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Automatic train regulation of complex metro networks with transfer coordination constraints: A distributed optimal control framework

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ABSTRACT

In designing the automatic train regulation strategy of metro networks subject to frequent disturbances, it is essential to coordinate the trains at the transfer stations among different lines to facilitate passengers transferring. In this paper, we systematically investigate the distributed optimal control method framework for automatic train regulation of large-scale complex urban metro networks with the transfer coordination constraints. A dynamic train traffic model of metro networks is elaborately developed in the form of the state-space equation. In case frequent disturbances happen, a dynamic optimization problem is developed to minimize the timetable and headway deviations for each line of the metro network under the interaction constraints of different lines on the transfer coordination. By regarding each line as a subsystem of the whole network, the optimization problem is formulated to coordinate a number of subsystems coupled by the state constraints. To satisfy the real-time control requirement, according to the dual decomposition technique, a new distributed optimal control method based on the distributed message passing mechanism is designed, which effectively decomposes the original large-scale problem spatially and temporally into multiple small-scale optimization subproblems that can be computed completely in parallel on a single computing platform to speed up the solution procedure, and thereby reduces the computational burden of centralized implementations for the large-scale urban metro networks. Numerical examples are given to illustrate the effectiveness of the proposed method.

1. Introduction

Urban metro traffic plays an important role in relieving the traffic pressure in many modern large cities, which is regarded as an environmentally friendly transportation mode with high capacity, good punctuality and low energy-consumption (Goodman and Murata, 2001; Assis and Milani, 2004; Mannino and Mascis, 2009; Ye and Liu, 2016). With the development of urban railway networks and the increase of the passenger demand, passengers will need to make several interchanges between different lines to arrive at their destinations. As a survey in Beijing metro network shows, more than forty percent of passengers need to experience the transfer activities during their trips, which calls for the transfer co-

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ordination among different metro lines to improve the transfer efficiency of passengers. Transfer synchronization or transfer coordination of different metro lines affects the service quality of passengers to a large extent. The transfer coordination problems for the bus transit have been well studied in Dessouky et al. (2003), Wu et al. (2015), Wu et al. (2016)s, and Fonseca et al. (2018). Correspondingly, it is important to take into account the transfer coordination of different lines in designing the train scheduling/rescheduling strategy of metro networks so as to shorten the total travel time and waiting time of passengers transferring among different lines (Liebchen, 2008).

Specifically, for the high-frequency metro networks, any deviation with respect to the nominal schedule of a given train will be amplified with the time due to the accumulation of passengers (Van Breusegem et al., 1991). When an inevitable disturbance happens on one metro line, such as infrastructure failures or signal errors, the train on this line will be delayed and train delay increases from one station to the next one with the accumulation of passengers on this line. Meanwhile, the train delays on one line will be propagated and further affect its transfer coordinations with other lines of metro networks at the transfer stations. In order to reduce the train delays caused by the disturbances on each line, the train regulation (train rescheduling) is essential to recover train delays and to suppress such instability of the metro line operation. Moreover, to enhance the performance of transfer coordination between different metro lines, it is necessary to ensure the transfer coordination for the train regulation design of metro networks. In addition, the provision of real-time information leads to a new realm of control strategies and opportunities to influence the train traffic dynamic. The real-time railway disruption management has become an active area of railway management currently (Cacchiani et al., 2014). The large-scale and real-time nature of the problem calls for the development of advanced control methodology to reflect the issue of computational efficiency. Based on the above considerations, the research scope of this paper is to design the real-time distributed optimal control for automatic train regulation of complex metro networks by taking into account the transfer coordination constraints, so as to reduce the train delays and the passenger waiting time of each line and meanwhile shorten the total waiting time of passengers transferring among different lines of the network.

1.1. Literature review

In recent years, with the development of urban railway networks, there are many research focusing on the train scheduling and rescheduling problems of metro networks with the consideration of schedule synchronization or transfer coordination. By taking into account the passenger transfer behavior and transfer waiting times, the train timetabling of metro network were intensively studied. Liebchen (2008) developed a timetable to optimize the arrival and departure times at the transfer stations of the metro network in Berlin so that the passenger transfer times between the lines were minimized. Wong et al. (2008) developed a mixed integer programming optimization model to minimize all passengers' transfer waiting times in certain railway system for the timetable synchronization problem. The problem in Shafahi and Khani (2010) was also formulated as a mixed integer programming model that gave the departure time of vehicles in lines so that passengers could transfer between lines at transfer stations with the minimum waiting time. Sels et al. (2016) derived a PESP model to minimize the total passengers' travel time in cyclic timetabling, and applied macroscopic simulations to generate a robust railway timetable. A last-train network transfer model was established by Kang et al. (2015) to maximize passenger transfer connection headways, which reflects the last-train connections and transfer waiting time, where a genetic algorithm was designed to test a numerical example to verify its effectiveness. By considering the origin-destination passenger demands, the train scheduling problem for an urban rail transit network was studied in Wang et al. (2015b) with the passenger transfer behavior. Guo et al. (2017) studied the multiperiod-based timetable optimization problem for metro transit networks to enhance the transfer synchronization performance between different rail lines.

In highly interconnected timetables or dense railway traffic, a single delayed train can cause a domino effect of secondary delays throughout the entire network. Therefore, if a disturbance or a disruption occurs, the railway system must be rescheduled (Cacchiani et al., 2014). Based on macroscopic models, the delay management problems were systematically investigated by Schöbel (2001), Schöbel (2007), Dollevoet et al. (2012) to determine which trains should wait for delayed feeder trains and which trains should depart on time. The microscopic railway traffic rescheduling problems were addressed by Tomii et al. (2005), Sato et al. (2013) with the aim to minimize the passenger dissatisfaction or inconvenience. Dollevoet et al. (2014) studied the delay management approach with the microscopic models in an iterative optimization framework to optimize the passengers delays. Corman et al. (2017) proposed a new comprehensive and detailed mathematical model for the microscopic delay management problem by incorporating both the traffic regulations and the passenger rerouting options to minimize the passenger travel time. In addition, Kroon et al. (2008) proposed a stochastic optimization model to allocate the time supplements and the buffer time in a given timetable so that the timetable is robust against the stochastic disturbances. Liebchen et al. (2010) proposed a delay-resistant periodic timetable in which the objective was to optimize the transfer time between any two adjacent trains to guarantee successful transferring and meanwhile minimize total travelling cost. Kecman et al. (2013) aimed at developing a global network-scale optimization tool to optimize the actual state over all network and controls traffic from a global perspective with adjustments to the timetable. Corman et al. (2012) developed a decision support system for the traffic management of large and busy railway networks in case of entrance delays and blocked tracks. Caimi et al. (2012) proposed a model predictive control framework for railway traffic management in bottleneck areas, which manages traffic by retiming and rerouting of trains as well as partial speed profile coordination. In particular, they proposed a closed-loop discrete-time control system. Corman et al. (2014) gave a novel approach to solve the problem of coordinating the tasks of multiple dispatchers in the disturbances. The problem