Transportation Research Part B 68 (2014) 1–16

Contents lists available at ScienceDirect

Transportation Research Part B

journal homepage: www.elsevier.com/locate/trb

Adding a new station and a road link to a road–rail network in the presence of modal competition

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ARTICLE INFO

Article history:
Received 4 November 2013
Received in revised form 6 May 2014
Accepted 7 May 2014

Keywords:
Station location
Road–rail network design
Infrastructure planning
Non-linear programming

ABSTRACT

In this paper we study the problem of locating a new station on an existing rail corridor and a new junction on an existing road network, and connecting them with a new road segment under a budget constraint. We consider three objective functions and the corresponding optimization problems, which are modeled by means of mixed integer non-linear programs. For small instances, the models can be solved directly by a standard solver. For large instances, an enumerative algorithm based on a discretization of the problem is proposed. Computational experiments show that the latter approach yields high quality solutions within short computing times.

1. Introduction

Railway systems offer many advantages with respect to other transportation modes. Among others they provide safety, speed, stable travel times, and non-dependency on petrol. For these and other reasons, large investments have recently been devoted to the construction or improvement of railway networks. When designing such networks it is not sufficient to take connectivity and efficiency issues into account, but one must also consider competition and interconnectivity with other transportation modes.

1.1. Literature review

The literature of optimal location of stations on a railway network dates back to the beginning of the 20th century (see Vuchic and Newell, 1968 for a review). The problems considered in the early papers dealt with the determination of the optimal interstation spacing by minimizing the total travel time of the passengers commuting to the city center along a railway line. Several papers have since been devoted to this problem, and a variety of criteria have been considered.

Starting with passenger travel time criteria, we mention Vuchic and Newell (1968), who examine the problem of determining a number of stations and the interstations spacings to minimize the total travel time. The model is limited to the people commuting to the central part of the city and takes into account several realistic aspects such as access speed, dwell times, kinematics of trains, modal competition and passenger population along the line. These authors solved the problem through a set of second order difference equations.

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http://dx.doi.org/10.1016/j.trb.2014.05.015
0191-2615/

A related criterion is the maximization of travel time reduction when introducing new stations. This problem was shown to be NP-hard by Hamacher et al. (2001) when the travel time includes both accessing and in-vehicle time. A similar problem regarding a high-speed line was treated by Repolho et al. (2013). These authors present a mixed-integer program which is applied to the location of stations on several corridors of a planned high-speed line in Portugal, which competes with other transportation modes.

The minimization of the additional travel time induced by the stops of the trains at the new stations while covering all the demand sites has been studied by Schöbel (2002) and Schöbel et al. (2009) in the context of urban public transport. The problem was proven to be NP-hard. The same problem has been studied in Carrizosa et al. (2013), but considering this time the kinematics of the trains between stops.

Since constructing stations is costly and such decisions are strategic due to their permanent character, one of the most commonly used criteria in real situations is to maximize coverage. This problem was studied in a paper by Laporte et al. (2002) where stations for a rapid transit line with lower and upper bounds on the interstations spacings are located on a predefined alignment. To solve this problem for a finite candidate set, the authors made use of a graph representation and applied a longest path algorithm. The continuous version of this problem, where the number of new stations is fixed, was shown to be NP-hard by Kranakis et al. (2003). Schöbel (2005) considered the biciteria problem of maximizing coverage while minimizing the number of new stations. This problem was solved in quadratic time for the particular case of a polygonal line with an additional assumption.

The maximization of ridership, which is a more realistic criterion, was introduced by Vuchic (1969) and further studied by Laporte et al. (2005). The context of the problem dealt with by Vuchic is similar to that of Vuchic and Newell (1968), while in Laporte et al. (2005) a bounded-length line and their stations are simultaneously located. Körner et al. (2014) used the same criterion for the location of two new stations on segments and on tree-like networks in a mixed planar network environment. The authors have provided a polynomial time algorithm. Gross et al. (2009) have dealt with the maximum accessibility problem where a fixed number of stations is to be located and the sum of distances to demand points is to be minimized. The problem was shown to be NP-hard for two different environments: in a plane and on a street network. Finally, the problem of minimizing the cost of constructing the new stations or the simpler one of minimizing the number of stations, while covering all sites was proved to be NP-hard by Hamacher et al. (2001).

1.2. Linking stations to the road network

Building train stations relatively far from city centers and linking these stations to the road network is becoming a trend in certain high-speed railway networks for several reasons. At a macroscopic engineering level, the main reason for constructing intermediate stations away from city centers is because this allows high-speed lines to have a smoother shape, also allowing higher speed between the end cities of the line (these end cities usually provide a larger traffic than intermediate stations). Cost minimization is a common reason since avoiding city centers often means building fewer stations, and bringing railway lines into city centers tends to be expensive. Another reason is political: when two nearby cities want a railway station, it is often politically expedient to build one half-way between them in order to avoid favoring one city at the expense of the other. As case in point, 30% of the stations of the Spanish high-speed railway network are now located outside cities. As an example, the Camp de Tarragona station on the Madrid–Barcelona line lies 12 km from Tarragona, the nearest large city with more than 100,000 inhabitants, (see Fig. 1). In such cases it becomes desirable or even necessary to build new links between the road network and the out-of-town station. Another example is the case of new stations in commuter systems. Line 5 of the commuter system of Seville (Spain) was established by partially using a regional railway. One of the stations of this line is the Valencina–Santiponce station which needed a new link to be connected with the road connecting both towns.

Some of the earlier station location models (see for instance Hamacher et al. (2001), Laporte et al. (2002), Schöbel (2005)) did not take into account competition with other transportation modes, whereas some others did, like Vuchic (1969) and more recently Repolho et al. (2013). Körner et al. (2014) introduced and solved a station-location problem consisting of locating two stations on an existing tree-like railway network. The problem presented in this paper also considers static modal competition but differs from that introduced in Körner et al. (2014) because we allow connections with any point of the road network, not just with a node.

The remainder of the paper is structured as follows. In Section 2 we introduce the input data for our problem. Section 3 details the variables and constraints needed to build the presented mixed integer non-linear programming models. In Section 4, an iterative process to solve the model in Section 3 and a heuristic procedure are introduced, which are tested and compared with each other in Section 5 via a computational experience. In Section 6 we illustrate our procedures on a realistic instance. Conclusions follow in Section 7.

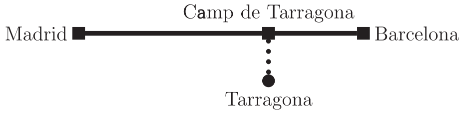

Fig. 1. The Madrid–Barcelona line (solid line). The Camp de Tarragona station is 12 km away from the nearest large city, Tarragona. A road link (dotted line) joins these two points.