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Equity-oriented skip-stopping schedule optimization in an oversaturated urban rail transit network

Pan Shang[a,b], Ruimin Li[a,b,*], Zhiyong Liu[a,b], Liya Yang[c], Yuqiang Wang[d]

[a] Department of Civil Engineering, Tsinghua University, Beijing 100084, China
[b] Hang Lung Center for Real Estate, Tsinghua University, Beijing 100084, China
[c] School of Public Administration, Renmin University of China, Beijing 100086, China
[d] School of Traffic and Transportation, Beijing Jiaotong University, Beijing 100044, China

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A B S T R A C T

In this study, we focus on improving system-wide equity performance in an oversaturated urban rail transit network based on multi-commodity flow formulation. From the system perspective, an urban rail transit network is a distributed system, where a set of resources (i.e., train capacity) is shared by a number of users (i.e., passengers), and equitable individuals and groups should receive equal shares of resources. However, when oversaturation occurs in an urban rail transit network during peak hours, passengers waiting at different stations may receive varying shares of train capacity leading to the inequity problem under train all-stopping pattern. Train skip-stopping pattern is an effective operational approach, which holds back some passengers at stations and re-routes their journeys in the time dimension based on the available capacity of each train. In this study, the inequity problem in an oversaturated urban rail transit network is analyzed using a multi-commodity flow modeling framework. In detail, first, discretized states, corresponding to the number of missed trains for passengers, are constructed in a space-time-state three-dimensional network, so that the system-wide equity performance can be viewed as a distribution of all passengers in different states. Different from existing flow-based optimization models, we formulate individual passenger and train stopping pattern as commodity and network structure in the multi-commodity flow-modeling framework, respectively. Then, we aim to find an optimal commodity flow and well-designed network structure through the proposed multi-commodity flow model and simultaneously achieve the equitable distribution of all passengers and the optimal train skip-stopping pattern. To quickly solve the proposed model and find an optimal train skip-stopping pattern with preferable system-wide equity performance, the proposed linear programming model can be effectively decomposed to a least-cost sub-problem with positive arc costs for each individual passenger and a least-cost sub-problem with negative arc costs for each individual train under a Lagrangian relaxation framework. For application and implementation, the proposed train skip-stopping optimization model is applied to a simple case and a real-world case based on Batong Line in the Beijing Subway Network. The simple case demonstrates that our proposed Lagrangian relaxation framework can obtain the approximate optimal solution with a small-gap lower bound and a lot of computing time saved compared with CPLEX solver. The real-world case based on Batong Line in the Beijing Subway Network

* Corresponding author at: Department of Civil Engineering, Tsinghua University, Beijing 100084, China.
E-mail addresses: shangp16@mails.tsinghua.edu.cn (P. Shang), lrmin@tsinghua.edu.cn (R. Li), liuzhiyongnew@163.com (Z. Liu), Liya_yang@263.net (L. Yang), 15120776@bjtu.edu.cn (Y. Wang).

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compares the equity and efficiency indices under the operational approach of train skip-stopping pattern with those under the train all-stopping pattern to state the advantage of the train skip-stopping operational approach.

1. Introduction

In most large cities worldwide, public transportation has played an important role among all means of transportation. Especially, the urban rail transit system with the characteristics of high security, wide accessibility, and reliable services transports a large proportion of passengers in cities daily (Krasemann, 2012; Timan, 2015; D'Acierno et al., 2017). For example, the passenger volume in Beijing Subway Network has exceeded 1,200,000 per day (Beijing Daily, 2016).

