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Service-oriented train timetabling with collaborative passenger flow control on an oversaturated metro line: An integer linear optimization approach

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ABSTRACT

With the drastic increase of travel demands in urban areas, more and more metro lines are nowadays suffering from oversaturated situations, leading to the accumulation of passengers on platforms with potential accident risks. To further improve the service quality and reduce accident risks, this paper proposes an effective method for collaboratively optimizing the train timetable and accurate passenger flow control strategies on an oversaturated metro line. Through considering the dynamic characteristics of passenger flow, a rigorous integrated integer linear programming model is firstly formulated to minimize the total passenger waiting time at all of involved stations, in which the train timetable provides a service-oriented operation plan and optimal passenger flow control is imposed to avoid congestion on platforms within the transportation capacities. To solve the problem of interest efficiently, a hybrid algorithm, which combines an improved local search and CPLEX solver, is designed to search for high-quality solutions. Finally, two sets of numerical experiments, including a small-scale case and a real-world instance with operation data of the Beijing metro system, are implemented to demonstrate the performance and effectiveness of the proposed approaches.

1. Introduction

With the expansion of residents in some megacities, passenger travel demands increase with an unprecedented speed and cause a series of serious transportation problems. To release the traffic pressure, the metro system has now been constructing and operating in a lot of cities due to its large-capacity, high-efficiency, punctuality and low emission. Nevertheless, with the huge passenger volume (e.g., Beijing, Shanghai, etc.), some metro systems are still undertaking great pressures due to the infrastructure limitations (Yin et al., 2016), leading to the urgent requirements for the accurate management methods to further improve the operation efficiency.

On the level of operation planning, a practical approach to enhance the operational efficiency focuses on the optimization of service-oriented train timetables. For instance, Niu and Zhou (2013), Canca et al. (2014a), Barrena et al. (2014b) and Yin et al. (2017) take the total passenger waiting time and average waiting time as objective functions to solve train timetabling problems through considering dynamic passenger demands. However, with the heavily congested passenger

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flow in peak hours, the passenger demands still cannot be satisfied even with the maximum departure frequency. Consequently, a large amount of passengers have to queue up on platforms to wait for the following available trains. In practice, the over-congested situation on the platform necessarily leads to serious disadvantages from perspectives of both passengers and train operations. (1) On one hand, the stranded passengers accumulate on platforms to cause potential accident risks. For instance, an over 60-year old man was ever pushed down into the tracks due to the serious congestion on the platform at "Sihui" station of Beijing metro system (Beijing youth daily, 2015). (2) On the other hand, the congested situations will lead to the delay of dwelling trains. In oversaturated scenarios, it usually takes several times to close the metro screen doors before the departure of a train, causing extra delay with 10–20 s. Once the delay propagates to upstream stations, the total delay will be enlarged and significantly influence the normal operations of the following trains.

In reality, if the service-oriented train timetable is still insufficient to satisfy the large travel demands, imposing passenger flow control at each station is the best choice to effectively reduce the congestion in metro systems. With accurate passenger flow controls, we can detain the oversaturated passengers in station halls instead of platform areas, by which the congestion on platforms can be prevented. Up to now, the passenger control strategies have been adopted by some metro systems to manage the metro traffic in peak hours. For instance, more than eighty stations in the Beijing metro system currently use passenger control strategies in their daily operations. However, to our knowledge, the currently adopted control methods are quite simple and usually implemented by professional judgments or experiences, which are also lack of mathematical formulations and accurate solution methods. Although some researchers have ever investigated passenger control strategies for oversaturated metro lines (Xu et al., 2016), the majority of current studies in general focus on one or two stations, and the collaborative passenger control with multiple stations still has not been well studied. Additionally, note that the passenger flow control is closely related to practical train timetables (e.g., the train capacity and departure frequency in essence determine the number of passengers allowed to board at different stations), then jointly optimizing the passenger flow control strategies and train timetable can improve the service level to a great extent, which is also a new problem and has never been studied before. This research intends to explore these issues explicitly.

1.1. Literature review

As a key component of public transit operations, the train timetabling problem has attracted tremendous attention in the past decades (Carey, 1994; Caprara et al., 2002; Cepeda et al., 2006; Vansteenwegen and Van Oudheusden, 2006; Zhou and Zhong, 2007; Liebchen, 2008; Hänseler et al., 2012; Corman et al., 2012; Cacchiani and Toth, 2012; Cacchiani et al., 2016; Jiang et al., 2017; Zhou et al., 2017). Recently, aiming to improve the service quality of passenger transportation, some researchers turn to study the service-oriented train timetabling problem (Chierici et al., 2004; Albrecht, 2009; Sun et al., 2014; Wang et al., 2015; Corman et al., 2017; Hassannayebi et al., 2016), which highlights the convenience, reliability and reduction of passenger waiting times (Niu et al., 2015). In general, the service-oriented timetabling aims to schedule train arrival and departure times at each station according to passenger demands, with the purpose of reducing the passenger waiting time or travel time. In the literature, this type of problems can be classified into two categories, which are associated with the static and time-dependent passenger demands, respectively.

For the train timetabling problem with static demands, passenger demands are usually assumed to be constants with no correlation to the time dimension in the decision-making process, in which the operational environment is always limited to common railways because passengers always plan their trips in advance. In this case, passengers arrive at the station typically according to the train departure time on tickets instead of in a random manner. For common railways, trains may overtake and cross each other at some specific locations, such as siding and crossing tracks. In the process of timetabling, different stop plans and speed levels, such as the skip-stop operation, zonal operation, express/local operation, as well as various travel speeds for different level trains, can be considered to reduce the passenger waiting/travel time (Yang et al., 2010; 2016; Yue et al., 2016). For example, Yang et al. (2016) considered two classes of trains (i.e., trains with maximum velocities 300 km/h and 250 km/h), and proposed a new collaborative optimization method for both train stop planning and train scheduling problems on the tactic level. The problem was formulated as a multi-objective mixed integer linear programming model, which can be effectively handled through linear weighted methods.

As for metro systems, the rail transit lines usually have double tracks, and train overtaking and crossing operations are normally not permitted during the operations. In this sense, trains are always operated with relatively fixed all-stop patterns from the first station to the last station. In metro systems, since passengers often arrive at stations randomly, some studies find that the timetable considering static passenger demands is quite limited and may possibly increase the passenger waiting time in reality (Wang et al., 2013; Sun et al., 2015; Hassannayebi et al., 2016). With these concerns, many researchers turn their attention to the timetabling methods with dynamic passenger demands, in which the operational environment is always limited to the metro system since the dynamic characteristic is more obvious in urban rail transit systems than common railways (Yang et al., 2016). Along this line, two situations can be taken into consideration in the process of scheduling trains. That is, (1) train timetabling with unsaturated passenger demands, in which no capacity limit is imposed on each train (that is, it is assumed that all the passengers on the platform can board the first-arrival train at each station); (2) train timetabling with oversaturated passenger demands, in which the limited capacity of each train is considered in the process of transporting passengers. For the studies in the first case, Barrena et al. (2014a,b) developed two nonlinear mathematical formulations to minimize the passenger waiting time at stations by considering dynamic demands, and a fast adaptive large neighborhood search (ALNS) algorithm was proposed to obtain a close-to-optimal solu-