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Link-based multi-class hazmat routing-scheduling problem: A multiple demon approach

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ABSTRACT

This paper addresses a hazmat routing and scheduling problem for a general transportation network with multiple hazmat classes when incident probabilities are unknown or inaccurate. A multi-demon formulation is proposed for this purpose. This formulation is link-based (i.e., the decision variables are link flows) and can be transformed into other forms so that a wide range of solution methods can be used to obtain solutions. This paper also proposes a solution strategy to obtain route flow solutions without relying on exhaustive route enumeration and route generation heuristics. Examples are set up to illustrate the problem properties, the method of obtaining route flows from link flows, and the computational efficiency of the solution strategy. Moreover, a case study is used to illustrate our methodology for real-life hazmat shipment problems. From this case study, we obtain four key insights. First, to have the safest shipment of one type of hazmat, different trucks carrying the same type of hazmat need to take different routes and links. Second, in case of multiple-hazmat transportation, it is recommended to use different routes and links for the shipment of different hazmat types. This may increase travel time but can result in safer shipment. Third, if the degree of connectivity in a transportation network is high, the shipment company may have multiple solutions. Fourth, the hazmat flows on critical links (whose removal would make the network disconnected) must be distributed or scheduled over different periods to have safer shipment.

1. Introduction

According to US Department of Transportation (DOT), a hazardous material (or hazmat in short) is defined as any substance or material capable of causing harm to people, property, and the environment. Hazmats are classified into nine classes according to their physical, chemical, and nuclear properties (Keller and Associates, 2001). They are transported daily in many countries because the demand and supply locations are always different. The shipments of hazmats can be substantial. In some countries such as the USA, the volume and weight of hazmat shipments even increase over time. In 1998, 800,000 domestic daily shipments of hazmats were estimated to be transported in the USA whereas in 2009, the estimate increased to almost 1 million (US DOT, 2014).

Given substantial shipments of hazmats, the related accidents do happen. Moreover, the accidents can occur anywhere along the trips, but these accidents only correspond to a small proportion of traffic accidents. The annual number of transportation accidents in the USA was about 6 million in 2008 (US DOT, 2008) in contrast to the approximately 20,340 hazmat transportation incidents in the same year (US DOT, 2009). According to the recent report of PHMSA (2014), between 2009 and 2013, the number of hazmat incidents increased by 3.8 percent. The number of hazmat incidents in a country is still miniscule compared to the number of road accidents currently. To get some ideas regarding the number of hazmat incidents in the US, interested readers may refer to (http://www.phmsa.dot.gov/hazmat/library/data-stats/incidents). However, the total number of injuries and fatalities from each hazmat accident is drastically higher than that from a normal accident. Moreover, the release of these materials during transportation can be extremely undesirable as this can cause environmental pollution in addition to economic damage, injuries, and fatalities (Smith, 2009). Meanwhile, many transportation companies in a country are in charge of hazmat shipments. These transportation companies need to consider safety and environmental issues and legal limitations to choose the best routes for their fleets but the regulations and constraints do not often apply to many non-hazmat trips with possible accidents. This is probably why the shipment of these hazardous materials has drawn considerable attention over the last few decades.

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The traditional approach to modeling the routing and/or scheduling decisions assume that incident probabilities are known (e.g., Meng, Lee, & Cheu, 2005). The alternative approach is that these probabilities are unknown. To deal with this assumption, non-cooperative game theory was often used in the literature (e.g., Bell, 2000, 2003, 2004; Bell & Cassir, 2002; Cassir, Bell, & Schmöcker, 2003; Laporte, Mesa, & Perea, 2010; Qiao, Lu, Xiong, & Haghani, 2014; Szeto, O'Brien, & O'Mahony, 2006). This theory was also used when attack probabilities in the defender-attacker framework were assumed to be known (e.g., Dadkar, Nozick, & Jones, 2010a,b; Reilly, Nozick, Xu, & Jones, 2012) or it was assumed that there was some information on link incident probabilities (e.g., Schmöcker, 2010). Here, non-cooperative games are those, in which "players are unable to make enforceable contracts outside of those specifically modeled in the game. Hence, it is not defined as games in which players do not cooperate, but as games in which any cooperation must be self-enforcing" (Shor, 2005).

This paper addresses the problem of routing and scheduling hazardous materials in a general transportation network with multiple origin–destination (OD) pairs, multiple classes of hazmats, and unknown link incident probabilities: *Multiple dispatchers are responsible for sending out their vehicles to transport various classes of hazmats in a network with multiple OD pairs and have both route and departure time choices on a given day. Moreover, during the journey, the dispatchers can decide their hazmat vehicles to stop at some locations and their stop duration before continuing the journey. However, the probability of an incident to occur for each combination of route choice, departure time choice, intermediate stopping location choice, and duration choice is unknown. If an incident occurs, the impact of the incident depends on the type and volume of hazmat involved.* We consider multiple hazmat vehicles, in which each individual vehicle may encounter an incident. This does not mean that the incident must be between two or more than two hazmat vehicles. Any incident in which a hazmat vehicle is involved is related to this research. This research also looks at the problem from the company's perspective while observing the country-wide restrictions and approved routes.

