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Time-of-day vehicle mileage fees for congestion mitigation and revenue generation: A simulation-based optimization method and its real-world application

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ABSTRACT

Congestion pricing of a large-scale network is characterized by expensive-to-evaluate objective functions without closed forms. This paper further enhances a computationally efficient simulation-based optimization (SBO) framework to solve the problem within tight computational budget. This paper applies surrogate models to solve the optimization problem with computationally expensive objective functions based on simulation-based dynamic traffic assignment (DTA). DIRECT (a deterministic search algorithm with modification to Lipschitzian optimization) is used for metamodel parameter tuning. A trade-off of different objectives (i.e. the average travel time minimization, expected network throughput maximization, and toll revenue maximization) are converted into a single desirability function. To demonstrate the SBO framework with an application to the vehicle mileage traveled (VMT) based pricing for a real-world freeway network, this paper utilizes a calibrated simulation-based DTA model to evaluate system performance. A stochastic mesoscopic simulator is applied. We investigate the existence of an invariant macroscopic fundamental diagram (MFD) for the network, and compare simulated MFDs with measurements of fixed detectors and probe data. The proposed SBO framework is generic and can be used to solve other congestion pricing problems.

1. Introduction

Public highway agencies aim to minimize total/average travel time via pricing under approximately fixed demands or maximize social welfare given elastic travel demands. From the system optimization perspective, how to minimize the network-wide travel time is a challenging research topic. As a promising policy, congestion pricing has been extensively studied in the literature (Yin, 2000, 2002; Verhoef, 2002a,b, 2007; Lou et al., 2010).

In the US, typical types of pricing strategies include variably priced lanes, e.g. express toll lanes or high occupancy/toll lanes, variable tolls on entire roadways, cordon charges (variable or fixed charges to drive within or into a congested area within a city), area-wide charges (per-mile charges on all roads within an area that may vary by level of congestion), etc., Fig. 1 shows toll facilities in operation, financed, or under construction by states and/or various toll authorities (FHWA, 2006, 2013). As shown in Fig. 1(a), the mileage of interstate and non-interstate toll roads increases to 3299 and 2135 miles

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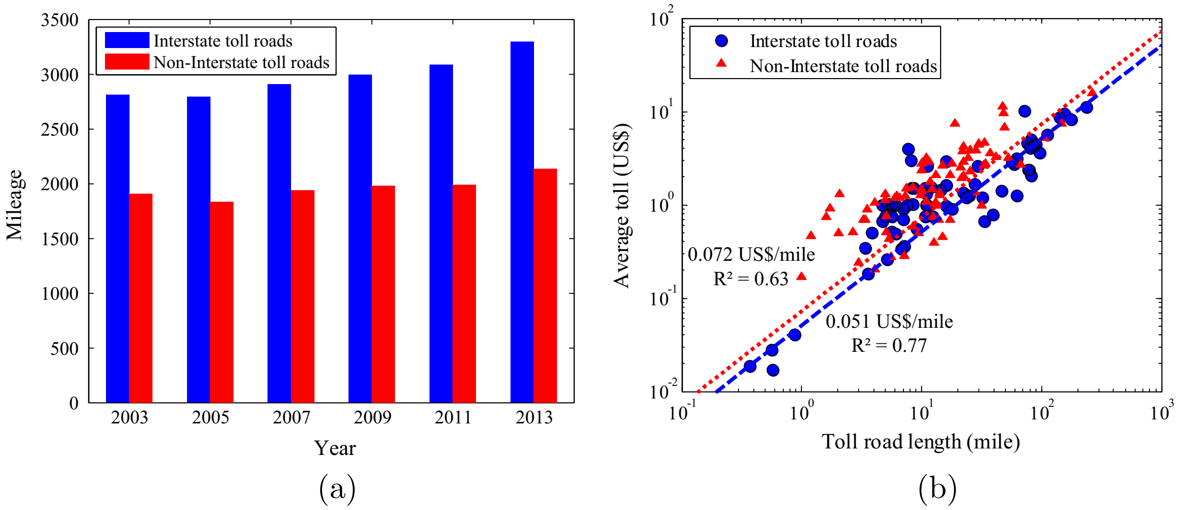

Fig. 1. United States toll roads. (a) Toll mileage trends from 2003 to 2013 and (b) toll rates of interstate and non-interstate roads in 2013. *Source:* Federal Highway Administration, 2013.

in 2013, respectively. Linear regression results in Fig. 1(b) indicate the average passenger vehicle costs are 0.051 and 0.072 US$/mile on interstate and non-interstate toll roads, respectively.

The network analysis, e.g., static user equilibrium (UE) traffic assignment, incorporates time-invariant variables and thus is inadequate to reveal the influences of dynamic shortest paths and en-route travel behavior Xiong et al. (2015a). It usually has limitations to evaluate impacts of traffic operational strategies such as signal timing, capacity constraint, and high-occupancy vehicle (HOV) lane management (Lou et al., 2011). In this study, we suggest use simulation models to evaluate the congestion pricing problem, particularly, in real-world large-scale networks. However, such simulation models accompany with expensive-to-evaluate objective functions (Osorio, 2010; Osorio and Nanduri, 2012; Osorio and Bierlaire, 2013; Osorio and Chong, 2015).

On a practical level, a large-scale network calibrated by empirical data is clearly valuable. Many factors can affect simulation results (e.g., driving behavior, routing, signal control plans, and parameters related to travel choices). In real-world large-scale networks, searching for the optimal solution often requires intensive objective function evaluations, especially when using black-box simulations to assess planning policies and/or operational strategies. The objective function evaluation via simulation may require several hours to several days. Thus algorithms that require intensive recalls of objective evaluations are inappropriate because of limited computational budget. In this case, it may be necessary to forgo an exact evaluation and use an approximate response surface that is more computationally efficient.

This study is devoted to the modeling of vehicle mileage traveled (VMT) based pricing of freeways. A real-world freeway network may consist of a sequence of road segments with multiple entry and exit ramps. The toll charge for a user depends on his/her VMT along the freeways, i.e. mileage specific, instead of section- or link-additive. Objectives of this pricing scheme are usually difficult to evaluate for large-scale networks when vehicle queueing simulations and dynamic traffic assignment (DTA) are taken into account (Chiu and Bustillos, 2009; Chiu et al., 2011). Chen et al. (2014b) compared a family of surrogate models to solve a link-additive congestion pricing problem for one particular freeway.

As an extension, this paper focuses on the VMT pricing with expensive-to-evaluate objectives for a freeway network. The objective functions (e.g., the average travel time minimization, expected network throughput maximization, and toll revenue maximum) have three important attributes/difficulties: (i) expensive to evaluate since each run of simulation usually costs a few hours; (ii) impractical to accurately approximate the derivative of the objective function; and (iii) system dynamics is explicitly simulated by individual travel behavior, which increases the computational burden. To deal with these issues, this paper enhances the SBO approach Chen et al. (2014b) for the time-of-day VMT pricing on freeways using simulation-based DTA. A stochastic mesoscopic simulator is applied. The approach can be implemented to a large-scale real-world network with dynamic flow patterns, rather than demonstrated by small numerical examples. Also, different responses are simultaneously considered for congestion mitigation and revenue generation.

The rest of the paper is organized as follows: Section 2 reviews related literatures and discusses differences and similarity of this paper with our previous work. Section 3 formulates the freeway VMT-based pricing problem. Section 4 shows a hierarchical SBO framework. Section 5 demonstrates the application of a regional network, validating the simulation model by heterogeneous measurements including fixed loop/microwave detections on freeways and probe data in major arterials. Finally, Section 6 concludes the paper.