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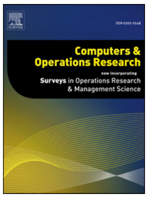

Corridor-based metro network design with travel flow capture

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ABSTRACT

We consider a metro network design problem in which the objective is to maximize the origin/destination traffic captured by the system. The lines of the network are located within some corridors that are also determined by the procedure. The amount of captured traffic depends on the ratio between travel time by metro and travel time using alternative modes. There is a limited construction budget. Lower bounds are imposed on the angles between alignments, which allows the generation of different network shapes. A matheuristic is proposed to solve the problem. The method is applied to a test case from the city of Concepción, Chile.

1. Introduction

In metro network design problems, the aim is to construct a set of interconnected alignments subject to a variety of constraints, including a fixed budget. For recent surveys, see Laporte et al. (2011) and Laporte and Mesa (2015). It is normally assumed that people living within a certain distance from a station, e.g., 400 m, or five minutes, will be attracted by the system (Vuchic, 2005). This norm can easily be extended to apply to both the origin and the destination of a potential user. One of two main objectives is typically optimized. The first is to maximize the population covered by the metro network (see e.g., Curtin and Biba, 2011; Escudero and Muñoz, 2009; Laporte et al., 2011; Laporte and Pascoal, 2015; Marín, 2007; Marín and García-Ródenas, 2009; Matisziw et al., 2006). The second objective frequently optimized is the travel flow capture (see e.g., Gutiérrez-Jarpa et al., 2013, 2017; Laporte et al., 2005; Marín and García-Ródenas, 2009). The traffic capture can be computed by means of a logit function (see e.g., Marín and García-Ródenas, 2009) or by using a preference threshold (see e.g., Gutiérrez-Jarpa et al., 2013). The latter approach is simpler in that it avoids calibration problems and non-linearities. In this paper we work with a travel flow capture and a threshold criterion.

Note that metro and rail network design problems differ in several aspects. Rail is mostly interurban, while metro is urban. In these two contexts, the commuters' spatial distributions and densities, as well as the required line lengths to serve the demand are very different. This results in topologies and distances between stations that are also very distinct. Metro trains (at least the underground part of the system) operate in dedicated corridors (tunnels) without any interference from other transportation modes. In the case of trains, there can be interactions with cars at level crossings, for example. Finally, once a metro system is built, the trains always operate in the same corridors (no rerouting is possible between the tunnels of different lines). This is not the case for trains networks where reroutings and new services are easily made possible by switching trains between different parts of the network. In this sense, trains are more flexible than underground metros. For more details on rail networks, see Farahani et al. (2013) and López-Ramos et al. (2017).

The solution space in metro design problems can be huge and it is therefore customary to solve the problem in a stepwise fashion or to restrict the search space. A classical study on the topic of metro network design is that of Wirasinghe and Vandebona (1999) who sequentially solved two optimization problems: the location of stations to minimize the sum of station costs and access costs, and the construction of lines to minimize the sum of passenger travel time, construction costs and operation costs. The first subproblem was solved by computing the ideal density of stations in an area, and then locating stations through a geometrical process that partitions the area into cells. The lines were obtained from a minimum spanning tree on the

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selected stations. Another way of limiting the search space is to locate alignments within predefined corridors. Such corridors are often determined by the planners who have a good knowledge of the broad traffic flows in their city. This approach was first suggested by Bruno and Laporte (2002) and later applied by Gutiérrez-Jarpa et al. (2013) and by Laporte and Pascoal (2015). Here we follow the same idea but we let the algorithm heuristically select promising corridors, while a mixed integer linear program is solved to optimally combine corridors. This type of algorithm is called a matheuristic because it integrates the use of an exact methodology within a heuristic. Note that we essentially minimize the same network costs as in Wirasinghe and Vandebona (1999) but, in contrast to what is proposed by these authors, our methodology simultaneously locates the stations and the alignments.

We believe our methodology can be useful to help planners quickly generate several embryonic solutions that can be later assessed in more depth or modified. It aims at generating good initial solutions rather than a final design which, we believe, is beyond the scope of operations research methodology alone.

The remainder of this paper is organized as follows. The problem is presented in Section 2, followed by a description of the matheuristic in Section 3. Section 4 provides the results of extensive computational experiments performed on data from the city of Concepción, Chile. Conclusions follow in Section 5.

2. The metro network design problem

An urban area to be served by a metro system consists of a set of points that represent the origins and destinations of commuter trips in a given region (demand nodes). Estimates of the volume of passenger traffic between each origin and destination (O/D) pair are available. We also know the average travel times currently spent by commuters to go from their origins to their destinations by alternative modes, e.g., the car or existing slower public transportation systems. We aggregate all alternative modes into one, instead of discussing them separately.

