growth of supply in the domestic air transport is mainly driven by increasing numbers of in size class 4 aircraft in the fleet.

Estimation to Shifted Demand

To examine our observation from Figure 3 more rigorously that airline supply growth starts to diverge from 2011, we conduct a Welch Two Sample *t*-test on the annual growth rates of average seats capacity per city pair by distance range in our sample. If there are no statistically significant difference in the growth rates between the treated and the controlled routes, we consider that they follow the same growth in that year, and vice versa.

TABLE 2 Mean growth rates of annual seat capacity in the treated and controlled routes.

Time period	Dist range	Treat growth	Control growth	Diff.	*t*-statistics	p-value
2000-2010	D1	0.1129	0.1059	0.0071	0.317	0.755
2000-2010	D2	0.1331	0.1329	0.0002	0.003	0.998
2000-2010	D3	0.1560	0.1581	-0.0121	-0.161	0.967
2011-2015	D1	-0.0355	0.0771	-0.1125***	-2.394	0.044
2011-2015	D2	0.0286	0.0767	-0.0481***	-2.537	0.048
2011-2015	D3	0.0594	0.0961	-0.0367	-1.835	0.134

The *t*-test results are shown in Table 2. We found that during the period over 2000-2010, the hypothesis that the growth rates of average seat capacity in the two groups have equal means cannot be rejected at a statistically significant level, for all the three distance groups. During this period, average growth rates in D1 group is 11.29% per year for treated routes and 10.59% per year for controlled routes. Growth rates in D2 is 13.31% (treated routes) and 13.29% (controlled routes); in D3 growth for treated routes is 15.60% per year and for controlled routes is 15.81% per year. However, since 2011, the hypotheses of equal means for seats are rejected at 5% statistically significant level for both D1 and D2 groups. This test statistically demonstrates what Figure 3 depicts: airline supply started to divert since 2011, where the growth rates of the HSR-entered city pairs become significantly different from those that do not face HSR competition. However, the 3.7% difference in growth rate observed in the D3 group was not found to be statistically significant illustrating how at long distances HSR substitution does not substantially impact air transport.

