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Optimal High-Speed Passenger Transport Network with Minimal Integrated Construction and Operation Energy Consumption Based on Superstructure Model

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Economy development and promotion of high-speed transport technologies result in the increase of inter-city high-speed passenger transport. The energy consumption over the lifetime of transport infrastructure, composed of construction and operation energy consumption, is a significant factor that should be considered at the planning stage. In this paper, we present a mixed-integer programming (MIP) model based on superstructure for the energy consumption optimization of inter-city high-speed transport systems, a network design integration of aviation and high-speed railway, accounting both energy consumption during infrastructure construction and energy consumption during subsequent operation processes, to optimize connections between large population centers and connections between modes of transport. Energy consumption during infrastructure construction is obtained related to investment costs using a lifecycle assessment based on the economic input-output method. The shares of construction energy consumption and operation energy consumption during infrastructure lifetime are compared in the case studies of East and Southeast China and the model results show the optimized network structure according to the total energy minimization objective. Optimized transport networks are analyzed in terms of hub-spoke characteristics and city transport functions as sources and sinks. Model results have implications in the energy-saving aspect for actual high-speed railway and civil aviation infrastructure layouts and high-speed transport technology development.

1. Introduction

From 2007 to 2011, the civil aviation and railway passenger volume have increased to 1.58 and 1.37 times of the original level, respectively. High-speed railway accounts for about 20 % of the total transport passenger volume in China in 2011. Civil aviation passenger volume has reached 293 million people in 2011, more than 10 % of all civil aviation passenger volume in the world. Civil aviation and railway passenger volume increased rapidly from 2007 to 2013 in China, and their operational energy consumption also increased proportionally.

Urbanization promoted the increase of inter-city high-speed transport passenger volume, mainly including high-speed railways, civil aviation and highways (Garmendia et al., 2012). Conventional railways suit well with long distance transport but are not competitive in speed. High-speed railway can compete in load capacity and speed level with civil aviation.

Transportation energy consumption mainly comprises energy consumption during operation and transport infrastructure construction process, and the operation process is related with passenger load factors, road conditions and specific operational features while the construction process is related with construction materials and infrastructure layouts. High-speed railways possess operational energy consumption of 0.449 tce/10^4pkm (t of standard coal abbreviated as tce) at target speed of 350 km/h while airplanes possess around

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7 tce/10^4pkm operational energy consumption on average. The unit area energy consumption for an airport terminal (excluding airport runways) or a railway station is about 0.18 tce/m^2.
Europe has developed more high speed rails while the US is known for its complicated "Hub & Spoke" civil aviation network which sets an example of high-speed transport layouts. Enhanced planning integrated of aviation and high-speed railways could lead to higher energy efficiency for inter-city high-speed transport (Givoni and Banister, 2006). In this work, we provide a generic systematic method for the optimal configuration of inter-city high-speed passenger transport infrastructure from an energy consumption perspective, which could be applied in different passenger transport demand patterns in different regions.

2. Data Preparation and Model Description

High-speed railways and civil aviation are the main research objectives in the model. The research was conducted to optimize the transport network considering the integration of different transport means, taking into consideration the amounts of construction, the passenger loads, and the transport operation energy consumption associated with passenger flows.
Due to the limited work on the construction energy data, EIO LCA (Economic Input-Output Lifecycle Assessment) method developed at Carnegie Mellon University was used in the study to obtain the energy consumption data (Bin and Dowlatabadi, 2005), unavailable from literature. EIO LCA models set with proper categories and boundaries show advantages in precise estimation of the supply chain process and good articulation of the relationship between economic input and possible impacts on the environment (Matthews and Small, 2000). Table 1 shows the average railway investment per kilometer and the energy consumption calculated by the EIO LCA model.
The airport construction energy consumption was related with the expected yearly dispatched passenger volume and the high-speed railway station energy consumption was related with the peak moment passenger volume. The railway track construction energy consumption was related with the track length.
The transport operational energy consumption is summarized in Table 2. The Conventional railways data were collected from China's government planning in 2010 and the research by Yang (2008). The High-speed railways energy consumption as embodied in Table 2 was classified into two categories according to the objective speeds.

