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The Railway Rapid Transit frequency setting problem with speed-dependent operation costs

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ABSTRACT

In this paper we deal with the problem of determining the best set of frequencies in a Railway Rapid Transit network considering convex non-linear variable operation costs at segments. The operation cost at each track will depend on the train model characteristics operating each line, the passenger load on trains and the average train speed. Given the network topology and the passenger mobility patterns, we propose a methodology to determine the best regular timetable, taking into account both, users' and service provider points of view. Since the frequency setting and the passengers assignment are intertwined problems, the proposed procedure solves a succession of interrelated transit assignments and frequency setting models. At each iteration, given a transit assignment, the resultant frequency setting problem turns into a Mixed Integer Non-Linear model which is solved to optimality in a sequential way, both considering the different train models and the passenger load on trains. The proposed methodology is illustrated on a real-size scenario.

1. Introduction

In the railway context, the timetabling problem consists in determining the departure and arrival times of trains at each station in the network, while satisfying demand constraints. Several optimization criteria have been proposed in the literature, as for instance, the minimization of the deviation with respect to an ideal timetable (Cacchiani and Toth, 2012), the minimization of passenger waiting time (Barrena et al., 2014), total travel time (Zhou and Zhong, 2005; 2006), number of transfers (Sato et al., 2013) or the minimization of service provider costs (Canca et al., 2014). In the case of Railway Rapid Transit (RRT) networks, i.e. urban railways or metro networks, a high number of hourly services is usually programmed in order to attend a high passenger demand, specially at rush hours where passengers prefer a regular departure pattern consisting in a service every certain number of minutes. Then, in such a kind of networks, working with frequencies becomes the preferred approach instead of designing a specific set of non-regular arrival and departure times (Higgins and Kozan, 1998). It should be noted that, in case of uniform passenger arrival patterns, regular timetables become optimal, (Larson and Odoni, 1981). Both aspects advise the selection of regular timetables in our case.

In the hierarchical railway planning process, the line planning stage, in charge of the design of lines, also produces a set of tentative line frequencies which further must be modified in later stages to produce final timetables (Bussieck et al.,

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2004; Claessens et al., 1998; Goossens et al., 2004). If the maximization of direct trips is pursued, a previous network loading problem is solved in order to determine passenger flows over the segments in the network. Moreover, when different rolling stock types are considered (as in Goossens et al., 2004), an a priori system split procedure has to be performed as a previous step before computing frequencies, (see Bouma and Oltrogge, 1994).

The design of optimal frequencies has been also considered by researchers working in networks. Guan et al. (2006) modeled the transit line planning design and passenger transferring processes in a dense transit network. They applied a branch-and-bound technique as solving mechanism. The optimization model was illustrated on a reduced version of the Hong-Kong mass transit railway network. Zhao and Zeng (2008) developed a hybrid metaheuristic, combining Simulating Annealing with Tabu and Greedy Search to solve a problem aimed at minimizing a user cost function which incorporates passengers random arrival times, headways and route choice. Szeto and Jiang (2014) proposed a bi-level approach with the aim of designing frequencies and routes. The approach simultaneously manages passenger transfers and passenger assignment. Herbon and Hadas (2015) determined the best frequency and vehicles capacity for a single bus route considering a generalized newsvendor formulation. Canca et al. (2016) proposed and solved a Mixed Integer Non-Linear Programming (MINLP) model for determining optimal line frequencies and capacities in dense RRT networks in which some lines can share the same tracks. The model determines optimal frequency and train capacity for each line taking into account track capacity constraints, allocating lines to tracks and assigning passengers to lines.

The transit network frequencies setting problem (TNFSP) has also received the interest of researchers working on the transit equilibrium assignment problem, with special emphasis in the case of bus networks. Scheele (1980) proposed a nonlinear optimization model with the objective of minimizing the total generalized passenger travel time in order to determine the transit assignment. A different formulation was proposed by Furth and Wilson (1982) aimed at maximizing the net social profit and taking into account fleet size, maximum headway and total budget constraints. Spiess and Florian (1989) introduced the concept of strategies as a set of attractive lines at each possible boarding point (see also Nguyen and Pallottino, 1988). (Constantin and Florian, 1995) proposed a method to minimize the total expected travel and waiting times considering fleet size constraints. Lam et al. (1999) proposed a stochastic user equilibrium assignment model for congested transit networks. They demonstrated that the Lagrange multipliers of their mathematical programming problem are equivalent to the equilibrium passenger overload delays in the involved congested transit network. Lam et al. (2002) proposed a new formulation for the capacity restraint transit assignment problem with elastic line frequency. Since passengers' waiting time and line capacities are dependent on frequencies, a fixed point problem with respect to line frequencies was devised. Kurauchi et al. (2003) proposed the use of absorbing Markov chains to solve the capacity constrained transit network loading problem. The approach handled congested transit networks, where some passengers will not be able to board because of the lack of space due to capacity constraints. Gao et al. (2004) proposed a bi-level programming approach. In the upper-level the objective was the minimization of the total travel time and the cost due to the frequency setting problem. The lower-level model considered a transit equilibrium assignment model which was used to describe the route alternatives for users. In Cominetti and Correa (2001) and Cepeda et al. (2006), a set of potential strategies had to be previously defined in order to determine optimal frequencies and to achieve equilibrium conditions. Sumalee et al. (2009) proposed a stochastic dynamic transit assignment model with an explicit seat allocation procedure. They developed a seat allocation model to estimate the probability of a passenger waiting at a station or boarding to get a seat. The explicit seating model allows a better differentiation of in-vehicle discomfort experienced by sitting and standing passengers. Schmöcker et al. (2011) proposed a model that considered the travelers' probability of finding a seat in their perception of route cost. The model introduces a probability of no seat at boarding points and consider travel costs based on the likelihood of traveling seated or standing. Leurent et al. (2014) proposed a bi-level macroscopic assignment model which takes into account vehicle and platforms capacity effects over passengers decisions. Note that none of these works consider special characteristics of railway systems, as those imposed by infrastructure capacity and signaling systems.

Some authors focused their efforts in schedule-based transit assignment models. Friedrich et al. (2001) presented an assignment procedure for transit networks using a timetable-based search algorithmm. In contrast to the existing timetable-based search methods employing a shortest path algorithm, the proposed procedure constructs connections using branch-and-bound techniques. This approach significantly reduces the computing time, thus facilitating the use of timetable-based assignment for big networks. Assuming that the time varying origin-destination (OD) trip demand is given, i.e., all travelers have full predictive information (that have been gained through past experience) about present and future network conditions and select paths that minimize a generalized cost function, (Poon et al., 2004) developed a user equilibrium assignment problem which was solved iteratively by the method of successive averages. Schmöcker et al. (2008) presented a first approach to a dynamic frequency-based transit assignment. The model aimed to close the gap between schedule-based and frequency-based assignment models. Hamdouch and Lawphongpanich (2008) proposed a user equilibrium transit assignment model that explicitly takes into account transit schedules and individual vehicle capacities. The model assumed that passengers use travel strategies that can be adaptive over time. In order to solve the problem, they proposed an iterative solving method by using successive averages following a dynamic programming approach. Hamdouch et al. (2011) proposed a new schedule-based equilibrium transit assignment model that differentiates the discomfort level experienced by sitting and standing passengers. The model assumed that passengers use strategies when traveling from their origin to their destination. Nuzzolo et al. (2012) presented a schedule-based dynamic assignment model for transit networks taking into account congestion through explicit vehicle capacity constraints. The core of the model was the use of a joint choice model for departure times, stops and runs that defines a space-time path in which users decide to leave the system, to access the