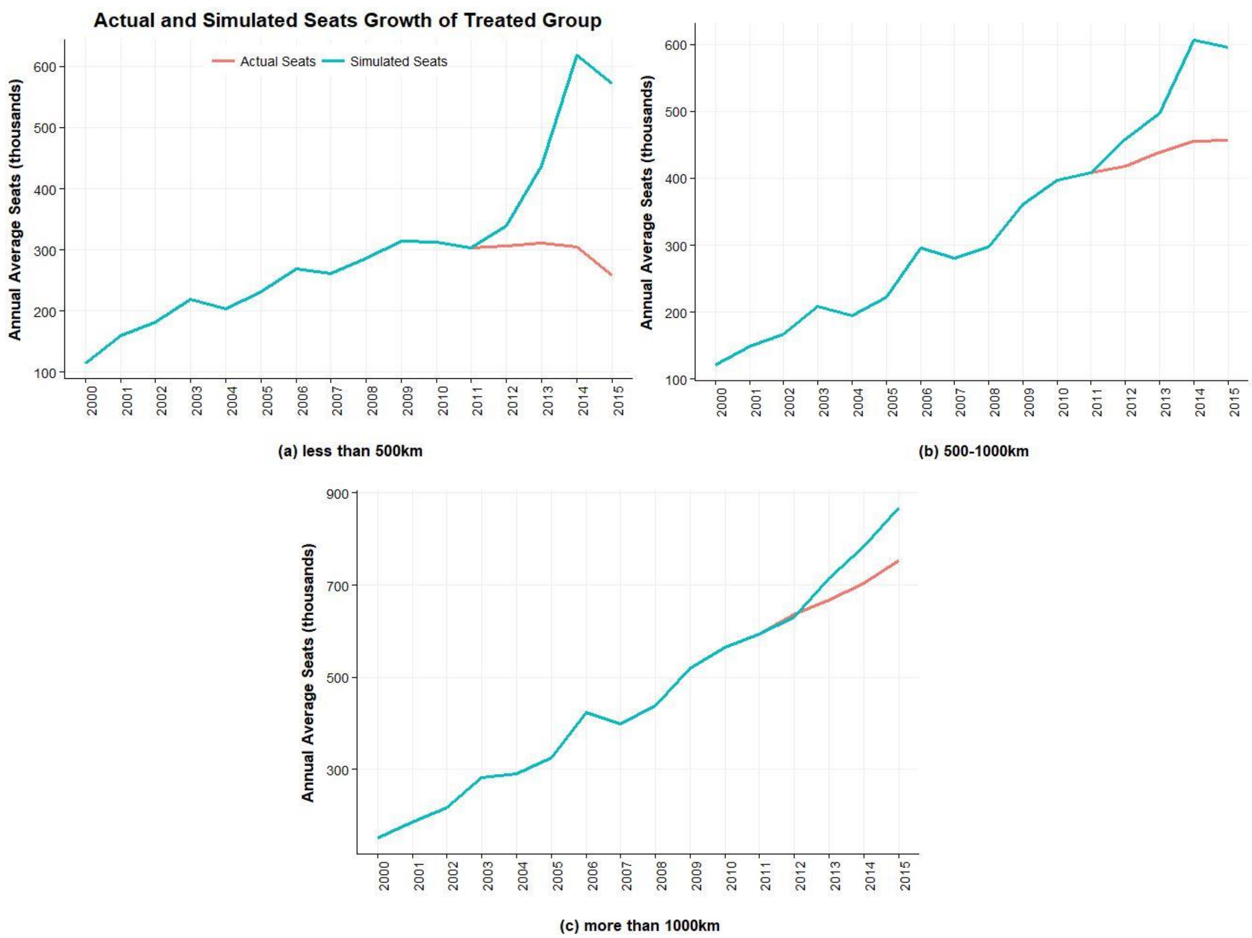

FIGURE 4 Actual growth vs. Simulated growth of the treated group airline seats capacity.

Based on the *t*-test, it can be inferred that if HSR were not introduced to city pairs in the treated group, airline supply would follow the same growth of the controlled routes, just as the growth during 2000-2011. In addition, as discussed previously from Figure 3, the capacity growth of domestic Chinese aviation market is largely driven by the growth of size class 4 aircraft, i.e. Boeing 737-800. Therefore, using the average growth rates of size class 4 capacity in the controlled routes during 2011-2015, we simulate a hypothetical growth trend for the treated group, assuming HSR were not introduced. A comparison between the actual growth and our simulated growth in airline seat capacity is shown in Figure 4.

From Figure 3, we can see that airline supply reduces most significantly in the short-distance range markets compared to treated routes without HSR intervention. Although traffic reduction shrinks as distance increases, the HSR impacts are still manifest in longer distance groups. Based on our estimation, between 2011 and 2015, the average reduced seats capacity per route are 196833 per year in D1 group, 97289 per year in D2 group, and 59234 per year in D3 group, respectively. Taking the reduced total seats capacity and the annual average airline load factor, the shifted passengers to HSR can be estimated, upon which we can calculate the reduced CO_2 emissions of air transport due to the HSR substitution effects.