The problem consists of determining a set of corridors within which metro lines are built, so as to maximize the flow of passengers captured from the alternative mode. The corridors represent the potential capture area, i.e., all the flow origins and destinations that could potentially be captured by the metro line built within it. The construction cost of the network cannot exceed a preset budget. What distinguishes this study from the work of Bruno and Laporte (2002), Gutiérrez-Jarpa et al. (2013) and Laporte and Pascoal (2015), who also used a corridor-based methodology, is that in our case these corridors are not given a priori. Rather, they are determined by the algorithm. A further difference consists in the representation of the network. As opposed to previous studies, here the edges of the network represent metro lines, instead of inter-station segments. To each line corresponds a corridor, and vice versa. The corridors and the corresponding metro lines are identified by the extreme nodes of the line.

The capture of the traffic between the origin and destination nodes is assumed to be a function of the ratio β between the travel time by metro and the travel time by the alternative mode. As β decreases, the captured traffic increases. As a way of testing different network shapes, we introduce a further parameter $\theta^{\min}$, which is the minimum angle between any two lines, measured at the transfer stations located on their extremes. Changing this angle, we obtain different network configurations. Finally, the corridors must be such that the lines form a connected network. The assumption of a connected network is highly realistic. When undertaking this study we have analyzed the 97 major metro networks depicted in Overden (2007) and we found all of these to be connected.

3. Description of the matheuristic

The matheuristic is divided it into four stages:

Stage I: Greedy generation heuristic. This stage consists of generating a large set S of candidate corridors, using a greedy generation heuristic. Initially S is empty. All possible corridors are candidates to be added to S. For each of these estimates of the travel time and traffic capture between all pairs of nodes lying within the corridor are computed. The capture of the traffic between an origin node a and a destination node b, both belonging to the corridor, is assumed to be a stepwise function of the ratio β between the travel time by metro and the travel time by the alternative mode:

$$\beta = \frac{\text{Metro\_Time(a,b)}}{\text{Alternative\_Time(a,b)}} \tag{1}$$

The captured traffic is given by the expression:

$$\%\text{Traffic\_Captured}(a,b) = \begin{cases} 0 & 1.00 & < & \beta & & \\ 25 & 0.75 & \le & \beta & \le & 1.00 \\ 50 & 0.50 & < & \beta & \le & 0.75 \\ 75 & 0.25 & < & \beta & \le & 0.50 \\ 100 & 0.00 & < & \beta & < & 0.25. \end{cases} \tag{2}$$

The pair's traffic is considered as candidate to be captured by the metro network if $\beta \le 1.00$. The corridor with the highest traffic capture is added to the set S, provided it is connected with some other corridor already in the set. This process continues while the construction budget multiplied by α is not exceeded. The parameter $\alpha \ge 1$ is used to generate different sets S as starting points of the remaining stages.

Stage II: Estimation of O/D travel times and captured traffic. By construction, all corridors in S form a connected network, i.e., there are always one or more routes joining any pair of demand nodes lying within the corridors. In Stage II, the shortest travel time by metro is updated for all O/D pairs, now considering that passengers can make transfers between the lines of the corridors in S. The traffic of an O/D pair is captured entirely, partially, or not captured, depending on the ratio β for that O/D pair. The total capture is also computed.

Stage III: Selection of corridors to be built. This stage uses an iterative procedure. A mixed integer linear formulation (P) is solved to select from S a set of corridors that maximizes passenger traffic without exceeding the available construction budget. Its optimal objective function value z is an upper bound on the actual captured traffic, because the captured O/D pairs were determined based on the travel time computed under the assumption that all corridors in S have their lines built. Once the solution z of (P) is known, the actual travel times and the capture estimates are recomputed and compared with z. If the difference exceeds a threshold ϵ, the travel times are updated with the recomputed ones, (P) is solved again,and its solution compared again with updated actual travel times. The procedure continues until convergence.

Stage IV: Opening transfer stations at corridor crossings. Finally, transfer stations are open at all corridor crossings. Travel times and capture are again recomputed.

Fig. 1 provides a pseudo-code for the Matheuristic.

3.1. Details of Stage I

The area to be served is represented by an undirected graph $G(N, E)$, where $N = \{1, \dots, n\}$ is the node set, and $E = \{(i, j) : i, j \in N, i < j\}$ is the edge set. In our case, $N = N_{O/D} \cup N_{EX}$, where $N_{O/D}$ is the set of commuters' origins and destinations, and N_{EX} is the set of nodes that are candidates to be extreme nodes of the corridors. A corridor is selected by choosing its two extreme nodes, which become its terminal stations. To each corridor corresponds an edge