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Planning and managing intermodal transportation of hazardous materials with capacity selection and congestion

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ABSTRACT

The current literature in the rail–truck intermodal transportation of hazardous materials (hazmat) domain ignores congestion at intermodal yards. We attempt to close that gap by proposing a bi-objective optimization framework for managing hazmat freight that not only considers congestion at intermodal yards, but also determines the appropriate equipment capacity. The proposed framework, i.e., a non-linear MIP and a multi-objective genetic algorithm based solution methodology, is applied to a realistic size problem instance from existing literature. Our analysis indicates that terminal congestion risk is a significant portion of the network risk; and, that policies and tools involving number of cranes, shorter maximum waiting times, and tighter delivery times could have a positive bearing on risk.

1. Introduction

Intermodal transportation, defined as the transportation of goods by a sequence of at least two different modes, continues to be one of the dominant segments of the transportation industry. Rail–truck intermodal transportation, which exploits the positive attributes of both trains and trucks, has experienced phenomenal growth since 1980 (AAR, 2010). According to the most recent study commissioned by the Department of Transportation, rail–truck intermodal traffic, measured in ton-miles, increased by 254% between 1993 and 2007 (US DOT, 2010). Note that the attractiveness of rail–truck intermodal transportation (RTIM), in part, stems from two sources: *first*, the significant reduction in both delivery and lead-time uncertainty because of the schedule-based operation of intermodal trains (Nozick and Morlok, 1997); and, *second* a more efficient and cost-effective overall movement ensured by combining the best attributes of the two modes (AAR, 2010).

Although intermodal transportation, in general, has received increasing attention from researchers over the past two decades, most of the discussion is focused on regular freight (SteadieSeifi et al., 2014; Macharis and Bontekoning, 2004). This is problematic since RTIM has also been used to move hazardous materials (hazmat), and the dependence of the industrialized society on hazmat has translated into a steady increase in volume over the past four decades. For example, the Bureau of Transportation Statistics estimated that the hazmat volume across the US intermodal transportation system increased from 1.5 million tons in 1997 to 111 million tons in 2007 (US DOT, 2004, 2010). It is important that such estimates are still on the conservative end, given that around one-quarter of chemicals are moved on railroads (AAR, 2009), and the projection of the US Chemical Manufacturers Association that the total volume of hazmat shipped by 2020 will be around 5.1 billion tons.

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In an effort to both motivate the need for this study and also to position it within the existing literature, we note that RTIM comprises three processes: (i) inbound drayage, (ii) rail haul and, (iii) outbound drayage. A significant portion of the transport distance is covered by intermodal trains, which operate on a fixed-schedule and hence are quite punctual. On the other hand drayage is carried out by truck, with inbound referring to the transport activity between a shipper and origin intermodal terminal, and outbound to that between a receiver and destination terminal. To the best of our knowledge, there are only seven refereed publications on intermodal transportation of hazmat. In one of the earliest studies, Mazzarotta (2002) presented a quantitative risk analysis approach for hazmat transportation, wherein risk mainly depended on the hazardous characteristics of the product. The author examined the data for Italy, and made the case for moving some transport activity from road to rail–truck intermodal. In a subsequent study, Bubbico et al. (2006) made use of three classes of hazmat to show that risk mitigation was possible by not just changing the route but also by using a different transportation mode. A total of 55 cases were analyzed, and the resulting analysis suggested that it was worthwhile to move some hazmat from road to rail or to intermodal to reduce risk. Since the objective of these studies was to compare risk stemming from road to that from rail–truck intermodal, not much attention was paid to modeling the characteristics of an RTIM system. To close that gap, Verma and Verter (2008) built an illustrative case study based in Canada to understand the trade-offs associated with rail–truck intermodal transportation of hazmat. The resulting insights were used to develop an analytical framework for planning rail–truck intermodal transportation across a network when shipper/receivers have access to a single terminal (Verma and Verter, 2010), and to multiple terminals (Verma et al., 2012). Given the exploratory nature of the studies, congestion at intermodal terminals was ignored by assuming enough equipment such that a just-in-time system could be implemented. Moreover, since delivery lead-times drove the selection of intermodal paths – feasible solution was possible only if at least one viable path existed. In a subsequent work, Verma (2012) relaxed the assumption about at least one viable path by adding a penalty function for late deliveries. Finally, Xie et al. (2012) studied the facility location and routing problem for multimodal transportation of hazmat by considering cost and risk stemming from both the transport and terminal location.

It is clear from the above studies that hazmat risk has been considered at the strategic and the tactical levels when planning intermodal hazmat freight, although the focus was only on decisions about transport and intermodal terminal location, while the issue of congestion at the terminals has been ignored. It is important that congestion at a terminal could likely affect the flow of traffic throughout a given network (SEROps, 2008), and thus postulate that accumulation of hazmat containers would increase the potential of incidents for the surrounding areas. Hence, there is a need to develop an analytical framework that takes into consideration the issue of congestion along the intermodal chain, especially at the terminals. Doing so would not only facilitate a better understanding of the resulting trade-offs, but also aid the appropriate equipment capacity decisions. It is important to note that although the impact of capacity on congestion has been well studied within the facility location literature, we are not aware of any effort involving hazmat freight. Hence, for capturing congestion (consistent with the existing literature, e.g., Elhedhli and Hu, 2010; Ishfaq and Sox, 2012; Marianov and Serra, 2003), we model arrivals of both regular and hazmat freight at the intermodal terminals as a Markovian queue. In this paper, we study the impact of terminal congestion and equipment capacity selection on the routing of regular and hazmat freight through a rail–truck intermodal network. Hence, this work is an extension of Verma et al. (2012) since both equipment selection and congestion at intermodal terminals are being considered. We pose the problem from the perspective of the intermodal railroad company, which offers a door-to-door service to the customers. In order to address the interest of both intermodal companies and regulatory agencies, we propose a bi-objective nonlinear programming model that considers both cost and risk, and solution methodology that combines the attributes of non-dominated sorting genetic algorithm and CPLEX.

In an effort to capture the hazmat volume and the resulting consequence, we resort to a more aggregate measure in this paper: *population exposure*. We represent transport risk as the total number of people exposed to the possibility of an undesirable consequence due to the shipment. For example, according to the North American Emergency Response Guidebook (2008), 800 m around a fire that involves a chlorine tank, railcar or tank-truck must be isolated and evacuated, and hence people within this predefined threshold distance are exposed to the risk of evacuation. This fixed bandwidth approach was first suggested by Batta and Chiu (1988), ReVelle et al. (1991), and has been used by many authors since then.

The rest of the paper is organized as follows. In Section 2 we define the managerial problem of interest, highlight the complexity and then outline the assumptions. Section 3 presents the nonlinear bi-objective optimization framework, the technique to estimate cost and risk parameters, and finally an outline of the genetic-algorithm based solution methodology. Section 4 makes use of the intermodal infrastructure of a Class I railroad operator to generate a number of problem instances of realistic size, which are solved and analyzed to gain managerial insights. Conclusion, contributions and directions of future research are outlined in Section 5.

2. Problem statement

In this section, we provide a formal statement of the problem, emphasize its complexity, and then state the modeling assumptions.

Our problem is to determine the best shipment plan for both hazardous and non-hazardous freight in an RTIM network, wherein a set of pre-defined lead times must be satisfied in choosing the truck routes and the intermodal train services to be used. The objective is to minimize the total cost as well as the total public risk associated with intermodal hazmat shipments. This task is complicated because hazmat risk at terminals needs to be determined by modeling congestion using Markovian queues, which in turn will drive the decision about equipment capacity (acquisition or operations) decisions, and only then