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Modeling the railway network design problem: A novel approach to considering carbon emissions reduction

Boliang Lin [a,*], Chang Liu [a], Huijun Wang [b], Ruixi Lin [c]

[a] School of Traffic and Transportation, Beijing Jiaotong University, Beijing 100044, China
[b] Institute of Planning and Standard, National Railway Administration of China, Beijing 100055, China
[c] Department of Electrical Engineering, Stanford University, Stanford, CA 94305, USA

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ABSTRACT

In recent years, air pollution has become a severe environmental problem. Many countries are seeking effective methods to reduce carbon emissions. Among the sources of air pollution, the transportation industry is a large one. Thus, developing low carbon emissions transportation is a new trend. Since railway transport possesses the advantages of high volume and low emissions, a new idea for transportation development is to divert truck freights to railway by improving the capacity of the railway. Based on this situation, this paper analyzes the carbon emissions of railway and highway transport and estimates the environmental benefit of building a railway. Next, a bi-level programming model for railway network design is recommended. Different from the classical model, the opportunity cost and carbon emissions of the infeasible flows, which cannot be transported by railway and will be served by highway, are considered in the objective function, enabling the model to balance the investment and carbon emissions. To comply with the practice of railway planning, we introduced the method to deal with passenger flow, empty car flow and relationships among the links in a corridor. In the end, a numerical example is conducted to test the model and compare the final decisions when different weights are set on the carbon emissions.

1. Introduction

As the problem of air pollution is becoming increasingly severe, carbon emissions reduction has attracted much attention from the international community.

Among the many sources of carbon emissions, the transportation industry is a large one. Thus, promoting the development of low-carbon transport will greatly benefit the world's carbon emissions reduction. Compared to highway transport, railway and water transport are better choices for developing green transportation because of their low energy consumption and carbon emissions.

Therefore, in 2011, the European Union issued a white paper, titled "Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system," stating that 30% of road freight over 300 km should shift to other modes such as rail or waterborne transport by 2030, and more than 50% by 2050 (European Commission, 2011).

* Corresponding author.
E-mail address: bllin@bjtu.edu.cn (B. Lin).

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At the end of 2015, the Ministry of Transport of China also recommended that railways and waterways should undertake more freight transportation.

Since the capacity of inland waterways is usually limited due to flood or drought, diverting some truck freight to the railway is a wise choice.

Take China as example, in 2015, the total freight transport completed by the 102 thousand kilometer railway (not including the high-speed railway) was 2375.43 billion ton-kilometers. The total freight transport completed by the 4577 thousand kilometer highway reached 5795.57 billion ton-kilometers, which was 1.44 times greater than railway transport.[1] Based on data from the Ministry of Transport of China, Fig. 1 provides the last five years of CO_2 emissions of railway transport and highway transport.

An analysis of the data in Fig. 1 reveals that the average CO_2 emissions per workload of highway transport is 3.36–4.64 times more than that of railway transport. Obviously, railway transport is more environmentally friendly. However, due to the capacity shortage of some railway corridors, hundreds of millions of tons of bulk freight (such as coal) is transported on highway for long distance, leading to significant consumption of high-level energy sources (such as diesel) and carbon emissions.

Fig. 1 shows that the total CO_2 emissions of highway freight transport is 7.89–10.45 times more than that of railway freight transport. Such a situation of these two modes is irrational because some freight that should have been transported by train is transported by truck. Therefore, adjusting the share ratio of the two modes and diverting a portion of freight flows from highway to railway will reduce the carbon emissions of the transportation system efficiently. Based on the CO_2 emissions per workload in 2015, if 1 ton-kilometer workload can be diverted from highway to railway, the CO_2 emissions will reduce 38.87 g.

Thus, if 10% of the highway transport workload (approximately 579.6 billion ton-kilometers) can be shifted to the railway, carbon emissions will reduce 22.53 million tons per year. And if 30% (about 1738.8 billion ton-kilometers) is shifted, 67.58 million tons carbon emissions will be reduced. This will make a great contribution to the world's carbon emissions reduction.

The issue is whether the railway can manage the highway's freight.

In previous decades, the capacity of China's railway has always been insufficient. The capacity shortage was not mitigated until a lot of high-speed railway was built, and some passengers were attracted to high-speed railways. However, there is little capacity surplus, especially the corridors for coal transport. Currently, the average load of the railway is still as much as 23 million tons per kilometer per year, which is higher than the load of most other countries.[2] Some railway corridors are even burdened much more than the average load. For example, the Da-Qin railway in northern China, which is known as the most famous coal-transport corridor, reached approximately 400 million tons in one year.[3]

Therefore, in order to reduce carbon emissions by diverting freight flow from highway to railway, optimizing the structure of railway network is a scientific problem that needs to be addressed urgently both in theory and practice. This is what we focus on in our paper.

2. Literature review

Railway network planning can be abstracted as network design problem (NDP), which is a classical problem in the field of traffic and transportation that many scholars have researched. Among the branches, the research for urban traffic network started relatively early. Leblanc (1975) addressed the problem of determining which links should be improved in an urban road network so that total congestion in the city is minimized. Later, many researchers were devoted to the discrete and continuous NDP for road transportation. Some of them focused on the problem of whether a link should be constructed, and the number of lanes that the constructed links should have (Drezner and Wesolowsky, 2003; Wang et al., 2013). Others aimed at determining the optimal capacity expansions of the links by using continuous decision variables (Liu and Wang, 2015; Wang et al., 2015). The research on railway network design problem (RNDP) started relatively late. Kuby et al. (2001) presented that railway projects can be built all at once or in stages and developed a heuristic time sequence procedure with a cost adjustment factor to solve the "project staging" problem. By removing all the small traffic demands below a certain cutoff level from the OD matrix and preloading them onto their shortest paths, the model size was reduced significantly while very little was lost in the way of realism and optimality. Lin et al. (2002) addressed the optimization decision for the RNDP to determine where a new railway line should be built, or where an existing railway line should be strengthened based on the project investment and cost of routing cars. Yan et al. (2007) discussed the impact of limited investment on the railway project's choice and developed a model of RNDP in several plan stages.

In terms of the research on multimodal network, Arnold et al. (2004) dealt with the problem of optimally locating rail/road terminals for freight transport. A linear 0-1 program was formulated and solved by a heuristic approach. Janic (2007) developed a model for calculating comparable combined internal and external costs of intermodal and road freight transport networks. This would be very helpful for transportation network design. Pazour et al. (2010) put forward that highway congestion could be reduced by diverting freight traffic to the high-speed railway. Thus an un-capacitated network

[1] The data are cited from National Bureau of China (http://data.stats.gov.cn/easyquery.htm?cn=C01).

[2] According to the data from the National Bureau of Statistics of China, the total freight transport completed by the 102 thousand kilometer railway (not including the high-speed railway) was 2375.43 billion ton-kilometers. Thus, in 2015, the average load of the railway line in one year is approximately 23 million tons per kilometer.

[3] The data is cited from the Compilation of National Railway Statistics of China.(2015).