The problem is considered to be a non-cooperative game between multiple dispatchers and multiple demons on a space–time expanded network. A demon is an imaginary evil entity that intentionally attacks a link to cause explosion or an incident on the link when a hazmat vehicle is on the link. Each demon has enough knowledge on all links, leading to the most number of fatalities and injuries when a particular link is selected. Each demon must cause an incident on one and only one link. Each demon aims at seeking its link selection strategy to maximize the impacts of the incident. The game is non-cooperative between dispatchers and demons because the dispatchers and the demons make decisions independently. We assume that the shipment between an OD pair is responsible by just one private company, and a company cannot handle the shipment between more than one OD pair. Therefore, the game among dispatchers is also non-cooperative. However, this game can be easily extended to consider cooperation between dispatchers, which will be mentioned in the conclusion.

The problem is formulated by both route- and link-based approaches. The route-based approach develops the formulation with route flows as decision variables whereas the link-based approach develops the formulation with link flows as decision variables. The equivalence of the route- and link-based problems, in terms of the maximum expected payoff to each demon, is proved. Both problems are formulated as a mixed system of equations and inequalities. The link-based problem is also reformulated into a variational inequality problem (VIP), a nonlinear complementary problem (NCP), an unconstrained minimization problem (UMP), and a fixed point problem (FPP) to allow a wider range of solution methods developed for VIPs, NCPs, UMPs, and FPPs to solve the proposed link-based problem.

Unlike solving the route-based problem, solving the link-based VIP, NCP, UMP, FPP, and mixed system of equations and inequalities do not require exhaustive route enumeration or route generation heuristics. However, the solutions to these formulations are link flows and link selection probabilities, which cannot tell the decision makers (or dispatchers) how to randomly select routes, departure times, intermediate stopping locations, and the corresponding stopping durations. This paper proposes a solution strategy, which is to first solve one of the link-based formulations by existing solution methods and then deduce route flows from link flows by our proposed route flow extraction algorithm. The route flow extraction algorithm is proved to be convergent. An example is given to illustrate the algorithm. Numerical examples are also provided to illustrate the problem properties. Problem insights and computational performance of the solution strategy are presented. Finally, a case study of Singapore is used to illustrate our proposed methodology for real-life hazmat shipment problems. The contribution of this paper includes the following: (i) This paper proposes link-based models to determine the routes and schedules of hazmat shipment under the situation of unknown incident probabilities, (ii) it introduces a solution strategy to obtain solutions on exhaustive route enumeration and route generation heuristics, and (iii) it presents the problem properties and problem insights.

The remainder of this paper is organized as follows: Section 2 reviews the literature of the subject. Section 3 presents the models and discusses their properties. Section 4 depicts the proposed solution strategy. Section 5 presents a numerical study. Section 6 focuses on algorithm complexity and computational results. Section 7 highlights the practical aspects of the formulated problem using a case study. Section 8 concludes the paper and provides some future research directions.

2. Literature review

Several streams of research are related to our work. Therefore, the literature is organized in terms of these streams as follows:

Hazmat routing and scheduling with known incident probabilities: To mitigate the level of the risk involved in hazmat transportation, a lot of research was done in the past. Comprehensive review papers on this research area can be found in Erkut and Verter (1995, chap. 20), Erkut and Verter (1998), List, Mirchandani, Turnquist, and Zografos (1991), and Verter and Kara (2008). As appropriate hazmat routing and scheduling decisions can reduce the level of the risk involved, most previous hazmat shipment studies focus on the planning of (1) routes (e.g., Akgün, Parekh, Batta, & Rump, 2007; Batta & Chiu, 1988; Carotenuto, Giordani, & Ricciardelli, 2007; Chang, Nozick, & Turnquist, 2005; Gopalan, Kolluri, Batta, & Karwan, 1990; Jin, Batta, & Karwan, 1996; Kang, Batta, & Kwon, 2014), (2) schedules (e.g., Cox & Turnquist, 1986), and (3) both routes and schedules simultaneously (e.g., Meng, Lee, & Cheu (2005); Zografos & Androutsopoulos, 2004). These studies assumed that link incident probabilities were known. For the low-probability events like incidents involving hazardous materials, these probabilities are usually unknown, because these events are rare and there is often insufficient data to estimate these probabilities (Bell, 2006). Over the time that it would take to accumulate adequate data to estimate the probabilities, circumstances may have changed (say, accident black spots may have been treated), making the calculated probabilities obsolete (Bell, 2006). Moreover, most dispatchers, when dealing with high-consequence events, exhibit risk aversion (Bell, 2006). This leads to one line of research given in the next subsection.

Hazmat transportation with unknown incident probabilities: To deal with unknown incident probabilities and risk aversion