Net CO_2 Emissions Calculation

The reduced CO_2 emissions from less air travel are calculated by taking the difference of emissions during 2011-2015 from the actual airline supply and the simulated supply of the treated routes. We assume that the reduced air traffic, which shows in Figure 4, has all been shifted to HSR. The total additional CO_2 emissions from HSR associated with carrying this shifted demand is then computed based on Equation 1, with an assumed static average capacity utilization of 70% *(25)*. Finally, the net CO_2 emissions savings from the substitution of HSR for air transport can be estimated as Equation 2:

$$Net.CO_2 = Reduced.CO_{2(Air)} - CO_{2\,(HSR)} \qquad \text{Eq. (2)}$$

As there are several input parameters in determining the final outcomes of the estimated net CO_2 emissions, in this section we not only discuss the results of net emissions savings estimated from the baseline case, but also conduct a scenario analysis by adjusting parameters of China's energy mix for electricity generation. Changing these parameters will influence emissions from the HSR and gives insights into the potential future total aviation CO_2 savings through mode shift. Since China has made the pledge in the Paris Agreement to decarbonize its power generation and replace coal with more renewable sources, this scenario analysis will provide important policy implications to possible futures of China's transport emissions. After briefly describing this scenario, the results of all cases will be analyzed and compared to yield more holistic conclusions.

Scenario: an energy mix with lower carbon intensity for electricity generation in China, using projections from the EIA (35):

In the reference case, the fuel mix of electricity generation in China are taken from the IEA *(35)* (see Figure 2). In this scenario, we calculate HSR emissions for a hypothetical case where China already achieved its 2030 climate target in the Paris Agreement: a 60-65% cut in its carbon intensity from the 2005 levels in its energy mix. Based on China's climate pledge in the Paris Agreement, the U.S. Energy Information Administration (EIA) provides projections of the possible shares of energy sources for electricity generation, as shown in Figure 5. EIA *(35)* projects that by displacing coal with renewables, nuclear, and natural gas, China will achieve its maximum level of CO_2 emissions before its 2030 targeted deadline. Share of coal in total electricity generation will drop from 70% of the 2015 level to 55% in 2030 and to 47% in 2040. In contrast, generation shares from renewables will increase, with annual growth between 2015 and 2040 at 7% in Solar PV and 5% in wind. In addition, share of nuclear generation will increase from 3% in 2015 to 11% in 2040, and over the same period, share of natural gas is expected to increase from 2% to 7%.

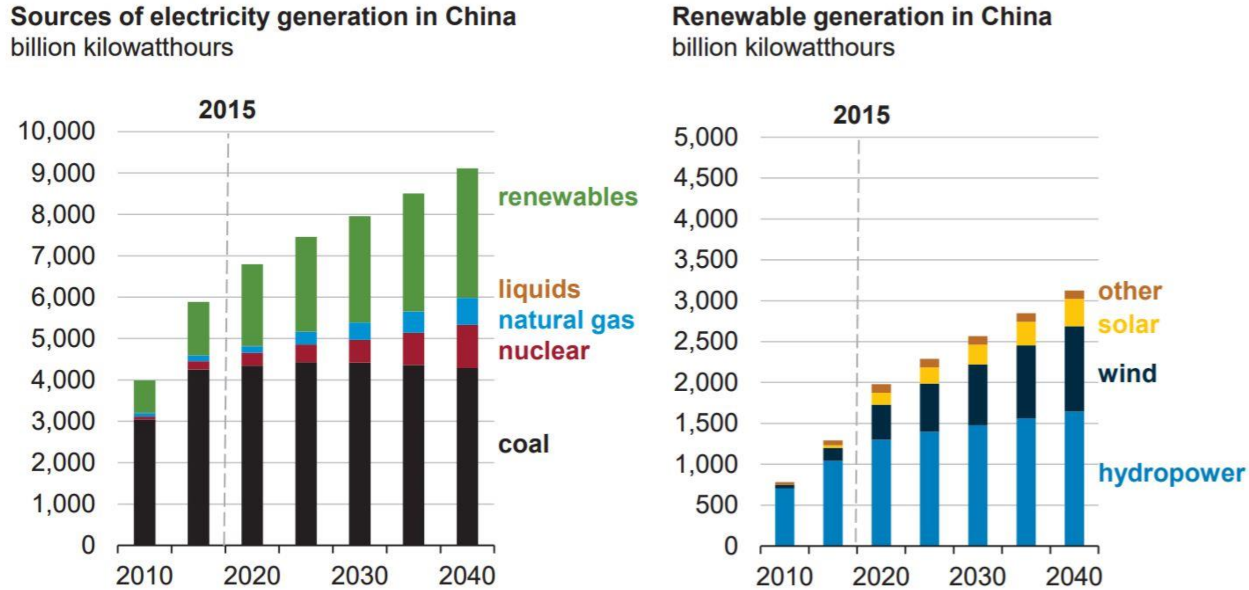

FIGURE 5 EIA projections on China's energy mix for electricity generation (2010-2040).

