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Configuration of inter-city high-speed passenger transport infrastructure with minimal construction and operational energy consumption: A superstructure based modelling and optimization framework

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ABSTRACT

Inter-city high-speed passenger transport, mainly aviation and high-speed railway, has been increasing around the world, in accordance with economic development and penetration of high-speed transport technologies. The energy consumption over the lifetime of transport infrastructure and operation is a significant factor at the planning stage. In this paper, we present a superstructure modelling and optimization framework of inter-city high-speed transport systems, accounting energy consumption during infrastructure construction and during subsequent operation, to optimize connections between large population centers and between modes of transport. Energy consumption during infrastructure construction is obtained from investment cost using lifecycle assessment. The first two cases considered differences between infrastructure construction and lifetime operation while the second case narrowed the study scope. Sensitivity analysis in the third case compared impacts of both transport means on system design. Model results have implications for actual high-speed transport technology development and infrastructure layout.

1. Introduction

Civil aviation and railway passenger volume increased rapidly from 2007 to 2013 in China (Fig. 1) (2013 Railway Statistical Bulletin, 2014; 2013 Civil Aviation Industry Statistical Bulletin, 2014), and their operational energy consumption also increased in a proportional manner. From 2007 to 2011, the civil aviation and railway passenger volume have increased to 1.58 and 1.37 times of the original value, respectively. High-speed railway passenger volume accounts for about 20 percent of the total travel passenger volume in China in 2011. Civil aviation passenger volume has reached 293 million passengers in 2011, more than one tenth of all civil aviation passenger volume in the world.

The passenger volume of inter-city high-speed transport, mainly composed of high-speed railways, civil aviation and highways, increases in line with urbanization rate (Garmendia et al., 2012).

Table 1 lists different features of high-speed passenger transport means (Zhao, 2012). Conventional railways suit well for long distance transport but are not competitive in the speed aspect. High-speed railway can compete with civil aviation in load capacity and speed level.

Transportation energy consumption mainly comprises energy consumption during operation related to passenger load factors, road conditions and specific operational features, and during transport infrastructure construction related to construction materials and infrastructure layouts (Cui, 2010). High-speed railways possess operation energy consumption of 0.449 tce/10^4pkm (tonnes of standard coal abbreviated as tce) at target speed of 350 km/h (Chen, 2011) while airplanes possess around 7 tce/10^4pkm operation energy consumption on average (Chang et al., 2010). The unit energy consumption for an airport terminal (excluding airport runways) or a railway station was about 0.18 tce/m^2.

China can increasingly build civil aviation and highways following a United States model or develop more high-speed railways as Europe has done. Enhanced integration of aviation and high-speed railway planning could lead to higher energy efficiency for inter-

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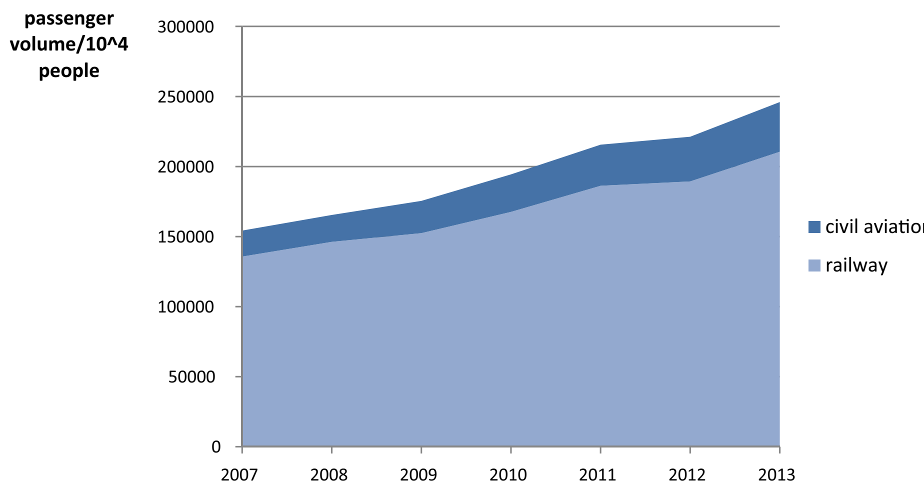

Fig. 1. Steady rise of railway and civil aviation passenger volumes in China from 2007 to 2013.

Table 1
Main features of high-speed passenger transport.

	Highways	High-speed railways	Conventional railways	Civil aviation
Highest speed (km/h)	160	390	169	1200
Passenger load upper limit	Normal	Larger	Larger	Smaller
Operation energy consumption per unit (kcal/pkm)	139	435	90	714
Purchase capital (10^4 RMB)	1.2	5	1.5	150
Punctuality	Worse	Better	Normal	Worse
Single direction maximum capacity (10^4 people/year)	8760	7000	5000	1800
Environmental effect	Worse	Better	Normal	Normal

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 for different passenger travel demand patterns in different regions.

Below are the literature study from the construction energy consumption, transport network and modelling method perspectives.

1.1. Construction energy consumption

Previous research shows that the railway operation energy consumption is mainly determined by the average load factor and the line utilization frequency. Transport energy consumption is usually calculated in terms of the basic unit per passenger per kilometer (Cui, 2010; Chen, 2011). Some studies have analyzed transport operation energy consumption influential factors, but work on the operation energy data as well as construction energy data is rather limited. Economic Input-Output Life Cycle Assessment (EIO LCA) method developed at Carnegie Mellon University was used in the study to obtain the energy consumption data (Bin and Dowlatabadi, 2005), unavailable from literature.

Life-cycle assessment (LCA) is a method based on the product cycle phases from the raw material to the finished product disposition (Matthews and Small, 2001; Lave et al., 1995; Durairaj et al., 2002). Some researchers developed different LCA models such as GaBi (a software) (Hendrickson et al., 1997) and a hybrid life-cycle assessment on construction process (Bilec et al., 2006) in which the most outputs are in of the same magnitude with the values out of EIO LCA (Hendrickson et al., 1997). The advantages of the EIO LCA model are effective use, 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, 2001).

1.2. Transport network types

Previous aviation network research can be classified into two categories, one focused on geographical networks and the other emphasized on national economic, cultural and social development strategy. Aviation network can be divided into direct connected "point to point" network, "Hub & Spoke" network and the integrated "Hub & Spoke" network (Jin and Wang, 2005) (Fig. 2). Improvement of the "Hub & Spoke" network also considers resource allocation and network density-scale effects (Wang et al., 2009). China has developed a "Hub & Spoke" structure, in which Beijing, Shanghai and Guangzhou are the most important transport centers. In national planning, ensuring transport demand and transport network optimization have been clearly stated (Civil Aviation Development Institute "Eleventh Five-Year" Airport Planning Research Group, 2004; Zhao, 2006).

"Hub & Spoke" network (Jin and Wang, 2005; Wang et al., 2003, 2009; Jin, 2001) are usually designed based on hub regional importance classification, which is rarely used in energy focused research. The most common criteria in transport network analyses are clustering coefficients, degree distribution of each node and average path length (Wang et al., 2011). These methods either concentrate on detailed geographical assessment or largely focus on single transport systems, and this limits their application in energy research to minimize life cycle energy consumption. Further study is needed to consider impacts of hub location and multi-mode transport integration design on energy consumption over the long run.

1.3. Modelling methods

In former transport network research, travel loads are simulated as demand flows from points to points or points to zones using the origin-destination(OD) model combined with the source-