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Discrete Optimization

# High-speed railway scheduling based on user preferences

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ABSTRACT

This paper proposes an optimization model for high-speed railway scheduling. The model is composed of two sub-models. The first is a discrete event simulation model which represents the supply of the railway services whereas the second is a constrained logit-type choice model which takes into account the behaviour of users. This discrete choice model evaluates the attributes of railway services such as the timetable, fare, travel time and seat availability (capacity constraints) and computes the High-Speed railway demand for each planned train service.

A hybridisation of a Standard Particle Swarm Optimisation and Nealder–Mead methods has been applied for solving the proposed model and a real case study of the High-Speed corridor Madrid–Seville in Spain has been analysed. Furthermore, parallel computation strategies are used to speed up the proposed approach.



## 1. Introduction

European Union competition policy is promoting an ongoing liberalisation process in the rail market and the setting up of an EU air market. In this single transport market, the low-cost air carriers and the high-speed railway (HSR) operators are competitors on routes that are interchangeable within a certain distance range, especially in point-to-point routes. Currently HSR systems are expanding their rail networks in the EU and incrementing their demand share. However, in order to meet the new scenario of competition between transport operators, the rail industry should focus the railway service on addressing passenger needs.

*The Train Timetabling Problem* (TTP) consists of the establishment of a set of conflict-free train routes with respect to given train requirements. TTP has received a great deal of attention in the scientific literature in recent years. The literature focuses on minimizing parameters related to train company operations (operations-centric models) but so-called passenger-centric models have also been developed but they are much sparser. These analytical models are crucial in improving the competitiveness of the rail industry.

HSR systems are an emergent technology whose singular features have not yet been widely discussed in the current literature on TTP modelling. The departure time choice, travel time, the pricing regime and the competition of these systems with the traditional or low-cost air, rail and private vehicles should be taken into account in the TTP models. Motivated by this need, this paper proposes a high-speed passenger-centric TTP model that uses a high-speed demand forecasting model to learn the behaviour of passengers with respect to the attributes (departure time, travel time, ticket cost and travel comfort) of the proposed timetable.

The remainder of this paper is structured as follows. Section 2 reviews related research papers. Section 3 describes the proposed HSR–TTP model in detail. Section 4 explains the algorithms used for solving this model, in Section 5 several computational experiments are reported, and finally Section 6 concludes with a discussion of our findings and future work.

## 2. Literature review

TTP has been addressed widely in the literature in the last thirty years. A rough taxonomy of TTP may be classified, see Cacchiani and Toth (2012), according to application: (i) freight or passenger transportation, (ii) railway network or single one-way line (corridor) linking two major stations with intermediate stations, (iii) cyclic (periodic) or non-cyclic timetables and (iv) objective function. In this section we focus exclusively on HSR–TTP approaches.

Cascetta and Coppola (2014) consider that a high-speed-generated demand obeys three main factors:

(1) The *diverted demand*, which represents the choice of a passenger between other means of transport (plane, car, other rail services, etc.) and HSR.
(2) The *induced demand*, which depends directly on the characteristics of the HSR services offered (ticket cost, travel time,

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**Table 1**
Review of HSR disaggregate models (source: Cascetta and Coppola (2014)).

| | | Frequency-based | Schedule-based |
|---|---|---|---|
| **Multi-modal** | Multi rail service | Ben-Akiva et al. (2010) | Cascetta and Coppola (2012), Cascetta and Coppola (2014), Espinosa-Aranda et al. (2014) |
| | Single rail service | Román et al. (2007), Yao and Morikawa (2005), Fröidh (2008) | |
| **Mono-modal** | Multi rail service | Couto and Graham (2008), Hsu and Chung (1997) | |
| | Single rail service | Urban case | Urban case |

timetable, etc.), or indirectly due to modifications of the travellers' mobility or lifestyle choices.

(3) The *economy-based demand growth*, which is linked to the trends of the economic system, considering that people travel more when they are wealthy.

Diverted demand and directly induced demand are considered as *endogenous* factors of the HSR system. Indirectly induced demand and economy-based demand growth are considered as *exogenous* factors of the HSR system. Numerous HSR demand-forecasting models have been developed to predict rail passenger flows. Some of these involve short-term forecasting (Jiang, Zhang, & Chen, 2014) and their aim is to provide daily user estimates that account for day-to-day demand variations in the near future. These models have been applied to problems of revenue management, improvement of facilities, operation mode, etc. and predictions are made considering the HSR system as a black box. A model which tries to solve the TTP for HSR systems must be capable of forecasting high-speed rail demand as a function of the endogenous factors of the system.

