Transportation Research Part B 83 (2016) 20–35

Contents lists available at ScienceDirect

Transportation Research Part B

journal homepage: www.elsevier.com/locate/trb

Regulating hazardous materials transportation by dual toll pricing

Tolou Esfandeh [a], Changhyun Kwon [b,*], Rajan Batta [c]

[a] Optym, Gainesville, FL, USA
[b] Department of Industrial and Management Systems Engineering, University of South Florida, Tampa, FL, USA
[c] Department of Industrial and Systems Engineering, University at Buffalo, SUNY, Buffalo, NY, USA

ARTICLE INFO

Article history:
Received 12 January 2015
Revised 27 October 2015
Accepted 30 October 2015
Available online 11 December 2015

Keywords:
Hazardous material transportation
Toll setting
Non-convex optimization
Bi-level programming

ABSTRACT

We investigate dual-toll setting as a policy tool to mitigate the risk of hazardous material (hazmat) shipment in road networks. We formulate the dual-toll problem as a bi-level program wherein the upper level aims at minimizing the risk, and the lower level explores the user equilibrium decision of the regular vehicles and hazmat carriers given the toll. When the upper level objective is to minimize the risk and all links are tollable, we decompose the formulation into first-stage and second-stage, and suggest a computational method to solve each stage. Our two-stage solution methodology guarantees nonnegative valid dual tolls regardless of the solution accuracy of the first-stage problem. We also consider a general dual-toll setting problem where the regulator rather wishes to minimize a combination of risk and the paid tolls and/or some links are untollable. To solve this truly bilevel problem, we provide heuristic algorithms that decompose the problem into subproblems each being solved by a line search. Case studies based on the Sioux Falls network illustrate the insights on the dual-toll policies.

1. Introduction

Despite the extensive use of hazardous material (hazmat) from fueling our vehicles and heating our homes to farming, medical and manufacturing purposes, they are potentially disastrous to the people and the environment. Common examples are explosives, gases, flammable liquids and poisonous substances shipped by trucks, trains, vessels, and planes containing undesirable consequences in the event that they release or explode due to an accident. According to the U.S. Department of Transportation Pipeline and Hazardous Materials Agency, among the close to 1 million daily shipments of hazmats crisscrossing the United States, during the year 2013, 16,769 hazmat incidents have been recorded. Nevertheless, these incidents caused a total of 12 fatalities, 23 major and 123 minor injuries and damages of over $114 million. These incidents underscore the importance of overseeing safe, reliable and environmentally sound hazmat transportation. This study specifically focuses on regulating hazmat transportation in road networks motivated by the fact that in 85% of the hazmat incidents truck has been used as the mode of transportation.

To mitigate hazmat transport risk, authorities usually attempt to separate hazmat flow from regular traffic flow while directing hazmat trucks to less populated areas. Two groups of policies are available to the governments: *network design* and *toll setting*. In the former approach, the authority restricts hazmat carriers from using certain road segments by imposing

* Corresponding author. Tel.: +1 8139745588.
E-mail addresses: tolou.esfandeh@optym.com (T. Esfandeh), chkwon@usf.edu (C. Kwon), batta@buffalo.edu (R. Batta).

http://dx.doi.org/10.1016/j.trb.2015.10.009
0191-2615/

(permanent or time-based) curfews (Bianco et al., 2009; Erkut and Alp, 2007; Erkut and Gzara, 2008; Kara and Verter, 2004). The latter approach diverts hazmat carriers to less risky areas based on their economical and time preferences by assigning tolls to road segments (Bianco et al., 2015; Marcotte et al., 2009; Wang et al., 2012). While toll pricing is most often used to reduce traffic congestion (Arnott and Small, 1994; Hearn and Ramana, 1998; Johansson-Stenman and Sterner, 1998), toll setting (TS) policy also provides a flexible and effective hazmat transport risk mitigation tool (Marcotte et al., 2009).

The majority of existing literature on hazmat risk mitigation policies focuses either on the restrictive network design policy, or single toll pricing that excludes the inevitable impact of regular vehicles on hazmat risk. Even though Wang et al. (2012) proposed a *dual toll* pricing problem to regulate both types of traffic, their model assumes a linear travel delay function for analytical tractability, which does not capture the regular traffic congestion properly. Our dual-toll pricing model uses a nonlinear travel delay function used by the U.S. Bureau of Public Roads.