Table 1: The average railway investment per kilometre and the energy consumption of the EIO LCA model outputs

	Average investment ratio (10^4 RMB/km）	Average investment ratio (10^4 $/km）	Energy consumption (TJ/km)	Energy consumption (tce/km)
Conventional railways (<250 km/h)	6,080	972.8	23.2	792.89
High-speed railways (250 km/h)	8,339	1,334.24	31.9	1,090.23
High-speed railways (350 km/h)	1,4049	2,247.84	53.7	1,835.27

Table 2: Conventional railways, High-speed railways, Civil aviation operational energy consumption

Comprehensive energy consumption intensity	Conventional railways	High-speed railways (Classified with target speeds)	
		350 km/h	250 km/h
tce/million-ton-km	9.4	26.93	13.55
tce/10^4pkm	0.1568	0.449	0.226

In former transport network research, travel loads were simulated as demand flows from points to points or points to zones using the origin-destination model combined with the source-sink model (Horn 2002). The transport network design problem has two branches: the discrete variables describing the addition or the segregation of the roads and the continuous variables resembling the road capacity. Mainly based on their suggestions, the research set transport demand as a restriction of the model, and the source-sink model is beneficial for simplification. The transport demand, a reflection of the required transport hub passenger handling capacity, was met with the proposed transport network.

The study adopted Mixed-Integer Programming (MIP) strategy involving both continuous and binary variables. The proposed routes selected as components of the local transport network were represented by binary variables. The passenger volume of each route was represented as continuous variable and the sum of all passenger volume should meet the minimum expected transport demand. The passenger flows can be divided into any small branches within the range of transport facility. The optimal layout was then obtained by eliminating dispensable routes corresponding to the integration of these transport means to minimize the total energy consumption.

In summary, in order to determine the impact of various inter-city high-speed passenger transport means on the overall life-cycle energy, there is a need to consider multiple configurations such as origins, destinations and transits of trips. Travel demand between two cities are met by different routes (with or without transit) and different transport means. The principle of mass conservation was introduced to the model based on passenger volume distribution.

In our previous research, a superstructure modelling method has been applied to typical process and system optimization. Our previous work has considered complex coal polygeneration schemes, commercial building energy systems (Liu et al. 2010), distributed energy systems (DES) (Zhou et al. 2013), China's carbon mitigation policy impact on power sector implementation (Zhang et al. 2012) and a future carbon dioxide pipeline network.

In this study, we use GAMS (GAMS Development Corporation, 2008) to establish a model to optimize the transport layout and to minimize the total transport energy consumption. Two cases are analysed considering operational and construction energy consumption and some suggestions on transport infrastructure are discussed.

3. Case study and results discussion

From the results of the model, the high-speed railways and the civil aviation show distinct differences in regard to the transport operation and the transport construction energy consumption. Details are discussed below.

3.1 Case 1: Assessing on the total energy consumption of the transport operation and the transport construction

The results show that in 50-y lifespan the transport operation energy consumption is higher than the transport construction energy consumption an order of magnitude or more, since the infrastructure energy consumption is fixed at the start of the whole lifespan of the construction. So the transport operation energy consumption dominates the final simulated layout. Due to the higher transport operation energy consumption per unit of civil aviation, high-speed railways possess overwhelming advantage.

Model results show that high-speed railways are chosen to meet all the transport demands with minimal energy consumption (Figure 1). In order to shorten the travel distances as much as possible, most transport demand is met with direct high-speed rail routes, only a small part of demand is met with transits.

Since transport operation energy consumption compared with construction energy consumption in lifespan is much higher, new infrastructure on new location or repairing construction on the present layout has no big difference in optimized layout.

In Figure 1 Beijing, Shanghai and Guangzhou forming a steady triangle are located in the centre of the transport network, and the distance between the three cities is labelled as medium to long haul transport distance. Distance from Beijing to Guangzhou is so long that the optimized secondary centre Changsha is located on the line. Each major hub is surrounded by a “city circle” which is enlarged in terms of high-speed transport. The city circle is enlarged to covering other small provincial capitals in the neighbourhood, such as Beijing surrounded by Tianjin and Shijiazhuang and Shanghai surrounded by Nanjing and Hangzhou. Chengdu and Chongqing regarded as spokes directly connect the cities in the central China.

3.2 Case 2: Assessing the influence of the transport infrastructure layout on transport construction energy consumption

The infrastructure energy consumption consists of airport terminal, railway station and railway track construction energy consumption. The results show the civil aviation is chosen to complete all the transport demands (Figure 2). Due to the increased costs of the transit airport construction, the optimized results show no transits, all passenger demands are met with direct routes.