Using the EIA's projections, we conduct a future carbon intensity scenario with respect to the impacts of China's power generation mix to the net CO_2 emissions from HSR substation for air transport. Specifically, we compare how much extra net emissions savings it would achieve, if since 2012 China already had the projected energy mix of 2030 and of 2040. By comparing this 'what-if' scenario with our baseline case, we aim to demonstrate the importance of decarbonizing China's fuel mix in electricity generation and the knock-on benefits for the transport sector.

Discussion

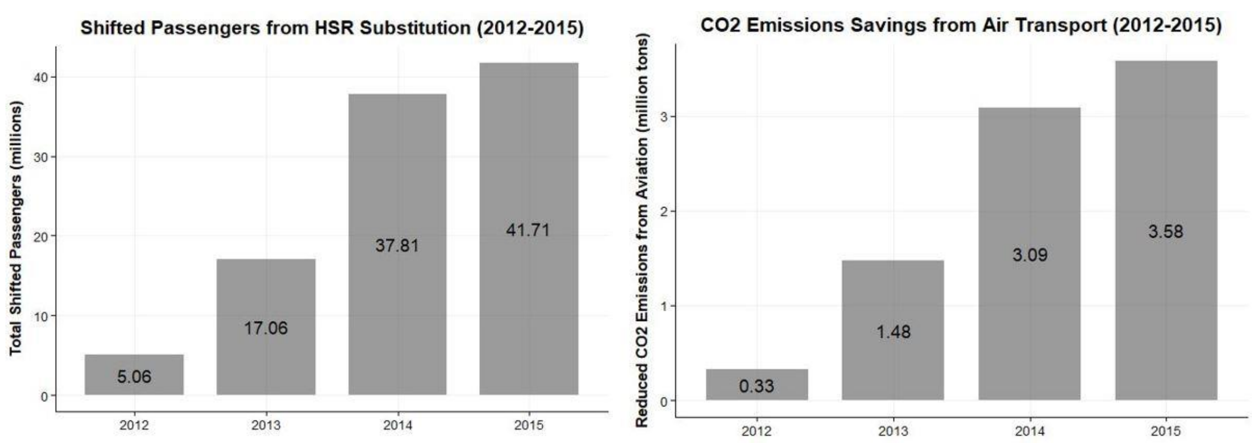

FIGURE 6 Estimated reductions in passengers and CO_2 emissions from air transport.

The total reduction of airline traffic and the corresponding CO_2 emissions savings are shown in Figure 6. Between 2011 and 2015, which has been demonstrated as the period that HSR began to appear significant substitution effects, the annual total shifted passengers from air transport to HSR are estimated to increase from 5.06 million in 2012 to 41.71 million in 2015. Correspondingly, reduction in total CO_2 emissions from air transport also increases by year. The gross emissions savings not including HSR emissions are estimated to be 0.33 million tons in 2012, 1.48 million tons in 2013, 3.09 million tons in 2014, and 3.58 million tons in 2015. The total gross emissions savings over 2012-2015 are 8.47 million tons. Given this increasing trend we expect that the future savings from the mode shift to HSR will make an increasingly significant contribution to carbon emissions reduction.

