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Energy-efficient metro train rescheduling with uncertain time-variant passenger demands: An approximate dynamic programming approach

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ABSTRACT

In a heavily congested metro line, unexpected disturbances often occur to cause the delay of the traveling passengers, infeasibility of the current timetable and reduction of the operational efficiency. Due to the uncertain and dynamic characteristics of passenger demands, the commonly used method to recover from disturbances in practice is to change the timetable and rolling stock manually based on the experiences and professional judgements. In this paper, we develop a stochastic programming model for metro train rescheduling problem in order to jointly reduce the time delay of affected passengers, their total traveling time and operational costs of trains. To capture the complexity of passenger traveling characteristics, the arriving ratio of passengers at each station is modeled as a non-homogeneous poisson distribution, in which the intensity function is treated as time-varying origin-to-destination passenger demand matrices. By considering the number of on-board passengers, the total energy usage is modeled as the difference between the tractive energy consumption and the regenerative energy. Then, we design an approximate dynamic programming based algorithm to solve the proposed model, which can obtain a high-quality solution in a short time. Finally, numerical examples with real-world data sets are implemented to verify the effectiveness and robustness of the proposed approaches.

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1. Introduction

Metro traffic plays an important role in urban economic and social developments for big cities (e.g., Beijing, London, New York), since it is regarded as an environmentally friendly transportation mode with high capacity, good punctuality and low energy-consumption (Xu et al., 2016a; Yang et al., 2016). With the expansion of residents in large cities (e.g., in Beijing), metro operational companies are usually undertaking great pressures in order to transport large amount of passengers under the infrastructure limitations. For example, in order to increase transport capacity in peak-hours, the headway time is compressed within only 2 min for Beijing metro Line 1 and Line 2. Accordingly, the operated trains have to follow the arrival and departure times given in the tight timetable with a high service frequency.

In reality, the real-time operations of a metro system are always disrupted by some unexpected disturbances, which are usually caused by train arrival time delays, departure time delays, and unplanned stops due to unsteady driving behaviors,

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passenger demand variations, infrastructure failures, signal errors, etc. Once these disturbances last for several minutes, they may reduce the service quality greatly and even cause serious interferences in peak hours. For example, in 2010, a total of 126 times of drivers' pulling the emergency handles occurred in the Helsinki Metro system, most of which delayed the trains for about 3–5 min and affected the passengers' traveling plan in different degrees (Karvonen et al., 2011). This situation seems to be even worse in a heavily congested metro line, where the first delayed train will affect the following trains sequentially, resulting in the infeasibility of the original timetable, longer traveling time of passengers, and even the disruption of a whole block. In such cases, the metro dispatchers are needed to change the timetable to recover from an incident to a feasible situation (Cacchiani et al., 2014) as soon as possible, which is called a real-time train rescheduling (TTR) problem.

Although some researches in literature (Cacchiani et al., 2014; Cacchiani and Toth, 2012; Corman et al., 2012; Dundar and Sahin, 2013; Li et al., 2016; Veelenturf et al., 2015, etc.) begin to stress this problem, most metro dispatchers presently still take these decisions manually on the basis of their experiences and professional judgments, which is typically lack of rigorous computation and optimization. In general, the difficulty of this problem is caused by the following reasons. (1) The real-time metro train operations are subject to the influencing factors caused by the complex passenger characteristics. Different from railway systems, the passenger flow in urban rail transit has a different characteristic, since passengers usually do not care about the train timetables before trips, leading to the time-variant and uncertain features (Yang et al., 2015). It is realistically difficult to formulate a feasible decision-making model that simultaneously takes these factors into account. (2) The headway time in a congested metro line is only 2–3 min. Then, a rescheduled timetable should be acquired in a short computational time, which disenables the practical applications of most existing optimization approaches. With these concerns, it is practically significant to propose a unified approach for quickly solving the rescheduling problem with the high-quality solutions. This study will formally address this issue.

1.1. Literature review

The train scheduling/rescheduling problem, which aims to obtain a timetable that is carried out by the trains in the operations, has attracted tremendous attention over the last decades (Huang et al., 2016; Niu and Zhou, 2013; Niu et al., 2015b; Wong et al., 2008; Xu et al., 2015; Yang et al., 2015; Zhou and Zhong, 2007). In general, the train scheduling problem is usually formulated by means of some mathematical models, e.g., a mixed integer programming (MIP) model (Wong et al., 2008; Zhou and Zhong, 2007), an alternative graph model (Cacchiani and Toth, 2012) and a nonlinear inter programming model (Niu and Zhou, 2013; Niu et al., 2015b), in which a schedule is optimized with various objectives functions, such as the total travel time (Zhou and Zhong, 2007), transfer waiting time (Wong et al., 2008), energy consumption (Li and Lo, 2014), etc. Meanwhile, the solution methodologies can be summarized into three categories, namely, (1) optimization approaches which use some mathematical optimization softwares (e.g, GAMS (Yang et al., 2013a)) and accurate algorithm (e.g., branch and bound algorithms (Zhou and Zhong, 2007)), (2) heuristic methods (Lee and Chen, 2009) (e.g., Lagrangian Relaxation (Caprara et al., 2002)) and (3) simulation methods (e.g., Dorfman and Medanic (2004); Mu and Dessouky (2013); Xu et al. (2015)). In addition, we can refer to Cacchiani et al. (2014) for the surveys that focus on this railway timetabling problem.

In practice, the railway operations might be often subject to a variety of disturbances (Karvonen et al., 2011), leading to the ineffectiveness and infeasibility of the original schedules. Due to the rising concerns on the service level and operation efficiency of a railway system, the disturbance management has currently become an active research area in operations research and railway operations (Cacchiani et al., 2014). Different from the train timetabling problem, the railway train rescheduling problem for disturbance management mainly focuses on reducing the delay of trains or the delay of passengers/freights, in order to regenerate a conflict-free timetable in case of unexpected disturbances in a railway network. For example, D'Ariano et al. (2007) treated the rescheduling problem as a huge job scheduling problem with no-store constraints, and they proposed a detailed alternative graph model for decision-makings of dispatchers by utilizing the accurate real-time information of train positions and speeds. Then, a real-time traffic management system, i.e., ROMA (railway traffic optimization by means of alternative graph), was developed, which can be applied to rail systems with heavy disturbances to solve expected route conflicts and increase the punctuality (D'Ariano, 2009). Corman et al. (2012) proposed a bilevel programming model for regional control centers to coordinate the dispatchers' work. In this model, the variables are the border constraints and the objective is to minimize the deviation between the real-time traffic and the off-line timetable. Louwerse and Huisman (2014) formulated integer programming models for adjusting a railway timetable in case of disturbance that all tracks of a segment are blocked and no trains can be operated in this segment. The objective aims to make a trade-off between canceling and delaying trains to maximize the service level.

In case of a sudden disruption, it is practically desirable to regenerate the optimal or near-optimal alternative timetable rapidly so as to recover the disturbance as soon as possible. Then, the computational speed is usually recognized as one of the key indictors to evaluate the rescheduling approaches. Along this line, Xu et al. (2016a) proposed the idea that the delayed trains are allowed to be rescheduled by using tracks in the opposite direction through crossover tracks to generate an optimal rescheduled plan that minimizes the total train delay, and an efficient train rescheduling strategy (ETRS) was developed to generate high-quality solutions within a fairly short computational time (at millisecond level). In order to solve the rescheduling problem on an *N*-track rail network, Meng and Zhou (2014) developed a time-space network modelling framework, and the original problem was decomposed into a sequence of single train optimization problems, which was

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