HSR demand forecasting models can be classified as *aggregate* or *disaggregate*. Aggregate models are based on aggregate demand elasticity values and make use of large data sets obtained from ticket sales and surveys. They are useful for rail demand growth predictions (see Wardman, 2006) or policy simulation, such as the estimation of the effects of $CO_2$ emissions taxes on the demands for airline and HSR travel (see Fu, Oum, & Yan, 2014) or to forecast the demand for a proposed new HSR service (see Börjesson, 2014). The fundamental limit on incorporating these models into TTP models is that they cannot simulate flows on individual rail segments or trains. Disaggregate models consider the individual as the basic unit of observation, dividing the passengers into different types depending on different factors. These models are consistent with travel choice theory using data at the level of individual travellers.

Cascetta and Coppola (2014) creates a taxonomy of HSR disaggregate demand forecasting models (see Table 1). The two essential classification criteria which apply are the type of transport network (*multi-modal* or *mono-modal*) and the way the range of services is represented (*frequency-based* or *schedule-based*). This classification is very useful for properly situating the model given in this study in its place in the literature. This is line of thought followed here.

*Mono-modal* models are focused on a specific transport mode and forecast the demand based on the operational improvement of this mode (for some examples see Couto and Graham (2008) and Hsu and Chung (1997)). These models are typically conceived to represent the behaviour of the passengers in an urban context. *Multi-modal* models include the competition between HSR and other modes of transports available for the same trip. Most of these models focus on the competition between HSR and air transportation (see Fröidh, 2008; Park & Ha, 2006; Román, Espino, & Martín, 2007), some include cars (see Mandel, Gaudry, & Rothengatter, 1997; Martín & Nombela, 2007; Yao & Morikawa, 2005) and very few add the competition between HSR operators (see Ben-Akiva, Cascetta, Coppola, Papola, & Velardi, 2010; Cascetta & Coppola, 2012).

The frequency-based approaches are focused on defining a frequency for each type of service over given time intervals. Greater flexibility in the modelling is given by scheduling-based approaches which allow scheduled services to be represented as individual trips following a timetable (see Wilson & Nuzzolo, 2004). The majority of the models presented in the literature to forecast HSR demand follow a frequency-based demand approach. The choice of one or other approach conditions the output of the TTP model, directing it towards establishing frequency o defining a timetable. For low-frequency transport systems the schedule-based approach reflects user choice in a specific service better.

Schedule-based studies like Espinosa-Aranda, García-Ródenas, López-García, and Angulo-Herrera (2014) where a constrained nested logit model is proposed with the objective of predicting the demand in an HSR system are scarce. This model considers the timetable, price of the ticket, travel time and capacity of the trains in the selection process. These authors use *Reproducing Kernel Hilbert spaces* to consider dynamic utilities, which is an essential issue for modelling the departure time choice.

The other main issue in TTP is the modelling of the railway services supplied. Traditionally to represent this problem several types of constraints like block capacity constraints, flow constraints, priority constraints, train service capacity constraints and rolling stock constraints have been considered (see Cordeau, Toth, & Vigo, 1998). HSR systems have received a great deal of investment which eases the operational control of these systems allowing the simplification of the traditional regional or intercity railway systems modelling. This paper proposes a discrete event simulation model for representing the supply of the network. This approach has been applied successfully in transportation (see Espinosa-Aranda & García-Ródenas, 2012; Sánchez-Rico, García-Ródenas, & Espinosa-Aranda, 2014). Furthermore, it is possible to extend the HSR model by changing the proposed supply model with previous approaches defined in the literature, such as methods based on the alternative graph model (see Corman, D'Ariano, Pacciarelli, & Pranzo, 2010; D'Ariano, 2008; D'Ariano, Pacciarelli, & Pranzo, 2008; Espinosa-Aranda & García-Ródenas, 2013), or including real-time optimisation methods for rescheduling rolling stock (see Almodóvar & García-Ródenas, 2013).

### 2.1. Summary and contributions of this paper

The proposed HSR–TTP approach can be classified as a disaggregate *multi-modal* schedule-based model and focuses on the endogenous factors (travel time, fare and departure time) associated with HSR passenger behaviour. The contributions of this paper can be summarized as follows:

- A novel HSR–TTP model is proposed. The model is able to accommodate the following two key features: (i) the interaction between demand and supplied capacity, explicitly considering the effect that a given set of services may be at capacity has on user choice and (ii) competition between means of transport (low-cost air carriers, other railway (HSR) operators or private car).
- An optimisation framework for the HSR–TTP model is analysed. The HSR–TTP model presents a bilevel structure which integrates a simulation approach (supply-side modelling) and an optimisation model (demand model) at lower level. The resulting model is implicitly defined and exact methods become inapplicable. Moreover, the evaluation of the objective function is expensive. This model poses a special challenge, since existing heuristic methods