In Figure 2 the civil aviation network is constructed more densely than the high-speed railway network in case 1. The network has more than three centres forming a balanced development. The optimized network largely depends on the geographical spatial distance and the unit construction energy consumption.

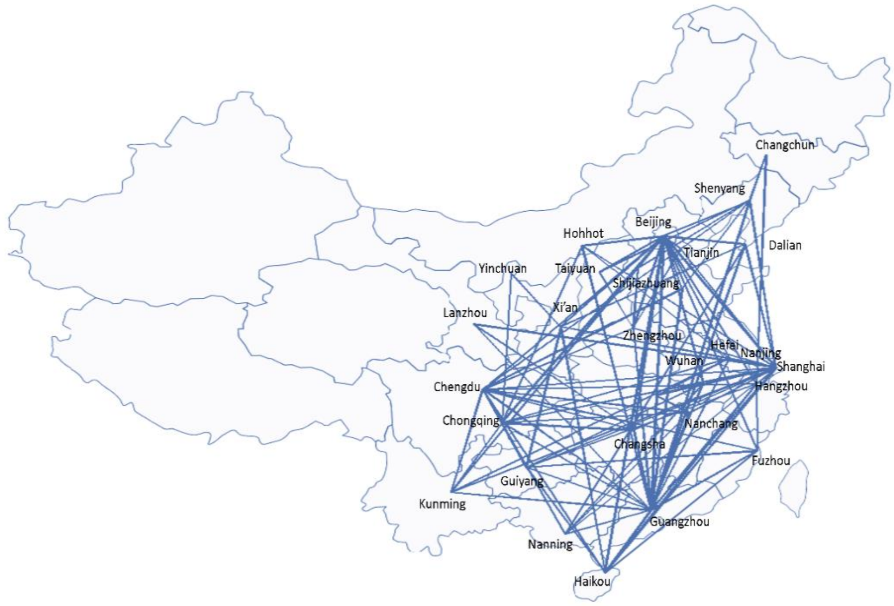

Figure 1: Case 1: Assessing on the total energy consumption of the transport process and the transport construction (only the high-speed railways are chosen)

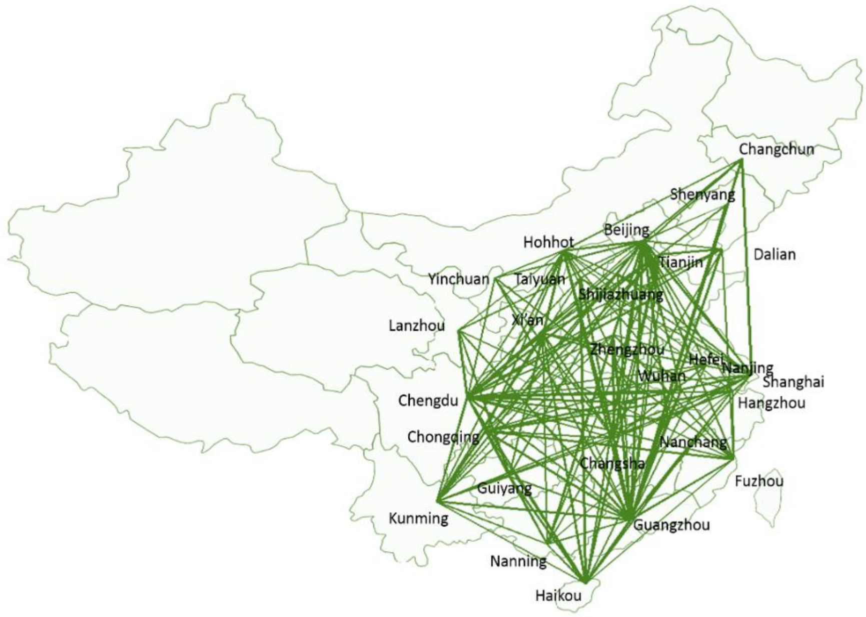

Figure 2: Case 2: Assessing the influence of the transport construction energy consumption (only the civil aviation is chosen)

3.3 Discussion

In operation or construction aspect, the model results show that only one transport mode has an absolute advantage. Because the high-speed railways deliver lower transport operational energy consumption per unit than the civil aviation whiles the civil aviation has an advantage over no fixed track construction energy consumption.