Representative peak hours occur in the morning and evening, in which many commuters are transported by the subway networks in Beijing and other large cities daily. When oversaturation occurs in an urban rail transit network during peak hours, some passengers cannot board the first train and will have to wait for subsequent trains. Basically, this phenomenon occurs because passengers who are waiting at different stations compete for the limited capacity of trains in an oversaturated urban rail transit network. From the system perspective, an urban rail transit network is a distributed system, where a set of resources (i.e., train capacity) is shared by a number of users (i.e., passengers). Equitable individuals and groups should receive equal shares of resources (Litman, 2002), which is important but often neglected in actual operations in an urban rail transit network. On an urban rail transit line, if the passenger demand at the origin station is constantly oversaturated, then the capacity of each train departing from the origin station is fully occupied. Therefore, other passengers waiting at subsequent stations may not be able to board any trains until the passenger demand at the origin station decreases to below the capacity of each train. This scenario is inequitable for passengers who wait at subsequent stations and miss a few trains due to the limited capacity of each train. From the perspective of operators, they want to achieve a more equitable scenario that the number of passengers who suffer the maximum number of missed trains is lower. Thus, the number of passengers who suffer the maximum number of missed trains in the system can measure the system-wide equity performance in an oversaturated urban rail transit network.

We take the Batong Line in Beijing Subway Network as an example to illustrate the inequity problem clearly. Fig. 1 shows that the passengers from other lines to the Batong Line (i.e., those who transfer at Sihui or Sihuidong Stations to board the trains in Batong Line to travel to Tongzhou District in the evening) are usually oversaturated during peak hours at Sihui and Sihuidong Stations. Several trains departing from Sihui and Sihuidong Stations have already reached their capacity. Thus, passengers waiting at Gaobeidian and Chuanmeidaxue Stations usually miss a few trains during peak hours to be transported, which results in exasperation among passengers due to the inequity problem. Thus, the inequity problem that usually occurs in an oversaturated urban rail transit network should be studied; this problem has already been paid close attention in rail and air transportation services (Luan et al., 2017; Zhong, 2012; Wu et al., 2015; Aalami and Kattan, 2017).

The aforementioned inequity problem can be mitigated through several operational approaches in theory and practice. Table 1 shows three operational approaches (i.e., adjusting the timetable, organizing rapid/express trains, and scheduling skip-stopping trains) and their application and restricted conditions for improving system-wide equity performance. Among the three operational approaches, scheduling skip-stopping trains in the process of train stop planning is a key component in providing high-quality transport services; this operational approach can greatly affect the quality of train schedules and service levels for passengers (Yang et al., 2016). The train skip-stopping pattern refers to that each train can stop or skip at a station along the line according to the objectives of the operators, such as improving the passenger service level (Wang et al., 2014; Niu et al., 2015b), maximizing the operation profit (Yue et al., 2016; Jiang et al., 2017), accelerating the circulation of trains after disruptions (Gao et al., 2016), and improving the system-wide equity performance. Scheduling skip-stopping trains can be implemented in the existing line without the need of other separate tracks and a separate automatic fare collection (AFC) system, which schedules some trains to skip some

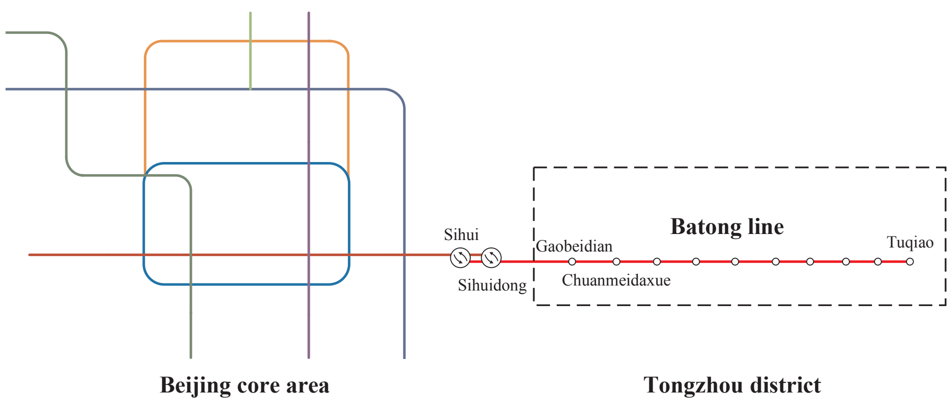

Fig. 1. Batong Line in Beijing Subway Network.