As mentioned previously, we calculated a number of HSR emissions inventories for transporting the shifted demand from air transport, using the EIA's projection on China's future energy mix in power generation. The total HSR emissions are computed for two different HSR vehicle settings (see Table 1): emissions of CRHs with their prototypes' electricity intensities (TYPE 1), and emissions of a generic HSR with an average electricity intensity value (TYPE 2). In the baseline case, we use the observed energy mix for electricity production taken from IEA *(35)*. Comparing with the baseline case outcomes, we further test on two future scenarios utilizing the forecast carbon intensity of the electricity mix in 2030 and in 2040 *(35)*, respectively. These two years are selected because 2030 is the year that China claimed to peak its total CO_2 emissions and to reduce its CO_2 emissions per unit of GDP by 60-65% from the 2005 level; and 2040 is the year that China is expected to have higher share of renewables than coal in its electricity generation (see Figure 5). By comparing the net emissions savings of the present day with the results of the future scenarios, we aim to highlight the significant impact that carbon intensity reduction of power generation could have.

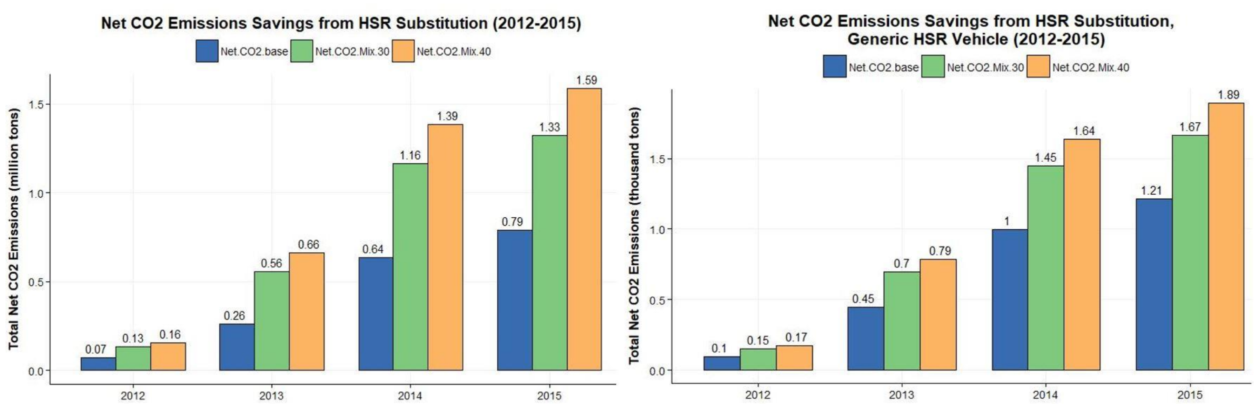

FIGURE 7 Net CO_2 Emissions from the HSR substitution for air transport (2012-2015).

Figure 7 depicts our estimation results of the net CO_2 emissions savings from HSR substation for air transport. Plot in the left-hand side shows the emissions savings of the TYPE 1 setting: the Chinese HSR follows their prototypes' electricity intensity values. Plot in the right-hand side provides estimates of the TYPE 2 setting, where the electricity intensity value is taken from the average of all HSR vehicles available in Chester and Horvath *(24)*. Therefore, we can consider our estimation from the two settings as a reasonable range of the net CO_2 savings for China's HSR.

Overall, from Figure 7 in almost all cases, HSR benefits to the environment by replacing air transport and yielding positive net CO_2 emissions savings. The TYPE 2 setting appears to have higher emissions savings across all cases, which means that the total HSR emissions of TYPE2 HSR are lower than those of TYPE 1 HSR. This is potentially because more CRH3C and CRH380 vehicles with higher electricity intensity (0.058 kWh/seat-km, see Table 1) are used in reality, which produce more emissions than the generic HSR model with a lower electricity intensity value (0.043 kWh/seat-km).

