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A toll-based bi-level programming approach to managing hazardous materials shipments over an intermodal transportation network

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ABSTRACT

This research proposes a bi-level bi-objective model to regulate the usage of rail intermodal terminals for hazardous materials (hazmat) shipments, where government imposes tolls to deter carriers from using certain terminals. The complexity of the resulting mathematical program motivates the development of a hybrid speed-constrained multi-objective particle swarm optimization algorithm, which is then integrated with CPLEX, to solve the model. Through a real problem instance based on the intermodal service chain of Norfolk Southern in US, the toll-setting model is examined and further compared with a regular network design approach, in which certain terminals are closed to hazmat containers. The computational results show that the toll-setting policy is more practical and efficient, and the two models can be combined as a two-stage strategy in long-term hazmat transportation regulations. Additional managerial insights are derived for different stakeholders.

Introduction

Hazardous materials (hazmat) pose an unreasonable risk to health, safety, and property when transported in commerce (US Environmental Protection Agency, 2013). Based on the latest statistics for the United States of America, approximately 111 million tons of hazmat was transported via the multimodal network in 2007 (US Commodity Flow Survey, 2007). In Canada, about $40 billion of hazmat are shipped annually, representing more than 8% of all manufacturing shipments in the country (Transport Canada, 2011). In both countries, majority of hazmat freight is transported via road and railroad, wherein the latter mode is primarily used for long-distance bulk shipments and forms an integral part of the rail-truck intermodal chain. It is important that rail-truck intermodal transportation, which exploits the positive attributes of the two modes, has experienced phenomenal growth over the last two decades and is increasingly used to transport hazmat shipments (US DOT, 2010). Fortunately, thanks to a number of efforts initiated by the industry and the regulators, railroads have an impressive safety records. However, some recent railroad incidents involving hazmat shipments have raised concerns about the inherent safety of the mode. For instance, in 2013, the crude oil derailment in Lac-Mégantic, Quebec (Canada) caused 47 lives (National Post, 2013), and the one in Western Alabama (United States) resulted in huge contamination to the surrounding wet lands (Reuters, 2013). Thus, there is a need to investigate better techniques and methodologies that could be used to mitigate hazmat risk.

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This research focuses on rail-truck intermodal transportation (RTIM), where shippers are connected to the receivers via railroad and trucks (i.e., drayage operation on highways). More specifically, shippers and receivers are linked via highway to a number of rail intermodal terminals, where shipments are transferred between the transport modes, and a number of intermodal train services link the terminals. Although intermodal transportation, in general, has received increased attention from researchers over the past two decades, most of the discussion is focused on regular freight and rather limited engagement in the hazmat domain. To the best of our knowledge, Verma and Verter (2010) was the first work to propose an analytical framework for planning rail-truck intermodal transportation for both hazmat and regular freight when shippers/receivers have access to a single terminal, which was then generalized for multiple terminals in Verma et al. (2012), and extended to consider penalty for late deliveries (Verma, 2012). Xie et al. (2012) proposed a bi-objective model, with cost and risk, to study the facility location and routing within a multimodal setting. Most recently, Assadipour et al. (2015) proposed a nonlinear mixed integer program to study the impact of congestion at rail intermodal terminals on hazmat risk. It is important that these studies made use of bi-objective models to incorporate hazmat risk, and then conducted risk-cost trade-offs to reflect the perspectives of the transport companies and the regulators. However, none of them endogenously captured the conflicting perspectives and incompatible powers of the two stakeholders within an intermodal setting, though there are a few relevant works in the highway domain that recognize the dominant power of the government. This line of research uses a bi-level program to capture the dominant power of the regulator in the network design decisions.

Kara and Verter (2004), the first to formulate the network design problem for hazmat transportation as a bi-level decision model, considered a situation where a regulator chooses to close certain road segments with consideration of carriers' route selection based on transportation cost, which was subsequently generalized by Erkut and Gzara (2008) for the undirected case. Bianco et al. (2009) considered the role of two authorities (i.e., regional and local) in regulating hazmat transportation by imposing restrictions on the amount of hazmat traffic over the network links. Finally, Gzara (2013) developed a bi-level network flow model, which was solved by a cutting plane algorithm incorporating a family of value cuts.

Though network design approaches have been effective in mitigating risks, they are deemed rigid due to the ignorance of carrier's priorities and the waste of available infrastructure resources (Wang et al., 2012). Hence, as an alternative, researchers have proposed toll-based policies to reduce system risk. It is noteworthy that toll pricing has been used in controlling transportation congestion, and in inducing the optimal use of the network for a long period of time (Morrison, 1986; Bergendorff et al., 1997; Verhoef, 2002). Marcotte et al. (2009), the first known application of tolls within hazmat transportation setting, showed that the toll policies can be more effective in reducing hazmat transportation risks than the regular network design policies. Assuming that both hazmat and regular traffic affect population safety, Wang et al. (2012) suggested a dual toll setting model to mitigate the risk. Bianco et al. (2012) developed a toll setting policy which minimizes the network total risk and achieves the risk equity. It is important that the aforementioned studies have been made for highway shipments, and thus are not amenable to intermodal setting, especially because the transfer operations being performed at the rail intermodal terminals cannot be captured. Hence, we introduce a framework that would reduce hazmat risk in the intermodal network by imposing a toll on the usage of certain terminals, which in turn would also affect the relevant drayage and rail-haul links of the intermodal chain.

We focus on a rail-truck intermodal transportation network, and propose a bi-level bi-objective toll-setting policy model (BOTP), in which the government deters the carriers from using certain rail intermodal terminals by assigning toll to each hazmat container passing through them. Note that our model differs from the existing literature in that we impose tolls on facilities and not on links, which in turn enables controlling hazmat shipments not only through the rail intermodal terminals but also the drayage and rail-haul links connected to those terminals. By focusing on intermodal terminals, without ignoring the cost and risk attributes associated with the links, the proposed mixed-integer program provides an effective tool to the government to regular hazmat shipments. To the best of our knowledge, this is the very first bi-level bi-objective model developed to study the terminal location and routing of hazmat shipments on an intermodal network. In addition, we also propose an intermodal network design approach (INDA), where at the upper level the government designs the rail-truck intermodal network by making decisions about the terminals that should be closed, and the carrier then selects among available route choices at the lower level that results in hazmat transportation risk. Through a comparative examination of BOTP with INDA, we show that the toll-setting policy is more practical and efficient, and that the two models can be combined as a two-stage strategy in long-term hazmat transportation regulations.

The remainder of this paper is organized as follows. Section 'Problem description' describes the problem in details and addresses the assumptions. In Section 'Mathematical formulation', we propose the mathematical formulation of BOTP. Section 'Solution procedure' introduces the solution methodology based on multi-objective particle swarm optimization. Sect ion 'Numerical experiments' discusses the numerical experiments based on a real-world problem instance. Then in Section 'An alternative policy', the INDA is formulated, and the two approaches are compared, providing additional managerial insights. Finally, Section 'Conclusion' concludes this paper with contributions and possible future research directions.

Problem description

As alluded, we focus on determining an appropriate toll-setting policy that would assist the government restrict the usage of certain rail intermodal terminals so that network level hazmat risk is minimized. Note that this is a complex problem, in part because of the need to capture the special characteristics of the rail-truck intermodal transportation network – such as