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Optimal allocation of protective resources in urban rail transit networks against intentional attacks

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ABSTRACT

This paper advances the field of network interdiction analysis by introducing an application to the urban rail transit network, deploying protective resources against intentional attacks. The resource allocation problem for urban rail transit systems is considered as a game between two players, the attacker interdicting certain rail stations to generate greatest disruption impact and the system defender fortifying the network to maximize the system's robustness to external interdictions. This paper introduces a game-theoretic approach for enhancing urban transit networks' robustness to intentional disruptions via optimally allocating protection resources. A tri-level defender–attacker–user game-theoretic model is developed to allocate protective resources among rail stations in the rail transit network. This paper is distinguished with previous studies in that more sophisticated interdiction behaviors by the attacker, such as coordinated attack on multiple locations and various attacking intensities, are specifically considered. Besides, a more complex multi-commodity network flow model is employed to model the commuter travel pattern in the degraded rail network after interdiction. An effective nested variable neighborhood search method is devised to obtain the solution to the game in an efficient manner. A case study based on the Singapore rail transit system and actual travel demand data is finally carried out to assess the protective resources' effectiveness against intentional attacks.

1. Introduction

The urban rail transit systems have been developed as the backbone of public transportation system in many large cities over the world. The dependence on the rail system keeps growing while the system itself is becoming to be potential targets for certain terrorists. Even limited random disruptions (e.g., random failures) of urban rail transit system can lead to widespread travel delay, not to mention intentional terrorist attacks. Security from terrorist attacks in cities rose to the forefront of political discourse and debate, particularly in the aftermath of 911 (Loukaitou-Sideris et al., 2006). Table 1 lists incidents of terrorist attacks on urban rail transit systems in recent years all over the world. Most of the terrorist attacks happen on working days and in megacities with high population density, generating massive economic loss and casualties. Besides, terrorist attacks have turned out to be more sophisticated and coordinated by multiple attackers. Taking the 2010 Moscow rail transit system bombing as an example, at the time of the attacks, two interchange stations were attacked by two individuals during the morning rush hour when estimated 500,000 people were commuting through the rail transit system. Urban rail transit

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Table 1
Urban rail transit terrorist attacks in recent years.

Date	Attack mode	Country	City	Casualties
1995.3.20 (Mon)	Poison gas	Japan	Tokyo	12 deaths, 5000 injuries
1995.7.25 (Tue)	Bombing	France	Paris	8 deaths, 117 injuries
1996.6.11 (Tue)	Bombing	Russia	Moscow	4 deaths, 7 injuries
1996.12.3 (Fri)	Bombing	France	Paris	4 deaths, 86 injuries
2000.11.20 (Mon)	Bombing	Germany	Dusseldorf	9 injuries
2001.9.2 (Sun)	Arson	Canada	Montreal	40 injuries
2003.2.18 (Tue)	Arson	Korea	Taegu	198 deaths, 147 injuries
2004.1.5 (Mon)	Arson	China	Hong Kong	None
2004.2.6 (Fri)	Bombing	Russia	Moscow	40 deaths, 134 injuries
2004.3.11 (Thur)	Bombing	Spain	Madrid	92 deaths, 1500 injuries
2004.8.31 (Thur)	Bombing	Russia	Moscow	10 deaths, 40 injuries
2005.7.7 (Thur)	Bombing	Britain	London	56 deaths, 720 injuries
2005.7.21 (Thur)	Bombing	Britain	London	1 injury
2010.3.29 (Mon)	Bombing	Russia	Moscow	40 deaths, 102 injuries
2011.4.11 (Mon)	Bombing	Belarus	Minsk	12 deaths, 200 injuries

Data source: from online news report and data in Ou (2014).

systems in cities have turned to be attractive targets by terrorists, because their efficiency would spread a contaminant among large numbers of people quickly over large distances (Brown et al., 2005) and the resulted service suspension would cause substantial travel delay and confusion among commuters (Jin et al., in press).

The robustness of the urban rail transit systems to external disruptions due to intentional attacks can be greatly enhanced by implementing counterterrorism measures. For example, most large cities in China, such as Beijing and Shanghai, have taken strict security check measures by deploying staff and screening detectors at the entrance of major rail transit stations. Given limited amount of protective resources, it is a critical challenge to determine the allocation of those resources among the entire rail transit network with specific consideration of intentional attacks, particularly if multiple locations are interdicted by coordinated attackers. The resource allocation problem for the urban rail transit systems can be considered as a game between the system operator (i.e., defender) and the attacker (Brown et al., 2005; Cappanera and Scaparra, 2011; Perea and Puerto, 2013). Specifically, the attacker aims to generate greatest disruption impacts via interdicting certain components (e.g., stations) of the system while the defender aims to maximize the system's robustness to external disruptions.

This paper introduces a game-theoretic approach for enhancing urban rail transit networks' robustness to intentional attacks via optimally allocating protection resources. With this objective, we developed a tri-level defender–attacker–user game-theoretic model that optimally allocates protective resources for urban rail transit systems. In the first level, the system defender allocates protective resources among vulnerable stations with the objective of minimizing the maximal potential disruption impacts that can be achieved by attackers. In the second level, the attacker responds correspondingly and interdicts rail stations in order to cause maximal travel delay for rail system users. Different attacking strategies are specifically considered in the game by modeling various attacking intensities, such as in-flow, out-flow, through capacity reductions for rail stations. With both of the defending and attacking patterns, the third level models the system users' behavior and assigns them to alternative paths once the original path is affected. In order to tackle the nonlinear property of the model, an effective nested variable neighborhood search method is devised. The contribution of this study lies in the following aspects:

- Propose a tri-level defender–attacker–user game-theoretic model that optimally allocates protective resources for urban rail transit system against intentional attacks;
- Consider the features of sophisticated attacking behavior and the characteristics of commuter flows in the rail network. The proposed model is capable of modeling multiple attacking locations as well as various attacking intensities while the commuter flow is modeled as a multi-commodity flow problem in the third level.
- Demonstrate the practical significance of the proposed model. A case study based on the Singapore rail transit system and actual travel demand data shows that the worst-case disruption impact achieved by the attack can be significantly mitigated by allocation of protective resources over critical interchange rail stations.

The remainder of this paper is organized as follows. Section 2 reviews relevant papers in the literature and highlights the research gap. A tri-level game-theoretic programming model is developed in Section 3 and a nested variable neighborhood search solution method is proposed in Section 4. Section 5 carries out a case study based on the Singapore rail transit network. Finally, conclusions are drawn in Section 6.

2. Literature review

Recently, research topics related to the robustness of urban rail transit systems to disruptions, including *disruption preventive planning* and *post-disruption response recovery planning*, are receiving more attention. Some disruption preventive planning methodologies and techniques have been proposed for enhancing the urban rail transit system's robustness to