From the baseline case, substituting HSR for air transport saves 0.07-0.1 million tons of CO_2 in 2012, when the total shifted passengers are relatively small. As HSR network expands, more passengers have shifted from air transport to HSR, and this results in an increasing net emissions savings. In 2013 the total net savings are more than tripled comparing with the previous year and increase to 0.26-0.45 million tons. This significant growth in total CO_2 emissions savings continues in 2014 reaching to 0.64-1 million tons. The growth slightly slows down in 2015, increasing by 0.15-0.21 million tons and reaching to 0.79-1.21 million tons of CO_2. The slowing-down growth of emissions savings in 2015 probably because compared with 2012-2014, fewer HSR lines were introduced in 2015. In total, the baseline case estimates a 1.76-2.76 million tons of CO_2 savings from the HSR substitution. At the upper end this saving equates to 5.1% of the 53.98 million tons of CO_2 emissions attributable to the domestic Chinese aviation market in 2015.

On the other hand, results from our future scenarios of a cleaner energy mix for electricity production will reduce significantly more HSR emissions than those of the baseline case and thus yielding higher net savings. In the 2030 energy mix scenario, the yearly total net savings are 0.13-0.15 million tons in 2012, 0.56-0.7 million tons in 2013, 1.16-1.45 million tons in 2014, and 1.33-1.67 million tons in 2015, respectively. As can be seen in Figure 8, since 2013, the total emissions savings from the Mix-2030 scenario remain about twice as large as the baseline case savings for the TYPE 1 setting and one third higher than the baseline results for the TYPE 2 setting. Our results here demonstrate the great potential of emissions reduction if China achieved its 2030 target in decarbonizing the power generation sector. The Mix-2030 scenario projects a total of 3.18-3.97 million tons net emissions savings.

Finally, for the Mix-2040 scenario where China already had an energy mix with more renewables than fossil fuels, a further improvement in emissions savings are projected. Specifically, in 2012 the total savings are 0.16-0.17 million tons, and the value increase by 312% to 365% in 2013 reaching to 0.66-0.79 million tons. Similar to the previous two cases, in 2014 the net emissions savings keep growing remarkably, and achieve a 1.39-1.64 million tons net CO_2 reduction. Again, the growth slows down in 2015 with a total emissions savings of 1.59-1.89 million tons in that year. Moreover, another interesting finding could be found from our estimation. Compared with the significant improvement of total net emissions savings from the 'present-day' energy mix case to the Mix-2030 case, the benefits of continuing decarbonizing China's energy mix yield smaller emissions reductions. If we compare the total savings of the Mix-2030 scenario against the Mix-2040 scenario, the improvement of net emissions is only 0.02-0.03 million tons in 2012, 0.09-0.1 million tons in 2013, 0.21-0.23 million tons in 2014, and 0.22-0.26 million tons in 2015, respectively. This suggests that although reducing carbon intensity of electricity generation from today's level will result in considerable and immediate improvement of emissions reduction, such potential will probably reach to a limit, once China cut the share of coal from 70% to 50% in its electricity generation sector. Nevertheless, decarbonizing this sector remains the most important method of reducing CO_2 emissions in a short- and medium term.

CONCLUSIONS

As a fast-growing economy and the world's largest CO_2 emitter, China is making massive infrastructure investments but has also committed to reducing emissions across all sectors. In this study, we demonstrate that investments in China's HSR infrastructure are having a beneficial impact on emissions from the aviation sector particularly over short ranges as HSR can be an effective means of reduction through mode substitution. The substitution from HSR for air transport was found to have positive environmental benefits producing a cumulative net savings of between 1.76 and 2.76 million tons of CO_2 from 2012 to 2015. This was equivalent to 3.2-5.1%

of 2015 domestic aviation emissions. Importantly, the net savings obtained are substantially lower than the gross cumulative saving of 8 million tons of CO_2 when HSR are not incorporated. Thus, the effect of HSR would be overestimated if it's electricity consumption was not taken into account. This also highlights the importance of the carbon intensity of the power generation sector. With the planned expansion of the HSR network nearly doubling from 19838km of track in 2015 to 38000km in 2025, combining with the greening of electricity supply, we can expect to see even greater reduction in domestic aviation emissions due to the HSR substitution in the future.

