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Optimal design of a regional railway service in Italy

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ABSTRACT

In order to assess the actual ability of planned infrastructure investments to satisfy the required demand of service, railway engineers also need to plan the new offer of train services. In turn, this requires a full re-planning of the line system and of the frequency of each line. In cooperation with the Sales and Network Management department of the Italian infrastructure manager, we developed a model to determine an optimal set of lines and the corresponding train frequencies. The model has been successfully applied to evaluate alternative infrastructure enhancements in the metropolitan rail network of Rome. A set of computational experiments has been carried out, providing interesting insights on the effects of different infrastructural intervention policies.

1. Introduction

This work stems from a project carried out with the Sales and Network Management department of the Italian railway infrastructure manager, Rete Ferroviaria Italiana (RFI). In RFI, infrastructure investments are carried out by iterating two planning phases: namely tentative infrastructure design followed by line planning. In general, line planning consists in selecting a set of lines in an infrastructure network and their frequency of operation such that a given travel demand can be routed. Remarkably, both infrastructure investment decisions and line planning are performed "by hand" in RFI, resulting in a very lengthy and exhausting trial-and-error process, with no guarantee on the quality of the final solutions. Actually, line planning also involves other municipal administrative and political bodies, making the process even more awkward.

We focus on the railway system in the metropolitan area of Rome where RFI has already established an ambitious investment plan, even though some options are still open. The plan includes the realization of new stations and tracks, plus the completion of a ring around the city center (*ring closure*). The ring closure is a particularly expensive decision, which is still under consideration. Our major contribution was to support the planners in evaluating investment alternatives, and in particular in analyzing the benefit of the costly ring closure. In particular, we compared three different options. A first option (*plan A*) is the "no-investment" option: Namely, we consider the line planning problem or, simply, the train frequency decision on the existing lines, in order to evaluate the current infrastructure in terms of some passenger-oriented performance indicators. The second option (*plan B*) considers line planning on the new infrastructure, excluding ring closure. Finally, in the last scenario (*plan C*) the ring closure is also taken into account.

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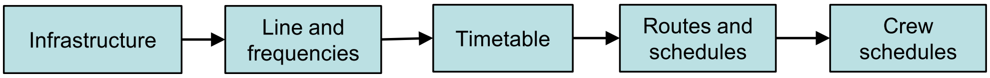

Fig. 1. Sequence of planning phases in public transportation.

1.1. *Line planning and related literature*

Line planning is a well studied problem in the literature (see Schobel, 2012, Karbstein, 2013 for surveys). In a recent survey paper (Schöbel, 2012), Anita Schöbel observes that the classical planning process in public transportation consists of a number of *consecutive* planning phases, reported in Fig. 1.

The first phase is infrastructure design, followed by the other phases as we move towards the actual transport operations. In our experience with railway infrastructure planners we quickly found out that things are not so straightforward as it may appear from this picture. For instance, in a recent project with the capacity department of the Norwegian infrastructure manager (*Jernbaneverket*), infrastructure decisions (on single lines[1]) were strongly intertwined with timetabling: indeed, in order to assess if a given railway design suffices to accommodate the expected traffic of trains, one needs to exhibit a suitable conflict-free timetable, see LaMaNa16. The planning process is in fact a trial-and-error process in which tentative infrastructure and timetabling are repeated until a satisfactory solution is found, see LaMaNa16. Things get even more complicated when the new infrastructure can change significantly the topology of the original network. In this case, to assess the quality of the new infrastructure it might be necessary to redefine the original lines. Therefore, infrastructure planning and line design converge in a single design problem. In particular, The most common approach (Ceder & Wilson, 1986, Schobel, 2012) in the literature is to select the lines to be activated from a predefined pool. In our case the pool is provided directly by RFI as the new lines are part of the overall plans to be realized. We remark that model presented here can still be used as a building block in a column (line) generation approach even when the pool of lines is not provided by some external source.

The models proposed in the literature typically assume the availability of an O-D matrix representing the demand on the network, and can be either cost-oriented or passenger oriented, or both (see e.g., Borndörfer et al. (2007); Karbstein (2016)). In the cost-oriented models, the goal is to find a set of lines serving all customers and minimizing the costs for the public transportation company (see e.g., Goossens et al. (2004)). The passenger-oriented approaches aim to minimize the passenger discomfort that can be measured either as the total travel time or as the number of transfers. As an example, in the direct travelers approach by Bussieck et al. (1996) the goal is to maximize the number of direct travelers (i.e. customers that need not change the line to reach their destination), keeping into account the capacity of the network. However, customers who actually need transfers are not considered, so that many transfers could be needed for some of them, and the traveling times are not taken into account. The number of transfers and traveling times are instead directly taken into account in the *change&go* model developed by Schöbel and Scholl (2006) and adopted by several authors, as for instance in Goerigk and Schmidt (2017). In this paper we propose an alternative model with fewer nodes (but potentially more arcs), which allows for a simpler representation of constraints and avoid to resort to big-M coefficients. In our model, passenger needs are expressed by suitable constraints, whereas we try to reduce operational costs by minimizing the total length of the selected lines. We remark that the O-D matrix is not available, so we resorted to use a demand estimate following the approach adopted by RFI's practitioners.

2. Problem description and MILP model

2.1. *Notation*

The railway network is represented by a directed graph $G = (N, E)$ where the nodes N correspond to the stations (and stops) of the railway, while the set of directed edges E corresponds to the actual tracks existing between the pairs of adjacent stations. We assume that between every pair of adjacent stations $u, v \in V$ we always have two directed edges, namely we have $(u, v) \in E$ and $(v, u) \in E$. Note that even a single track between two stations, say station A and station B, is normally used in both directions to connect A to B and B to A. Correspondingly, we have two directed edges in the graph. A line with terminal stations $s, t \in N$ is simply a pair of directed paths, one from s to t and the other from t to s, going through the same sequence of stations but in reverse order. Next, we are given a set $\mathcal{L}$ of potential lines to be activated. For each line $\ell \in \mathcal{L}$, we let $N^{\ell} \subseteq N$ be the stations on the line and $N^{\ell}_{\text{stop}} \subseteq N^{\ell}$ be the actual stops of ℓ. Also, we let $E^{\ell} \subseteq E$ be the set of edges on line ℓ. For each line $\ell \in \mathcal{L}$, we also define a set of "logical" arcs between each pair of stations in N^{ℓ}_{stop}, i.e., there is an arc $(u, v) \in E^{\ell}_{\text{stop}}$ if u and v are stops on line ℓ: note that E^{ℓ}_{stop} is not a subset of E^{ℓ} since the former set includes arcs between non-consecutive stops. Additionally, we indicate by θ^{ℓ}_{uv} the time necessary to run edge $(u, v) \in E^{\ell}_{\text{stop}}$ for a train of line ℓ. If s and t are the terminal stations of line ℓ, we let $\theta^{\ell} = \theta^{\ell}_{st}$. Finally, we assume here that all trains have the same capacity κ. For a given line, the number of trains running in the peak hour is called *line frequency*.

2.2. *Problem statement*

Roughly speaking, our problem consists in choosing a subset of lines from $\mathcal{L}$ and decide the hourly frequency of trains on each line

[1] A *line* is defined as a sequence of stations traversed by a train from an origin station to the a destination station.