Due to higher track construction energy consumption, the model results show high-speed railway infrastructure levels of the 28 provincial capitals are formed more homogenized than civil aviation under the energy minimization objective function. However, the optimized layout of civil aviation is consistent with the transport demand variation among the 28 cities, which shows significant differences between the 28 cities (Figure 3). City construction is controlled largely by policy and the transport infrastructure should be in line with city development. So high-speed railway construction can be applied to suit rigid demands and civil aviation can be adjusted according to transport demand variation.

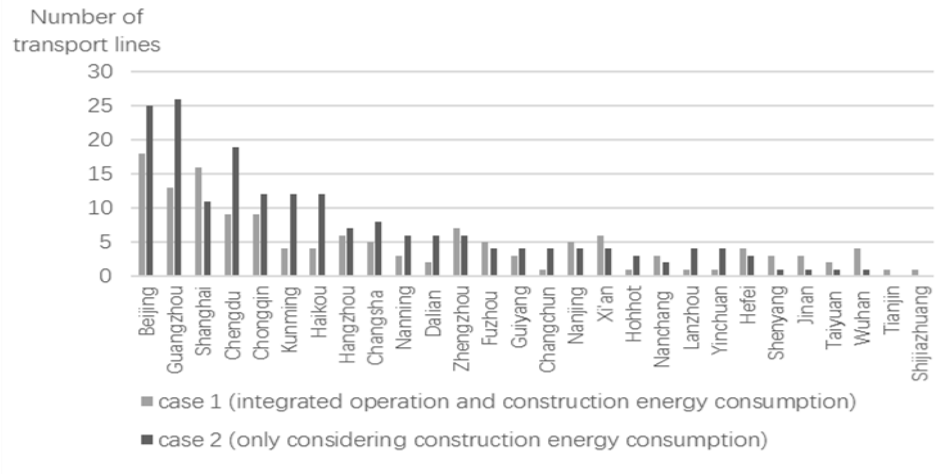

Figure 3: Number of planned transport lines of 28 provincial capitals in China in case studies

Comparing the high-speed railways and the civil aviation, the high-speed railways are found to be applicable to large-volume passenger transport, across middle-distances or long-distances while the civil aviation is more applicable to long-distance transport.

Evaluation of the transport life-cycle energy consumption in the US has found that total life-cycle assessment including the infrastructure and the supply chains contributed to an addition of the normal value of the operation process, a share of 155 % for rail and 31 % for air (Asongu and Jellal 2003). This indicates that the contribution of infrastructure to the overall lifespan energy consumption, although rather large as shown previously, could be even larger.

The choice between high-speed railway and civil aviation has to consider more relevant elements, such as different forms of energy: oil derived jet fuel for aviation and electricity for high-speed railways, and if we select a cleaner way to generate the electricity used by rails, there will be different energy consumption results. So there is an opportunity to reduce carbon footprint of inter-city transportation if trains are encouraged over air.

4. Conclusions

This paper aims to introduce a general modelling method for the optimal configuration of inter-city high-speed passenger transport infrastructure from the energy consumption perspective, which could be applied to providing solutions for meeting different passenger travel demands in different regions. The superstructure built in GAMS was used to minimize the total transport energy consumption and optimize the transport layout. Two cases are studied and the results show that the transport operational energy consumption are larger than the transport construction energy consumption over the infrastructure lifespan. The paper shows great significance in transport network optimization in the energy perspective and the comparison between the transport operational energy and the construction energy consumption in the case study.

Two case studies are provided to illustrate how transport modes impact the choice of transport technologies and systems. The first case aims to minimize the overall energy consumption so railway dominates in comparison. In the second case, construction of transport infrastructure is given more emphasis, and the simulation results show aviation is favoured. Civil aviation is preferred in the model for lower unit construction energy consumption while high-speed railways are preferred considering lower long-term operational energy. The civil aviation network is constructed more densely than the high-speed railway network in case 1. The network forms polycentric balanced development.

It should be noted that energy consumption of the high-speed transport system in the long term poses heavy reliance on technology choice. Therefore, it provides an opportunity to reduce the carbon footprint of the sector via planning. In a scenario where aviation fuel is supplied from low-carbon sources, biofuel for instance, and electricity for railway transport is also from a grid with high renewable power percentage, the overall carbon emissions of the high-speed transport sector could be much lower.

It should also be noted that whilst the high-speed railways possess lower operational energy consumption per unit than civil aviation, high-speed railway construction which consists of stations and lengthy track construction are more complex civil engineering challenges than those encountered in civil aviation.

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