To explore this issue further, we looked at future energy mix scenarios for 2030 and 2040 and found that the net emissions savings are highly sensitive to the energy mix of electricity production. Since China relies heavily on coal in its electricity generation, with the current energy mix, HSR still has a great potential to reduce its CO_2 emissions even further if China gradually displaces coal by nuclear and renewable energy sources. Our scenario analysis demonstrates that by just maintaining an energy mix with the share of coal at 55% (compared with the 70% in 2015), each year HSR could save emissions as twice much as the savings from the baseline case. Therefore, we demonstrate that decarbonizing China's fuel mix in electricity generation is vitally important to the CO_2 emissions impacts of transitioning inter-city travel from air transport to HSR.

This study has attempted to estimate the impacts of HSR substation from aggregate data for forecasting trends and comparing growth rates. Though robustness of this approach could be potentially improved through the use of discrete choice models to predict market shares of both HSR and air transport and this is an area for future work. Additionally, our calculation on net CO2 emissions focuses only on the operation phase of air transport and HSR. Such calculation could potentially expand to the life cycle level, however, obtaining data at that scale for China is challenging.

AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design: Bojun Wang; data collection: Bojun Wang; analysis and interpretation of results: Bojun Wang, Aidan O'Sullivan, Andreas Schäfer; draft manuscript preparation: Bojun Wang. All authors reviewed the results and approved the final version of the manuscript.

ACKNOWLEDGMENTS

This work is supported by EPSRC grant EP/M027031/1. We are grateful for their support. The first author also personally acknowledges the Chinese Scholarship Council (CSC) for the scholarship provided to his PhD.

REFERENCES

1. International Energy Agency (IEA). Railway Handbook 2017: Energy Consumption and CO_2 emissions. 2016.
2. Natural Resources Defense Council (NRDC). The Road from Paris: China's Progress Toward Its Climate Pledge. 2017.
3. China Ministry of Railway. China Railway Yearbook, in Chinese (2007-2015).
4. China Statistical Yearbook 2017. http://www.stats.gov.cn/tjsj/ndsj/2017/indexch.htm. Accessed on 13th April 2018.
5. China State Council. National Railway Network Development Plan (2016-2025), in Chinese. http://www.ndrc.gov.cn/zcfb/zcfbtz/201607/W020170213333938328309.pdf. Accessed on 3rd March 2018.
6. Airbus. Global Market Forest: Growing Horizons 2017-2036. 2017.
7. Schäfer, A, Evans, A., Reynolds, T. and Dray, L. Cost of mitigating CO_2 emissions from passenger aircraft. *Nature Climate Change*, 2016. 6: 412-417.
8. Jiang, C. and Zhang, A. Airline network choice and market coverage under high-speed rail competition. *Transportation Research Part A*, 2016. 92: 248-260.
9. Chen, Z. Impacts of high-speed rail on domestic air transportation in China. *Journal of Transport Geography*, 2017. 62: 184-196.
10. Wan, Y., Ha, H.K., Yoshida, Y. and Zhang, A. Airlines' reaction to high-speed rail entries: Empirical study of the Northeast Asian market. *Transportation Research Part A*, 2016. 94: 532-557.
11. Jimenez, J. and Betancor, O. When trains go faster than planes: the strategic reaction of airlines in Spain. *Transport Policy*, 2012. 23: 34-41.
12. Roman, C., Espino, R., Martin, J.C. Competition of high-speed train with air transport: the case of Madrid-Barcelona. *Journal of Air Transport Management*, 2007. 13: 277-284.
13. Steer, D. Air and Rail Competition and Complementarity: Final report for the European Commission (DG TREN). 2006.
14. Clever, R. and Hansen, M. Interaction of air and high-speed in Japan. *Transport Research Board*, 2008. 2043: 1-12.;
15. Pagliara, R., Vassallo, J.M., and Roman, C. High-speed rail versus air transportation: case study of Madrid-Barcelona, Spain. *Transport Research Board*, 2012. 2289:10-17.
16. Adler, N., Pels, E., and Nash, C. High-speed rail and air transport competition: Game engineering as tool for cost-benefit analysis. *Transportation Research Part B*, 2010. 44: 812-833.
17. Yang, H. and Zhang, A. Effect of high-speed rail and air transport competition on prices, profits, and welfare. *Transportation Research Part B*, 2012. 46: 1322-1333.
18. Xia, W. and Zhang, A. High-speed rail and air transport competition and cooperation: A vertical differentiation approach. *Transportation Research Part B*, 2016. 94: 456-481.
19. Dray, L., Al Zayat K., and Schäfer, A. The Global Potential for CO_2 Emissions Reduction from Jet Engine Passenger Aircraft. *Transport Research Board*, 2018. In press.

