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Train timetable design under elastic passenger demand

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ABSTRACT

A passenger centric timetable is such a timetable that the satisfaction of the passengers is maximized. However, these timetables only maximize the probability of a passenger to take the train, but provide no insight on the actual choices of the passengers. Therefore, in this manuscript we replace the deterministic passenger satisfaction function with a probabilistic demand forecasting model inside of the passenger centric train timetable design. The actual forecasts lead to a realistic train occupation. Knowing the train occupation, we can estimate the revenue and to use pricing as a mobility management to further improve the level-of-service. We use a logit model that we calibrate to reflect the known demand elasticities. We further include a competing operator as an opt-out option for the passengers. Subsequently, we integrate the passenger centric train timetabling problem with a ticket pricing problem. We solve the elastic passenger centric train timetabling problem for various types of timetables using a simulated annealing heuristic on a case study of Israeli Railways. The results of our case study show that the generated revenues can be increased by up to 15% when taking into account the passengers' behavior along with a specific pricing scheme. This study further confirms the advantages of hybrid cyclicity.

1. Introduction

From economic theory, it is well known that the demand is influenced by the supply. In the railway context: Different timetables would attract different passengers, as they provide different levels of services. Therefore, it is important to include the passenger demand and its elasticity in the timetable design. This is particularly crucial nowadays, when the railway market is open for competition. This has lead to a release of the government's subsidies and the operators thus face a pressure to be profitable by increasing their revenues.

The passenger demand itself can be predicted through the choices that the passengers face: Mode, route, operator, service and departure time. In reality, the passengers make an integrated decision that is split into the 4-step procedure due to its complexity. At first, the passengers decide on their mode of transport, *i.e.* car, bus, train, *etc.* Subsequently, they decide

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on their exact path within the selected mode, *e.g.* the exact trains and interchanges. As transportation is offered by several providers, the passengers can select which one to take and in what kind of service, *e.g.* first class with a private operator, having a club card of a specific operator, *etc.* Lastly, the departure time choice of the passengers is affected by the trip purpose (commuting to be on time at work, leisure to be on time for cinema for instance, *etc.*). This choice is the so called time dependency of the demand. The mode choice and the operator choice are especially important when optimizing a service. If not included, the passengers are captive in the system and such optimization would lead to unrealistic performance (*i.e.* departure times leading to a lower ridership than anticipated).

A train timetable is defined as a set of arrival and departure times of each train from each of its stopping stations and it is the output of the Train Timetabling Problem (TTP). Typically, the TTP models use the simplifying assumption that the passengers always take their shortest paths (see Caprara et al., 2002 for instance) and omit the demand from the problem. The issue of this approach is that being a shortest path is dependent on the actual departure time. Therefore, recent models relax this assumption and include the demand in the optimization (see Schmidt and Schöbel, 2015 for instance). However, these models only increase the attractiveness of a timetable and cannot estimate the realized demand and the underlying revenue. In order to do so, a demand forecasting model is needed. One of such models, integrating the train timetabling and the demand forecast, is presented by Cordone and Redaelli (2011). However, they only consider the mode choice and omit the other choices. Moreover, they consider the timetable only as a single cycle within a cyclic timetable. In the model of Espinosa-Aranda et al. (2015), the mode choice is combined with a departure time choice. But their application involves a single high speed railway line and lacks the network dimension (*i.e.* the route choice).

In this paper, we extend and adjust the Passenger Centric Train Timetabling Problem (proposed by Robenek et al., 2016), that can design a timetable for a whole railway network, with a demand forecasting model. We denote the new model as the Elastic Passenger Centric Train Timetabling Problem (EPCTTP). The objective of the new optimization framework is to maximize the Train Operating Company's (TOC) revenue. The framework is using a discrete choice model to predict the demand throughout the timetable design process. We assume prior solving of the mode choice model and we solve the route choice model along with the departure time choice and the operator choice. The following attributes have influence on the passengers' choices: The travel time, the desired arrival time to their destinations (the time dependency), the ticket fare and the capacity of the trains. We include a universal option of opting out into the passengers' choice set(s), in order to avoid their captivity. The demand elasticity and other parameters of the discrete choice model are calibrated to known values from the literature and provide a "ready to use" framework. It can design cyclic, non-cyclic and hybrid cyclic timetables. The resulted timetables increase the ridership through accounting for the passengers' wishes and therefore, they increase the operator's revenue as well. We test this approach on a case study of Israeli Railways.

In addition to the above, we further relax the ticket fare to be a decision variable. Such approach leads to a better utilization of the TOC's fleet and to a further increase in its revenue: Shift passengers from overcrowded trains to under-used trains, attract back the passengers, who would otherwise opt-out, *etc.* The resulting framework combines pricing problem with an integrated demand-supply timetable design. It differs from the existing literature, where the pricing and revenue management is performed on a fixed timetable.

The manuscript is structured as follows: Section 2 presents a survey of the literature, depicting the demand interaction in the current timetabling models, along with the literature on railway demand forecasting as well as pricing and revenue management in railways. Subsequently, we propose a demand forecasting model in Section 3, that is further incorporated into a train timetable optimization problem described informally in Section 4. The insight, about the methodology of how to solve such integrated demand-supply optimization framework, is given in Section 5. The benefits and the impacts of the framework are shown on a case study of Israeli Railways in Section 6. We finalize the paper by drawing some conclusions and discussion of possible extensions in Section 7.

2. Literature review

Since the aim of this study is to introduce the demand and its elasticity into the train timetabling, the focus of our literature review is on the passenger demand representation in the railway planning literature. At first, we present the demand representations used in the train timetabling problems (Section 2.1) and continue with the various demand forecasting techniques used in the railway context (Section 2.2). Lastly, we discuss how some of the forecasting techniques are used in the revenue management and ticket pricing within the railways (Section 2.3).

2.1. Demand representations

The most basic representation of the railway demand is an Origin-Destination (OD) matrix. Such a matrix is typically used in the Line Planning Problem (LPP) to determine the frequency of a train line (Schöbel, 2012). However, one of the recent models by Canca et al. (2016a) considers the actual paths of the passengers while minimizing their travel time.

Once the lines are designed, the Train Timetabling Problem (TTP) assigns a departure time to each train subject to the operational constraints. Two versions of this problem exist: Cyclic and non-cyclic. In the cyclic TTP (Peeters, 2003; Zhou et al., 2017; Sparing and Goverde, 2017, for instance), the main focus is on the cyclicity constraints, whereas in the non-cyclic TTP (Caprara et al., 2002) the departure times do not have to follow any specific pattern. Traditionally, both problems