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Integrated optimization for train operation zone and stop plan with passenger distributions

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ABSTRACT

With the aim of generating system-optimal operation strategies, this paper proposes a new integrated optimization method for train operation zone, stop plan and passenger distribution optimization problems on the basis of a train stop planning model. Through the introduction of a set of critical system constraints, the problem is rigorously formulated as a two-objective mixed-integer linear programming problem with the objectives of minimizing the total running distance of unoccupied seats and the total number of stops for all involved trains. Finally, two sets of numerical experiments are implemented using GAMS to demonstrate the performance of the proposed approach.

1. Introduction

As one of the basic modes of transportation, railway transportation plays an important role in production activities in society due to its advantages of high capacity, safety and resistance to poor weather in comparison with other transportation modes (e.g., road, air and water transportation). To enhance market competitiveness, it is critical for railway operators to provide high-quality services to passengers and to improve the utilization efficiency of the limited available railway infrastructure. Generally, since it is much simpler and more economical to optimize the management and operations of current railway systems than to implement innovations in technology and equipment, the design of more efficient and effective transportation plans is a main focus of railway operators and researchers.

A train stop planning model, which is a basic tool for providing high-quality transport services, specifies the detailed services that each train can provide to passengers and greatly affects subsequent processes for railway operations, especially the train timetabling process (Yang et al., 2016). However, because passengers may travel for various purposes (e.g., going to work, going on a business trip), passenger demands are usually heterogeneously distributed over a railway corridor/line. To enable the satisfaction of various passenger demands, such as long-distance and short-distance trips, the entire railway line is usually decomposed into a series of operation zones representing different subsections of the corridor based on practical experience before the specific stop plans for each train are optimized. Obviously, the individual operation zone (defined by the origin and terminal stations) of each train is critically important to the design of train stop plans since it specifies the basic information of the stations at which each train can originate, pass by and terminate, which are usually determined based on expert experience in practice. Given a pre-specified operation zone, the train stop plan further specifies the details of the stations at which each train can stop to provide services for passengers. Since the selected operation zone for each train usually cannot be changed during the train stop planning process, the zone selections will influence the final train stop plans, as all trains must start from their pre-specified origin stations and end at their terminal stations

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and cannot stop at stations outside of their operation zones.

Realistically, an efficient and effective transportation plan is always associated with both suitable train operation strategies and the satisfaction of passenger demands, which means transporting passengers from their origins to their destinations at the minimum cost. Thus, during the process of optimizing train operations, it is also meaningful to consider the passenger distributions over different trains and services on the railway lines. This information not only can specify the detailed loading capacity of each train at each station but also can enable the tracking of passengers' behaviors during their transportation activities and explicitly provide a reference for the distribution of tickets on each train. More specifically, given the detailed passenger distribution, the unoccupied capacity, which can be calculated from the numbers of passengers boarding/alighting from each train at each station in different interstation sections, can be minimized to improve the efficiency of train services. However, specifying the detailed passenger distribution is also a complex problem since it is, in essence, associated with the details of the operation zones and train stop plans (i.e., these three factors can interfere with each other), and this problem has still not been well considered in the literature.

With the aim of generating a jointly optimized operation zone, stop plan and passenger distribution plan for each train on the strategic level, we are particularly interested in designing effective linear programming methods to simultaneously optimize these three aspects of the problem using an integrated optimization model, which can be effectively solved by several commercial optimization software tools (e.g., CPLEX, GUROBI). Since this topic has not attracted sufficient attention in the literature, the current research explicitly addresses this issue.

1.1. Literature review

In practice,train stop planning is usually performed as part of the line planning process, which is of particular importance for real-world operations once the numbers and types of trains are given. The aim of the train stop planning problem is to determine the set of stations at which each individual train will stop. With the rapid development of railway transportation, the train stop planning problem has attracted tremendous attention from railway operators and researchers seeking to provide services to passengers at the minimum operational costs.

In the literature, most researchers have studied the train stop planning problem for urban rail transit systems, and the majority of the existing studies have focused on investigating different train stop strategies, including all-stop operation, skip-stop operation, zonal operation, express/local operation and combined stop operation. Obviously, the all-stop strategy is the simplest stop pattern for operation since all trains have the same stop plan, and this strategy is still popularly used in many cities (e.g., the Beijing metro network in China). However, this strategy unavoidably increases the total travel time for long-distance passengers due to the large number of stops made during their journeys. Hence, the other four stop strategies have also been emphasized in recent studies, especially the skip-stop operation strategy. For instance, by summarizing, analyzing and comparing skip-stop operation, zonal operation and express/local operation, Vuchic (2005) developed evaluation methods for the use of each of these three stop strategies. Guo (2007) further formulated corresponding bi-level optimization models for these three stop strategies by considering the passengers' behavior in terms of their travel mode choices. Lee (2012) and Lee et al. (2014) proposed mathematical models for optimizing the skip-stop operation strategy in urban rail transit systems by considering different realistic conditions and also designed an efficient genetic algorithm to search for near-optimal solutions. Jamili and Aghaee (2015) proposed a new model for skip-stop patterns in urban transport systems in the presence of uncertainty and also designed two heuristic algorithms (i.e., a decomposition-based algorithm and simulated annealing) to obtain a robust and rational solution. Ghoneim and Wirasinghe (1986) investigated the optimization of services along an existing two-track rail line by adopting a zone-stop plan during peak periods. Salzborn (1969) proposed a method for generating timetables that largely relied on the stop plan, and zone-stop plans received special attention in his formulated model. For the express/local operation strategy, Xiong (2012) formulated a 0–1 linear programming model to determine the stop stations for express trains with the purpose of maximizing the reduction in passenger travel time enabled by express trains and minimizing the increased travel time associated with slow trains. Finally, for combined stop operation, Cheng and Peng (2014) formulated a bi-level optimization model for a combined stop plan with elastic demands, and the results illustrated that a combined stop plan is more suitable for certain special passenger flows.

However, although some of the aforementioned stop patterns developed for urban rail transit systems can also be used in main line railway systems, as mentioned by Yang et al. (2016), main line railway systems (i.e., our study environment) also have various unique characteristics compared with urban rail transit traffic, especially in the case of high-speed railways; these unique characteristics affect many components of the problem, including the stop plans, train timetables, and passenger flows. Hence, some researchers have turned their attention to studying the train stop planning problem for common/high-speed railway systems. In general, there are two main methods for studying the train stop planning problem in railway systems. (1) One is to treat the stop planning problem as a sub-problem of the entire operation plan and to investigate the other problems for given stop patterns or to simultaneously optimize combinations of the given patterns. Using this approach, Goossens et al. (2004, 2005) studied the line planning problem for multi-type trains and given stop patterns. Chang et al. (2000) proposed a multi-objective programming model for the optimal allocation of passenger train services on an intercity high-speed rail line with embedded train stop plans, in which the objectives included the minimization of the operator's operating cost and the passengers' travel time loss. Zhang et al. (1998) analyzed the effects of stops on high-speed railways and then proposed a multi-objective 0–1 programming model for the train service problem, which was further transformed into a multi-layer 0–1 programming model and solved by employing an ordinal combined tree method through embedding the number of stops and the corresponding stop stations. (2) The other method is to treat the stop planning problem as an independent problem and study it for given operation section and given numbers and types of trains in each section to determine the specific stop stations for each train in its operation sections. For instance, based on the concept of node