20. Dessens O., Köhler M.O., Rogers H.L., Jones R.L., and Pyle J.A. Aviation and Climate Change. Transport Policy, 2014. 34: 5-13.
21. Krammer, P., Dray, L., and Köhler M. Climate-neutrality versus carbon-neutrality for aviation biofuel policy. *Transportation Research Part D*, 2013. 23: 64-72.
22. Chester, M. Life-cycle Environmental Inventory of Passenger Transportation in the United Sates. *PhD Thesis.* UC Berkeley. 2008.
23. Chester, M. and Horvath, A. Life-cycle assessment of high-speed rail: the case of California. *Environ. Res. Lett.* 2010. 5: 014003.
24. Chester, M. and Horvath, A. High-speed rail with emerging automobiles and aircraft can reduce environmental impacts in California's future (Supplementary Information included). *Environ. Res. Lett.* 2012. 7: 0304012.
25. Yue, Y., Wang, T. Liang, S. Yang, J. Hou, P., Qu, S., Zhou, J., Jia, X., Wang, H., Xu, M. Life cycle assessment of High Speed Rail in China. *Transportation Research Part D*, 2015. 41: 367-376.
26. Akerman, J. The role of high-speed rail in mitigating climate change – the Swedish case Europabanan from a life cycle perspective. *Transportation Research Part D*, 2011. 16: 208-217.
27. Bueno, G., Hoyos, D., and Capellan-Perez, I. Evaluating the environmental performance of the high-speed rail project in the Basque Country, Spain. *Research in Transportation Economics*, 2017. 62: 44-56.
28. SABRE Market Intelligence passenger demand, routing and aircraft schedule databases.2016. http://www.sabre-global.com. Accessed November 2016.
29. Dray L., Krammer P., Doyme K., Wang B., Al Zayat K, O'Sullivan A., Schäfer A. AIM2015: Validation and Initial Results from an Open-Source Aviation Systems Model. *Transport Policy*, 2018. In press.
30. Sustainable Aviation. The SA Noise Roadmap, 2015. http://www.sustainableaviation.co.uk/wp-content/uploads/2015/09/SA-Noise-Road-Map-Report.pdf. Accessed April 2018.
31. Clewlow, R. The Climate Impacts of High-Speed Rail and Air Transportation: A Global Comprehensive Analysis. *PhD Thesis*. MIT. 2012.
32. Zhou, J. Improving the energy efficiency of high speed rail and life cycle comparison with other modes of transport. *PhD Thesis*. Imperial College. 2014.
33. IEA Statistics. China (People's Republic of China and Hong Kong China): Electricity and Heat for 2010-2015. https://www.iea.org/statistics/statisticssearch/report/?year=2015&country=CHINAREG&product=ElectricityandHeat. Accessed on 20th May 2018.
34. IEA Statistics. CO_2 emissions from fuel combustion. 2017.
35. U.S. Energy Information Administration (EIA). International Energy Outlook 2017.