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A bi-objective bi-level signal control policy for transport of hazardous materials in urban road networks

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ABSTRACT

A bi-objective bi-level signal control optimization for hazardous material (hazmat) transport is considered to assess trade-offs between travel cost and environment impacts such as public risk exposure. A least maxi-sum risk model with explicit signal delay is presented to determine generalized travel cost for hazmat carriers. Since the bi-level signal control problem is generally a non-convex program, a bundle method using generalized gradients is proposed. A bounding strategy is developed to stabilize solutions of the bi-level program and reduce relative gaps between iterations. Numerical comparisons are made with other risk-averse models. The results indicate that the proposed bi-objective bi-level model becomes even amiable to signal control policy makers since provides flexible solutions whilst is acceptable to carriers since takes account of travel delay at signal-controlled junctions. Moreover, the trade-offs between public risk and generalized travel costs are empirically investigated among different risk models with a variety of weights. As a result, the proposed model consistently exhibits highly considerable advantage on mitigation of public risk whilst incurred less cost loss as compared to other alternatives.

Introduction

For most urban road networks, transportation of hazardous materials (hazmats) is of primary concern to policymakers due to the serious safety, human health, and environmental impacts associated with the release of hazmat. Because of the danger associated with the accidental release of hazmat, the people living and working around the roads heavily used for hazmat incur most of the risk during transportation. One strategy available to local authorities is the restriction of hazmat transport to certain roads. Despite hazmat transport risks can be reduced by limiting access on urban city roads to hazmat traffic, carriers will incur increased costs due to limited routing available. Planning to both cope with mitigation of environmental impact such as public risk induced by hazmat shipments on population exposure and minimization of travel cost incurred by carriers has long become one of the most challenging issues facing decision makers in the field of transportation (List and Mirchandani, 1991; Erkut and Verter, 1995; Kara and Verter, 2004; Erkut and Alp, 2007; Erkut et al., 2007; Verma, 2009; Bianco et al., 2013). A bi-level programming approach has often been recognized as one effective alternative (Yang and Bell, 1998; Clegg et al., 2001; Kara and Verter, 2004; Chiou, 2005; Erkut and Gzara, 2008; Marcotte et al., 2009) to regulate traffic flow for a variety of road network design problems. For urban road networks with signal-controlled junctions, the growing complexity of signal-controlled road junctions has also increased opportunity of a formidable risk of sudden disruption. The reliability of a signal-controlled road network for hazmat traffic thus heavily depends on its vulnerability to a dangerous mix of probabilistic threats such as lane closure and road capacity loss. Although traffic congestion would be incurred by travelers as a result of inappropriate signal design, potential severe environmental impacts could be induced. While the

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local authority is able to designate the hazmat network, it cannot dictate routes to hazmat carriers for moving their shipments. Carriers for hazmat transport are not obliged to take minimum risk routes but free to select their routes based on cost minimization. This choice complicates hazmat network design problem, because the local authority must consider the decisions of the carriers in response to the hazmat network design.

While the authority is primarily concerned about mitigation of public risk, the carriers are more interested in minimizing transport costs. The routes in a road network with minimum travel delay would often be considered by carriers for hazmat transport. Kara and Verter (2004) were the first ones to propose a deterministic bi-level network design model for hazmat transportation with the objective of risk minimization. A bi-level problem of minimizing population exposure risk is addressed by banning hazmat traffic from traveling on certain segments of road network. At the upper level, the local authority minimizes total transportation risk imposed on the population centers due to heavy hazmat traffic through the prohibition on the use of certain road segments. At the lower level, the carriers minimize their total travel distance through route choice over the available road network. Numerical results have shown significant reduction in population exposure can be achieved through effective government interventions on the use of road segments by hazmat traffic while the carriers incurred more increased travel costs compared to the use of minimum cost routes. Erkut and Gzara (2008) improved the hazmat network design problem as a bi-objective bi-level problem by including the travel cost in the regulator's objective function. Marcotte et al. (2009) introduced a risk-control model to mitigate hazmat risk and find minimum cost routes for hazmat carriers. A flexible regulation policy was proposed to deterred hazmat carriers from using certain road segments via toll setting rather than road closure. By imposing tolls on certain road segments, the hazmat traffic is expected to be directed on less risky roads to population and environment exposure according to hazmat carriers' own selection due to economic considerations instead of restriction imposed by local authority. Recently, Erkut and Ingolfsson (2000) introduced a maximum risk model to avoid catastrophes by minimizing the maximum risk along a route. Bell (2006) also proposed a mixed route strategy to reduce the maximum population exposure under uncertain probability of incidents.

