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Optimizing station location and fleet composition for a high-speed rail line

Hugo M. Repolho [a,*], Richard L. Church [b], António P. Antunes [c]

[a] Department of Industrial Engineering, Pontifícia Universidade Católica do Rio de Janeiro, 22451-900, Brazil
[b] Department of Geography, University of California Santa Barbara, Santa Barbara, CA, 93106-4060, USA
[c] Department of Civil Engineering, University of Coimbra, Pólo II, 3030-788 Coimbra, Portugal

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ABSTRACT

This paper proposes a new strategic planning model for high-speed rail ventures. It is a mixed-integer optimization model that applies to a given line and focuses on two key strategic decisions: station location and fleet composition. Our purpose is to improve on previous station location models by including fleet composition decisions. In the new model, we additionally take into account in an approximate fashion the interrelationships between strategic and subsequent tactical decisions, regarding line planning, train scheduling and fleet assignment issues. The usefulness of the model is demonstrated for a case study involving a planned Lisbon-Oporto high-speed rail line.

1. Introduction

Rail planning consists of a hierarchy of decision-making problems, often only loosely coupled. Anthony (1965) and Ghoseiri et al. (2004) define three major problem levels: strategic (5–20 years), tactical (1–5 years), and operational (up to one year). For tractability purposes, each sub-level or specific problem is usually addressed separately in a sequential fashion (i.e. strategic first, then tactical, and then operational).

The strategic level deals with infrastructure and fleet decisions. It includes determining the alignment of the rail corridor, the location of stations, and the composition of the fleet, which as defined by Hoff et al. (2010) stands for the determination of both the number and the type of trains. Next, the tactical level addresses line planning (in particular, the definition of stop-patterns), train scheduling (definition of a master timetable or stop-schedules), and fleet assignment. Finally, the operational level entails setting schedule and fleet circulation details, crew rostering, and adjustments in response to service disruptions.

The literature is rich in optimization models to assist in rail planning, particularly at the tactical and operational levels. Comparatively, strategic problems have received much less attention from an optimization perspective, and according to Caprara et al. (2007) infrastructure and fleet composition have not been dealt with adequately, despite representing the bulk of the investment costs of a new rail line. Hoff et al. (2010) also state with regard to fleet composition that "a large part of the literature focuses on operational questions" answering "what to do given a certain fleet mix and a given set of service requests", however they neglect the strategic decision of "which vehicles should be acquired". Additionally, Cadarso and Marín (2014) argue that the separation between strategic and tactical decision tools means that decisions regarding infrastructure

* Corresponding author.
E-mail addresses: hugorepolho@puc-rio.br (H.M. Repolho), church@geog.ucsb.edu (R.L. Church), antunes@dec.uc.pt (A.P. Antunes).

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and fleet are usually modeled without being sensitive to service decisions, e.g. stop-patterns and stop-schedules, which can significantly affect overall ridership, revenues and benefits, and lead to inefficient solutions.

In line with the previous discussion, the main objective of this paper is to propose a new strategic planning model for high-speed rail (HSR) ventures that includes both station location and fleet composition decisions, and where the interrelationships between strategic and subsequent tactical decisions are taken into account in an approximate fashion. Our motivation stems from the gap we identified in the literature and from the belief that the results we obtained for a station location model (Repolho et al., 2013) could be improved if fleet composition and tactical planning issues were considered.

The model was formulated based on four important (and realistic) assumptions. First, and as is usually the case in Europe, the HSR line is owned and operated by a public entity whose objective is to maximize net public benefits. Second, the line is to be operated on an exclusive basis (Campos et al., 2009a), i.e. it is dedicated to HSR services. Third, the HSR line is of the double one-way type (each track is reserved for one direction) linking two terminal stations known a priori and a number of intermediate stations (Cacchiani and Toth, 2012). Fourth, the rail corridor has already been defined, but the number and locations of intermediate stations are yet to be chosen among a given set of alternatives.

In detail, our model determines the optimal number and locations for the stations to be built along an HSR line whose corridor is already defined (or, for which, there are few alternatives that can be studied separately), as well as the number and type of trains to be used in that line. The objective is to maximize net public benefits. These benefits are measured as the travel cost savings to members of the public, minus the (discounted) investment costs for construction of stations and acquisition of trains. We do not consider operating costs including crew, fuel, etc., as we assume they are covered by ticket revenues. The model also generates supporting tactical line planning, train scheduling and fleet assignment elements in order to better estimate the ridership captured and therefore the benefits achieved by the HSR service.

It is important to note that the benefits of constructing a high-speed rail line can include more than travel cost savings. Such projects may have significant medium- and long-term urban development impacts along the corridor, increasing transport demand, and enhancing broader social and economic impacts (Abreu e Silva et al., 2011; Hensher et al., 2012, 2014). Although these issues may be important to consider at the strategic level of planning, our focus here is on more direct effects of a new HSR line. In this way, our approach may be seen as complementary to broader-scale analyses encompassing such impacts.

The choice of corridor alignment is also of critical relevance as it involves complex construction and financial options (related to e.g. land acquisition, tunneling, and excavations), but is outside of the scope of the paper. However, we argue that the number of possible corridors for an HSR line connecting two principal cities is usually small, and therefore those corridors can be studied separately using the proposed model and then compared. A recent survey on rapid transit network design can be found in Laporte et al. (2011).

The remainder of the article is organized as follows. Section 2 presents details of various aspects of strategic and tactical rail planning. Section 3 introduces the optimization model we developed to address station location and fleet composition decisions. Section 4 describes a case study involving the application of the model to the Lisbon-Oporto HSR project in Portugal that illustrates the advantages of using the proposed model. Finally, in Section 5 we offer some concluding remarks and point out directions for future research.

2. Problem background

We start out this section by placing demand analysis within the rail planning process and stating the importance of using elastic demand predictions as inputs for strategic planning. Then, we present a literature overview on rail strategic planning, with particular emphasis on station location and fleet composition models. Finally, we discuss the subsequent tactical decisions and the reasons for integrating them with strategic decisions.

2.1. Demand analysis

The rail planning process is usually initiated by a demand analysis, which essentially consists of estimating the potential passengers for a rail line (or a rail network). Strategic decisions and any subsequent decision-making stages are primarily based on these estimates of long-term demand, which are typically assumed deterministic and inelastic (Cadarso et al., 2014). However, as pointed out by Caprara et al. (2007), strategic decisions affect rail services, which in turn impact on demand. In an intercity environment, as is the case with HSR, travelers choose their transportation mode based on four principal service features: (1) travel cost; (2) frequency; (3) in-transit travel time; and (4) waiting times to board and transfer (KPMG, 1990; Bhat, 1995). For rail, these features are determined by, or at least depend on, the service provided, particularly stop-patterns and stop-schedules (Zhou and Zhong, 2005) and, indirectly, on the infrastructure and fleet used to provide the service. The dynamic relationship between passenger demand and each one of these four service features is clearly shown in a study by Fu et al. (2009).

2.2. Strategic planning

The number and location of stations influences the ridership captured by the rail service. More stations imply less access time to rail services and therefore greater ridership. Conversely, more intermediate stations along a given passenger route