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Rescheduling a metro line in an over-crowded situation after disruptions

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ABSTRACT

In the case of a metro disruption, the planned timetable cannot be operated and a large number of passengers are left stranded in the stations. When the disruption is over, some stations may be skipped in the recovery period, which speeds up the circulation of trains and makes the number of stranded passengers reduce faster. Considering an over-crowded and time-dependent passenger flow, this paper proposes an optimization model to reschedule a metro line. To achieve a balance between theoretical validity and computational convenience, the optimization model is decomposed, and an iterative algorithm is proposed to solve the model. Numerical experiments based on the Beijing Metro are carried out, the results of which verify the effectiveness and efficiency of our method.

1. Introduction

In big cities, metro systems transport millions of passengers every day, taking a significant part of the public transit volume. During the morning and evening peak hours, the departure interval between two consecutive services is reduced to 2 min in some busy metro lines. Under the condition of such a high frequency of services, a disruption of 15 min significantly blocks the normal operation, and, as a consequence, this will lead to a large number of passengers being stranded in stations.

Typically, trains circulate along metro lines, providing services in upstream and downstream directions. A disruption is caused by a complete or partial blockage of the train circulation on a metro line. During the disruption, the time interval between two consecutive services becomes much longer, and sometimes all services are even required to dwell at stations. In other words, the transport capacity is drastically reduced. When the disruption is over, dispatchers want to transport the passengers stranded during the disruption as soon as possible. Inserting more trains would be a possible way, but during peak hours there are few redundant trains to use. Another effective way is using a *skip-stop pattern* after the disruption. The skip-stop pattern means that a service skips some stations (Jamili and Pourseyed Aghaee, 2015; Vuchic, 2005), while in the *standard stop pattern*, each service stops at every station. In this paper, we find that compared with the standard stop pattern, an optimized skip-stop pattern can reduce the number of stranded passengers faster and reduce the passengers' total waiting time more effectively in the rescheduling of an over-crowed metro line.

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Note that the concept of rescheduling in this paper is different from the traditional concept, which aims to minimize the deviation from the original timetable after a disruption. Metro systems provide high-frequency services, and passengers don't plan their arrival at the station, but arrive randomly (Cepeda et al., 2006; Trozzi et al., 2013). When a disruption occurs, the original timetable cannot be used. The rescheduling of metro trains is more like a temporary replacement of the original timetable by a new timetable, which is better in some aspects. The new timetable may use a different frequency and different stop patterns. When the termination condition of the new timetable is satisfied, the metro system switches back to the normal operation.

To our best knowledge, there is no literature on rescheduling a metro line after a disruption, in which the over-crowded passenger flow is taken into account. In this sense, the first contribution of this paper is that we develop a real-time method to reschedule an over-crowded metro line, in which a skip-stop pattern is used. The proposed method is based on an optimization model with bi-objective, namely, to minimize the total travel time of the considered services and to minimize the number of passengers waiting in stations.

The second contribution is that we give an analysis of time-dependent passenger flows under the condition of limited train capacity. Due to the limited train capacity, various ODs and different service types, there are a variety of variables used to model the passenger flows. We analyze the relationships among these variables and express them in detail. Since some relationships are non-linear, which makes the optimization model difficult to solve, we further use linearization techniques to deal with these relationships, leading to a mixed integer linear programming model (MILP).

The third contribution is that we develop a heuristic iterative algorithm to solve the model. Due to the real-time nature of the problem, a rescheduling algorithm may require only a short computation time to be applicable in practice. We heuristically decompose the original model into a series of subproblems according to the starting time of each service. For each subproblem, we only pay attention to one service, which is an optimization problem with a much smaller size than the original one.

It should be pointed out that in the optimization model of this paper, detailed information about routes and signaling systems is neglected, which indicates that we consider the rescheduling problem at a macroscopic level. We carry out the numerical experiments based on the data of the Beijing Yizhuang Metro line. Under different conditions, such as increasing and decreasing passenger arrival rates, and short and long disruption periods, we test the effectiveness and efficiency of our rescheduling method. At last, we also check the validity of the linearization used in the optimization model.

The rest of this paper is organized as follows. Section 2 reviews relevant literature on train scheduling and rescheduling problems. In Section 3, we give a detailed description of the considered problem, and introduce the skip-stop pattern. In Section 4, we formulate the optimization model for rescheduling in detail, and linearize the non-linear constraints. In Section 5, we propose an optimization strategy to deal with the original model. In Section 6, numerical experiments are carried out to show the effectiveness of the proposed method. In Section 7, we draw some conclusions and outline directions for further research.

2. Literature review

In the daily operation of rail systems, disturbances and disruptions are inevitable, which may lead to blockages of trains and passengers, and make the planned timetable infeasible. As a result, timetable rescheduling is always a hot topic in the research of rail transport.

Timetable rescheduling can be further classified into two groups, known as train-oriented and passenger-oriented (Cacchiani et al., 2014). Train-oriented rescheduling, which pays more attention to the details of the rail system and the handling of disruptions or disturbances, focuses on minimizing the delays of trains or the number of canceled trains. In recent years, D'Ariano et al. (2008); D'Ariano and Pranzo (2009); D'Ariano et al. (2007) and Corman et al. (2010,2012,2014) developed alternative graph models in a series of papers, and applied their methods in a real-time traffic management system ROMA (railway traffic optimization by means of alternative graphs) to resolve conflicts. In order to handle disruptions under a dynamic and stochastic environment, Meng and Zhou (2011) employed a stochastic programming model with recourse, and a branch-and-bound algorithm was proposed to solve the model. Louwerse and Huisman (2014) developed a MIP model to adjust the timetable in the cases of a partial or complete blockage after a major disruption. The objective of the model was to minimize the weighted sum of the number of cancelled trains and the delay of other trains. Taking into account station capacities, Zhan et al. (2015) optimized the rescheduling of the Beijing–Shanghai high speed railway line in the case of a complete blockage. A detailed discussion of rescheduling at the end of the disruption was presented, and a two-stage optimization approach was proposed to improve the computational efficiency.

Passenger-oriented rescheduling aims at minimizing the passengers total delay after a disruption or disturbance. Schöbel (2009); Schöbel et al. (2007) and Schachtebeck and Schöbel (2010) used an event-activity network to represent operations of trains, and proposed models for delay management, which decides if connecting trains should wait for delayed feeder trains or if they should depart on time. Branch-and-bound algorithms with heuristic rules were designed to solve the models, and furthermore, the proposed models and algorithms were tested on the high speed railway network in Germany. Dollevoet et al. (2012) and Dollevoet et al. (2015) extended the model for delay management by integrating rerouting of passengers and limited capacities of stations, respectively. Since it is usually difficult to deal with passenger flows in optimization models, some researchers separated the passenger flow part and the timetable part. Kanai et al. (2011) proposed a concept of passengers dissatisfaction in a railway network, and focused on minimizing the dissatisfaction in the case of a