For a signal-controlled road network, a more amiable and flexible policy for regulators on effective road control can be achieved through appropriate signal design when takes account of environmental impacts. Li et al. (2011) proposed a two-stage approach to investigate the effects of signal timings at isolated junction on vehicle emissions. The emissions induced by traffic near isolated junction thus can be estimated by a microscopic emission model. An optimization model using a dynamic programming algorithm is presented to examine the trade-off between vehicle delays and number of stops. Numerical results find that effective decrease in the number of stops may result in reduced pollutant while it will increase vehicle delays. Ma et al. (2014) presented a multi-criteria analysis of optimal signal plans for an isolated signal-controlled junction. A micro-traffic simulator is integrated with emission model to assess trade-offs among various objectives between mobility and sustainability. Two control signal control schemes are also optimized using a genetic algorithm and implemented at an isolated junction where good numerical results have been obtained. Yin (2008) applied robust optimization to determine optimal signal timings for a single junction under uncertain travel demand. Although the proposed signal settings are less sensitive to fluctuations of traffic flow, the network effect of route choice from travelers is not taken into account. Zhang et al. (2013) also presented a bi-objective optimization model for coordinated traffic signals to minimize traffic delay and the risk associated with human exposure to traffic emissions. A conditional value at risk (CVaR) model is used to evaluate signal timing optimization under uncertainty. A bi-objective model was formulated to minimize total system delay and the mean excess exposure simultaneously. The Pareto optimal solutions for bi-objective optimization model were solved by employing a genetic algorithm (GA). Numerical computations were performed for coordinated traffic signal design along an example arterial. However, no account of effect of route choice from travelers to signal settings was taken into account.

In this paper, a bi-objective bi-level signal control policy is proposed to effectively regulate the risk associated with hazmat traffic whilst the generalized travel costs of carriers are explicitly taken into account. For a general bi-level problem, as commented in the literature (Luo et al., 1996; Outrata et al., 1998; Dempe, 2003), only local solutions can be found due to the non-linearity of the constraints at the lower level problem. As expected, the minimization of travel cost for hazmat routings favors expedience at expense of safety whilst the minimum public risk policy increases road safety by restricting hazmat shipments to routes where accident rates are lower. In order to effectively cope with potentially conflicting objectives for hazmat routing, List et al. (1991), Zografos and Davis (1989), List and Mirchandani (1991), Giannikos (1998), Rakas et al. (2004), Verma (2009), and Verma et al. (2012) addressed the importance of multi-objective programming models at one-level optimization. For example, Hu et al. (2002) presented a linear mathematical model that minimizes total reverse logistics operating costs for transportation of hazard wastes taking account of government regulations which are represented as constraints. Miller-Hooks and Mahmassani (1998) established optimal routing of hazmat in stochastic, time-varying transportation networks where Pareto-optimal paths can be generally identified using label-correcting procedures. Huang et al. (2005) moreover, proposed a multi-objective optimization model for routing hazmat where Pareto-optimal shortest paths can be conveniently identified without pre-emptive preferences to focus directly on paths of interest from decision-makers. Rakas et al. (2004) developed a multi-objective model for determination of location of undesirable facilities where a fuzzy logic linear programming was employed to determine the locations with a maximum possible level simultaneously satisfied by the objective function and constraints. Using a fuzzy multi-objective program, Tzeng et al. (2007) also established an emergency relief distribution model for the reference of the decision-maker. More recently, Lai et al. (2011) presented an integrated optimization model to effectively manage risk of hazmat on railroad networks and proposed a mixed-integer programming model where a linear combination of transportation cost and potentially release risk was represented as an objective. Verma (2009) also proposed a bi-objective model to manage railroad transportation of hazmat