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Robust Infrastructure design in Rapid Transit Rail systems

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Abstract

Incidents and rolling stock breakdowns are commonplace in rapid transit rail systems and may disrupt the system performance imposing deviations from planned operations. A network design model is proposed for reducing the effect of disruptions less likely to occur. Failure probabilities are considered functions of the amount of services and the rolling stock's routing on the designed network so that they cannot be calculated a priori but result from the design process itself. A two recourse stochastic programming model is formulated where the failure probabilities are an implicit function of the number of services and routing of the transit lines.

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1. Introduction

Designing a Rapid Transit Network (RTN) or even extending one that is already functioning, is a vital subject due to the fact that they reduce traffic congestion, travel time and pollution. Usually a RTN is in operation with other transportation systems such as private transportation (car) and this makes that the design must take into account this factor. Another factor that needs to be considered is the capability of the newly designed system to keep operating under more or less suitable conditions under a set of predictable disruptions.

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In Bruno G. *et al.* (2002), a RTN design model is presented where the user cost is minimized and the coverage of the demand by a public transport network is made as large as possible. Laporte G. *et al*. (2007) extend the previous model by incorporating the station location problem, the alternative of several lines and the budget constraints as side constraints. The model is defined using the maximum coverage of the public demand as an objective function. Marín (2007), studies the inclusion of a limited number of lines. Also, in Laporte G. *et al* (2011) a design model is developed to build robust networks that provide several routes to passengers, so in case of failure part of the demand can be rerouted.

Liebchen, C. *et al.* (2009) applied the recoverable robustness (RR) concept in railway networks with the focus on finding recoverable solutions in a limited number of steps. In case of disruption, they allow a feasible solution to be modified by a recovery algorithm. They use the maximum deviation of the recovered solutions from the planned solution, where the maximum is taken over a set of disruption scenarios. Another classical approach is two stage stochastic programming for which the disruption scenarios have an associated probability.

Connections between two-stage stochastic programming network design and RR in railway networks planning models have been studied in Cicerone *et al.* (2009), Caprara et al. (2008) and in Cacchiani *et al.* (2011). Also, in Cadarso and Marín (2012) a two-stage stochastic programming model for rapid transit network design is developed in which disruption probabilities are assumed known a priori, illustrating some of its recoverable robustness properties.

This paper presents a conceptual scheme that permits to incorporate a probability model for the disruptions of a RTN. The network modeling framework followed is that of Marín (2007) and Cadarso and Marín (2012). It is assumed that disruptions arise when transportation units present some failure during operation leaving a link blocked. Other sources of disruption with their associated scenarios could be added, but this is not done for ease of exposition. As a consequence of this, the disruption probabilities will depend on the level of traffic on the network links. The probabilities of failure follow the following hypothesis: a) disruptions are due to a single event and scenarios with several simultaneous disruptions are discarded a priori as they are assumed to have a much lower probability, b) a preselected set of scenarios is considered, c) the number of failures that a train unit may experience along a large number of services distributes accordingly to a geometrical law and the individual probability of failure of a service is constant along the planning horizon and depends only on the train unit characteristics (e.g., quality of material and maintenance). The resulting model has a bilevel structure and it is solved by a specific heuristic method.

The paper is organized as follows. In section 2 a two-stage stochastic model is presented for the design of a RTN. Section 3 describes a probability model for the disruptions. In Section 4 the probability model is integrated in the two-stage stochastic model resulting into a bilevel scheme solved heuristically by means of the method of successive averages (MSA). Finally the model recoverability features are analyzed in section 5.

2. Rapid transit network design model

In this RTND model it is assumed that the locations of the potential stations are known. There already exists a current mode of transportation (for example, private cars or an alternative public transportation is already operating in the area) competing with the new RTN to be constructed. The aim of the model is to design a network, i.e. to decide at which nodes to locate the stations and how to connect them covering as many trips by the new network as possible.

- A potential network (N, A) is considered from which the optimum rapid transit network is selected. The node set is composed by centroids (N_c) and stations at RTN (N_r), the node set is then $N = N_c \cup N_r$. Links will be denoted either by a single subscript (e.g., a) or by a double subscript (i.e., (i, j)) when considered convenient. Because both riding directions are always considered, the set of potential links is so that $(i, j) \in A \Leftrightarrow (j,i) \in A$. Let $N(i) = \{ j \in N \mid (i, j) \in A\}$ be the set of nodes adjacent to node i.

- Each feasible link (i, j) has a generalized travel cost which may depend on the scenario of disruption. This is further discussed in section 3.

- The nodes and alignments are connected with a finite number of transit lines: $L = \{1,..,|L|\}$.

- The total demand is given by the trip matrix $G = (g_w)$, where g_w is the number of users willing to travel from origin $o(w)$ to destination $d(w)$. Users may choose between two transportation modes: a private (and current) mode or the public transportation mode made up by the set of new lines that are to be build up. The generalized cost