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Vulnerability Analysis of Railway Networks in Case of Multi-Link Blockage

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Abstract

In this paper, we propose a methodology to analyze the most critical links of a railway network based on flow interdiction. Our strategy for network interdiction is to maximize network disruption by removing the links with the greatest impact to the system. For this purpose, we first introduce our primary model to determine vulnerable links based on routing costs, which are based on the minimum cost model. Next, we propose a heuristic approach to solve this model with partial enumeration of network components to assess the most vulnerable parts. Since an important factor in system vulnerability is flow, we introduce the time-space network flow model as the second model to simulate train flow in the network. After interdicting critical links in the railway network, the trains are scheduled in the residual network with considerations of various factors including customer demand, track and station capacities, and time planning horizon. The paper includes a computational instance which has been analyzed by the proposed models under various disruption scenarios, and the results are compared with full enumeration of network components using a network scan method. The accuracy of obtained results indicates the effectiveness of the proposed method in addition to fast computational time compared to the enumeration method.

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Keywords: Railway network, Vulnerability, Scheduling, Combinatorial optimization

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1. Introduction

An important indicator of the economic growth of every society is its transportation infrastructures. Among various transport modes, railways have a vital role in the national economy by moving great amount of passengers and goods across the country. In Iran, railroads annually shipped over 35 million tons of goods and 25 million passengers along the 10,000 km integrated network which play a key role in the economy which contribute to 8.5% Gross Domestic Product (GDP) of the country (RAI, 2014). In light of the above, it is evident that disruption in the network operation resulting from temporary track blockage would not only have an unfavourable impact on the customer service but also an adverse effect on the economy. Examples of such events include natural disasters like earthquake, flood, or extreme weather conditions, and less frequently occurring events like terrorist attack or strike which cause the stations and tracks to be closed. Such disruptions often necessitate rescheduling and/or rerouting of trains and invariably result in longer trip times and unexpected delays. Therefore, railway authorities may be eager to know the most vulnerable nodes/links of their network in order to establish protection priorities to improve those parts of the networks.

This paper focuses on the model building methodology to analyze the most critical links of a railway network based on the concept of interdiction. Our strategy for network interdiction is to maximize network disruption by removing the links with the greatest impact to the system. For this purpose, we first introduce our primary model to determine vulnerable links based on routing cost. Next, we propose a heuristic approach to solve this model with partial enumeration of network components to assess the most vulnerable parts. Since an important factor in system vulnerability is flow, the time-space flow network model is introduced to model real train flow in the network.

The paper is structured as follows. In the next section, related studies on the transportation vulnerability are described and an overview of the most recent accomplishments on this topic is provided. Section 3 introduces our models of vulnerability assessment in two subsections. Section 4 applies the proposed methodology to a numerical case. The final section, section 5, summarizes the main results and conclusion, and also provides potential directions for future research.

2. Literature review

The vulnerability of transportation networks has been a well-researched topic in recent years. The initial engagements in this domain were introduced by interdiction models. They identify critical nodes and links by modeling a game between an adversary and an operator of the network, who routes flow through the network after the adversary makes his attack. Fulkerson and Harding (1977) were among the first to study how to interdict arcs in a network to maximally increase the length of the shortest path. Wollmer (1964) provided a model for interdicting a maximum-flow network; they are followed by others (Israeli and Wood, 2002). Researchers have also considered other objectives such as minimizing the maximum reliability path (Pan and Morton, 2008) and minimizing the maximum profit (Lim and Smith, 2007). Further, Church et al. (2004) presented models for interdicting a set of facilities. However, early optimization attempts had a limited success and could not incorporate many real-life characteristics of rail operations.

The concept of vulnerability of transportation network was first introduced in the literature by Berdica (2002). She defines vulnerability as susceptibility to disruptions that could cause considerable reductions in network service or the ability to use a particular network link or route at a given time. Jenelius et al. (2006) argued that road network vulnerability is composed of the probability and consequences (represented by an increased generalized travel cost) of single or multiple link failures.

Until now, most work in transport network vulnerability analysis has focused on the road network and personal vehicle travel with consideration network structure and travel patterns of the users (Jenelius, 2009, Scott et al., 2006, Taylor, 2012). Among these studies, railway transportation is the mode which has received less attention compared to other modes. A review by Wang et al. (2014) revealed only 8 present of research efforts focused on vulnerability of railway systems. Besides, the research methodology and vulnerability characteristics of different transportation modes varied significantly.

In some recent studies, Burdett and Kozan (2014) proposed an approach to prepare a robust timetable that is capable of detecting the critical operations and their impacts on others in case of any delay. Gedik et al. (2014)