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Analyzing the theoretical capacity of railway networks with a radial-backbone topology

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ABSTRACT

In this work we propose a mechanism to optimize the capacity of the main corridor within a railway network with a radial-backbone or X-tree structure. The radial-backbone (or X-tree) structure is composed of two types of lines: the primary lines that travel exclusively on the common backbone (main corridor) and radial lines which, starting from the common backbone, branch out to individual locations. We define possible line configurations as binary strings and propose operators on them for their analysis, yielding an effective algorithm for generating an optimal design and train frequencies. We test our algorithm on real data for the high speed line Madrid–Seville. A frequency plan consistent with the optimal capacity is then proposed in order to eliminate the number of transfers between lines as well as to minimize the network fleet size, determining the minimum number of vehicles needed to serve all travel demand at maximum occupancy.

1. Introduction

Railway capacity refers to the allocation of resources (tracks and vehicles) to achieve a certain quality of service, defining a tradeoff between operators and passengers' service level. The set of actions that enable increasing the capacity of railway infrastructures can be classified into two main groups: actions on the infrastructure, which belong to the context of long-term measures and usually require large initial investments, and actions on the operations, which are economically cheaper and applied in the short and medium term horizon. In the latter group, there exist simple strategies to increase the railway lines capacity, such as speed homogenization, traffic management, selection of stops (Lee, 2012; Freyss et al., 2013), acceleration strategies (Canca et al., 2014b), and the use of alternative routes. None of these requires financial investments as large as splitting existing tracks.

The radial-backbone (or X-tree) topology is one of the most widely used network schemes in conventional railways and tramways in urban transportation networks (Laporte et al., 1994). On a radial-backbone platform, vehicles belonging to two types of lines can travel: those that travel exclusively on the main corridor (primary or backbone lines) and those that, starting from the common backbone, branch out to individual locations (radial lines). The proliferation of the radial lines without adequate planning can inefficiently saturate the capacity of the railway infrastructure.

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In practical terms, the main lines canalize main services that are complemented by shuttle services provided by the radial lines (Musso and Vuchic, 1988). Thus, the stations located in the central segment of the corridor can be served by radial and backbone lines, while the stations in the branches can only be served by the radial lines. Based on this hierarchical structure, we propose a general mechanism to optimize the capacity of the backbone corridor within an X-tree structure by determining the line design and optimal frequencies in order to serve the whole demand while eliminating transfers between lines.

The transport capacity of a rail corridor is a complex, loosely defined concept having multiple meanings. In fact, the International Union of Railways (UIC, 2004) states that the railway capacity is not a concept that can be clearly determined, but that depends on the way in which the railway infrastructure is used. Nevertheless, based on the proposal of Krueger (1999), the railway capacity can be defined as a measure of the ability to move a certain traffic volume along a line over a period of time, with a given set of resources, and a specific service plan. The objective sought when quantifying the capacity of a railway corridor is to achieve an optimal use of the involved resources, scheduling train services according the available capacity.

The capacity of a railway line depends primarily on its physical characteristics (number of railways, number of stations, the existence of auxiliary lines and sidings (Kendra et al., 2012; Harrod, 2009), and on the signaling systems (Goverde et al., 2013). See Dicembre and Ricci (2011) for a study on the correlation between capacity, block sections length, types of services and timetables for high density lines. Other important factors are the trains' composition, the different running speeds, and the priorities for certain services on the infrastructure use. Abril et al. (2008) mention the existence of four types of railway capacity:

a. *Theoretical capacity:* Maximum number of trains that could be used by a railway line in ideal conditions during a given time period.
b. *Practical capacity:* Traffic flow that can be offered under normal operating conditions, driving on the railway line with an acceptable level of reliability. This typically corresponds to between 60% and 75% of the theoretical capacity since it depends on the priorities established among different kinds of trains, and on the traffic clustering.
c. *Used capacity:* Effective traffic flow that is canalized through the line (usually less than the one established by the practical capacity).
d. *Available capacity:* Difference between the practical and the used capacity. It quantifies additional traffic flow that could be introduced in a line.

The different types of capacity measures are illustrated in Fig. 1.

The factors that determine the capacity of a railway line can be grouped into those derivative of existing infrastructure, those attributable to traffic and those conditioned by the operation of the line. There exist various types of approaches that have led to methods for evaluating the capacity of a railway line. Among the most important techniques are analytical methods, simulation methods and optimization methods.

1.1. Analytical methods

These are usually based on obtaining the theoretical capacity of a line by assuming that its train departures follow a certain probability distribution. Subsequently, the practical capacity is estimated by including regularity margins or by applying the correction percentages imposed by the different types of concurrent services. This general scheme is followed by Petersen and Taylor (1982), Martland (1982), Kraft (1988), Chen and Harker (1990), and Burdett and Kozan (2006). Recently Malavasia et al. (2014) analyzed and compared three synthetic methods for the evaluation of capacity of railway

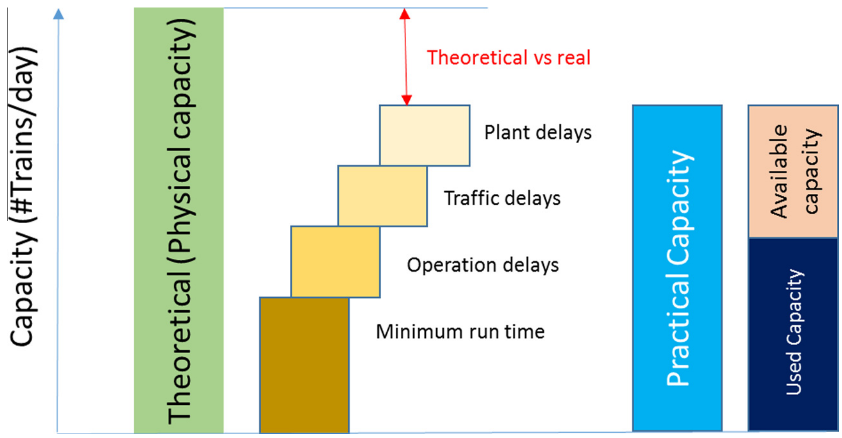

Fig. 1. Types of capacity measures (Krueger, 1999).