We develop computational methods for both *first-best* and *second-best* dual-toll pricing policies. When every road link is tollable, it is called first-best, and when some links are not tollable, it is second-best. For the first-best toll pricing, we extend the two-stage approaches of Yang and Huang (2004) and Marcotte et al. (2009) that are based on inverse optimization. As the first-best toll pricing policy seeks a nonnegative toll vector that can lead traffic flow to the desired optimal traffic pattern, it naturally involves the notion of inverse optimization (Ahuja and Orlin, 2001). In the conventional inverse optimization approaches for toll-pricing, we must obtain an optimal solution to the first-stage problem to ensure the existence of a valid toll. In our work we consider nonlinearity of the travel delay function, which makes the objective function of the first stage problem non-convex; hence an *optimal* solution is difficult to find. Nevertheless, we propose a solution method to guarantee the existence of a valid toll even with an *approximate* solution to the first stage problem. When only a subset of links is tollable, we formulate the second-best toll pricing problem as a mathematical program with equilibrium constraints (MPEC), and propose a two-step equilibrium-decomposition-optimization (2-step EDO) method that extends the work of Suwansirikul et al. (1987).

In the literature of hazmat routing, risk measurement typically relies on two link attributes: *accident probability* and *accident consequence*. The accident consequence can be the population, which may be measured using the λ-neighborhood concept (Batta and Chiu, 1988), or it can also include damages to individuals who are directly involved in an incident as well as damage to the environment and properties (Abkowitz and Cheng, 1988). Various measures of hazmat accident risk can be defined by considering different distributions for these two link attributes such as quantile-based measures (Kang et al., 2011; Toumazis et al., 2013). We use a duration-population-frequency risk measure to model the dependence of hazmat risk on congestion induced by regular traffic.

The rest of this paper is organized as follows. Section 2 reviews technical contributions related to our research. Section 3 develops the dual toll pricing model. Section 4 is devoted to our solution methodology for the first-best dual-toll pricing. Section 5 explains the 2-step EDO method to solve the second-best dual-toll pricing. We present an application on the realistic road network of Sioux Falls in Section 6. Finally, Section 7 concludes the paper and suggests some future research directions.

2. Review of related technical contributions

We review technical contributions in past research efforts for both regular and hazmat traffic control that use toll pricing. We build upon these techniques in developing our solution methodology.

2.1. Regular traffic control

In regular traffic control, the primary objective of the network administrator is to minimize a certain system total cost function such as the total travel time or the total emissions-denoted by system optimum. Consider a directed network $\mathbb{G}(\mathcal{N},\mathcal{A})$, with a set of nodes $\mathcal{N}$, and a set of arcs $\mathcal{A}$. Let $f_{ij}(v_{ij})$, a function of arc traffic volume v_{ij}, denote such a performance measure in each arc $(i, j) \in \mathcal{N}$ that the network administrator wants to minimize. We assume there is travel demand d^w for each O–D pair w in the set of O-D pairs $\mathcal{W}$. The administrator's problem is written as follows:

$$\min_{v\in V} \sum_{(i,j)\in\mathcal{A}} f_{ij}(v_{ij}) \tag{1}$$

where

$$V := \left\{ v : v_{ij} = \sum_{w\in\mathcal{W}} y_{ij}^w \quad \forall (i,j)\in\mathcal{A}, \sum_{j:(i,j)\in\mathcal{A}} y_{ij}^w - \sum_{j:(j,i)\in\mathcal{A}} y_{ji}^w = b_i^w, \quad \forall i\in\mathcal{N}, \forall w\in\mathcal{W}, \;\; y_{ij}^w \geq 0, \quad \forall (i,j)\in\mathcal{A}, \forall w\in\mathcal{W} \right\}, \tag{2}$$

y_{ij}^w is the traffic flow in arc (i, j) for O–D pair w, $b_i^w = d^w$ if node i is the origin of O–D pair w, $b_i^w = -d^w$ if node i is the destination of O–D pair w, and $b_i^w = 0$ for all other intermediate nodes. We let an optimal solution to the administrator's problem (1) to be $\bar{v}$.

While $\bar{v}$ is the desired traffic flow of the administrator, network users will not necessarily follow the desire. Instead, they are often interested in their own benefits; hence a game-theoretic model is necessary. Given a tolling scheme from the administrator, according to the Wardrop's first principle (e.g. Florian and Hearn, 1995), the users, in an attempt to minimize their individual travel cost, will take the User Equilibrium flow pattern. When arc traveling time/cost is $c_{ij}(v_{ij})$, the user equilibrium of network users can be modeled as a variational inequality (e.g. Dafermos, 1980). Let us introduce toll prices τ_{ij} for each arc $(i, j) \in \mathcal{A}$.