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Optimal distance- and time-dependent area-based pricing with the Network Fundamental Diagram

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ABSTRACT

Given the efficiency and equity concerns of a cordon toll, this paper proposes a few alternative distance-dependent area-based pricing models for a large-scale dynamic traffic network. We use the Network Fundamental Diagram (NFD) to monitor the network traffic state over time and consider different trip lengths in the toll calculation. The first model is a distance toll that is linearly related to the distance traveled within the cordon. The second model is an improved joint distance and time toll (JDTT) whereby users are charged jointly in proportion to the distance traveled and time spent within the cordon. The third model is a further improved joint distance and delay toll (JDDT) which replaces the time toll in the JDTT with a delay toll component. To solve the optimal toll level problem, we develop a simulation-based optimization (SBO) framework. Specifically, we propose a simultaneous approach and a sequential approach, respectively, based on the proportional-integral (PI) feedback controller to iteratively adjust the JDTT and JDDT, and use a calibrated large-scale simulation-based dynamic traffic assignment (DTA) model of Melbourne, Australia to evaluate the network performance under different pricing scenarios. While the framework is developed for static pricing, we show that it can be easily extended to solve time-dependent pricing by using multiple PI controllers. Results show that although the distance toll keeps the network from entering the congested regime of the NFD, it naturally drives users into the shortest paths within the cordon resulting in an uneven distribution of congestion. This is reflected by a large clockwise hysteresis loop in the NFD. In contrast, both the JDTT and JDDT reduce the size of the hysteresis loop while achieving the same control objective. We further conduct multiple simulation runs with different random seed numbers to demonstrate the effectiveness of different pricing models against simulation stochasticity. However, we postulate that the feedback control is not applicable with guaranteed convergence if the periphery of the cordon area becomes highly congested or gridlocked.

1. Introduction

Road user pricing has been studied extensively both in practice and in theory as an effective means of mitigating urban traffic congestion. Back in 1975, Singapore successfully launched the world's first pricing scheme called the area licensing scheme. Following Singapore's success, several other pricing schemes have been implemented worldwide, such as in London, Stockholm, and Milan. See Gu et al. (2018) for a comprehensive overview. More recently, instead of looking into cordon and zonal schemes, a number of advanced pricing schemes have been proposed and implemented thanks to the development of various pricing technologies. For example, (i) the Move NY Plan in New York City which aims to charge taxis based on both distance and time[1]; (ii) Singapore's ERP 2.0 (from 2020) which uses satellites to charge vehicles based on distance traveled[2]; (iii) the opt-in user-pays system OReGo in Oregon, USA which is a state-wide distance-based charge[3]; (iv) a per-km charging system considered by the Metro Vancouver Independent

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[1] See https://nyc.streetsblog.org/2015/02/17/the-complete-guide-to-the-final-move-ny-plan/.
[2] See https://www.lta.gov.sg/apps/news/default.aspx?scr=yes&keyword=ERP2.
[3] See http://www.myorego.org/.

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Mobility Pricing Commission (Lee, 2018); and (v) a joint distance- and cordon-based scheme trialed in Melbourne (Transurban, 2016). Interested readers may refer to De Palma and Lindsey (2011) for an overview of different technologies applied to pricing.

In theory, since the seminal studies by Pigou (1920) and Knight (1924), a variety of models have been proposed for designing an optimal pricing system. These models, however, cannot be easily applied to a large-scale dynamic traffic network because of their demanding requirement of highly detailed information of each origin-destination (OD) pair and each individual link in the network. See Yang and Huang (2005) for a comprehensive overview. Recent advances in network traffic flow theory through the Network Fundamental Diagram (NFD) or Macroscopic Fundamental Diagram (MFD) (Geroliminis and Daganzo, 2008; Mahmassani et al., 2013) have established a new branch of pricing theory that largely facilitates the study, design, and implementation of large-scale pricing models. Nevertheless, studies so far are mainly limited to the cordon-based regime which, although being simple, suffers from inefficiency and inequity. Therefore, this paper aims to propose a few alternative distance-dependent area-based pricing models for large-scale dynamic traffic networks. To find the optimal toll levels that keep the network from entering the congested regime of the NFD, we develop a simulation-based optimization (SBO) framework combining the NFD and a simulation-based dynamic traffic assignment (DTA) model.

1.1. Literature review

The first pricing model is known as first-best pricing or marginal-cost pricing (MCP), which was first applied to a single link (Li, 2002) and then to a general traffic network (Yang et al., 2004). Despite perfect theoretical basis, its practical applications are rather limited for two main reasons (Simoni et al., 2015; Yang and Huang, 2005): (i) charging all links in a network is infeasible and inefficient given the high operating cost and the poor public acceptance; and (ii) assuming an abstract and constant demand-supply relationship is invalid. As a result, a variety of second-best pricing regimes have been proposed in which only a subset of links is tolled. A widely practiced way to solve the second-best pricing problem is to formulate it as a bi-level optimization problem or, equivalently, a mathematical program with equilibrium constraints (MPEC) (Liu and McDonald, 1999; Liu et al., 2013; Liu et al., 2014; Meng et al., 2012; Verhoef, 2002; Yang and Zhang, 2003; Zhang and Yang, 2004). Solving the MPEC particularly for a large-scale dynamic traffic network remains challenging because of the required computational complexity. Time-dependent information of each OD pair and each individual link in the network is needed for formulating the optimization model. Often the resulting objective function is of an expensive-to-evaluate type that cannot be solved directly through any exact solution algorithm (Chen et al., 2016; Chen et al., 2014; Ekström et al., 2016; He et al., 2017).

To develop an effective and efficient pricing model for large-scale dynamic traffic networks, an understanding of traffic dynamics at the network level is critical (Zheng et al., 2016). Macroscopic traffic flow relations for an urban traffic network were initially proposed by Godfrey (1969) followed by Daganzo (2007); Mahmassani et al. (1987); Olszewski et al. (1995). The formal demonstration of the existence of the NFD was shown only recently using field data from Yokohama, Japan (Geroliminis and Daganzo, 2008). Since then, the NFD has been widely studied for network-wide control and management (Geroliminis et al., 2013; Haddad, 2017; Haddad et al., 2013; Keyvan-Ekbatani et al., 2012; Ramezani et al., 2015; Ramezani and Nourinejad, 2017; Yang et al., 2017) due to its macroscopic nature and favorable properties (see Geroliminis and Daganzo (2008) for further description). In particular, an innovative NFD-based approach to modeling congestion pricing has emerged.

Since macroscopic modeling does not involve detailed route choice, an urban traffic network governed by an NFD can be modeled as a simple queuing system (e.g. a bottleneck) represented by the cumulative arrival and exit curves. Congestion is interpreted as vehicles queuing behind the bottleneck while demand results from their endogenous scheduling preferences considering the discrepancy between the desired and actual arrival times (Arnott et al., 1990; Arnott et al., 1993; Vickrey, 1963). Geroliminis and Levinson (2009) first integrated the bottleneck model with the NFD to consider the capacity drop. Daganzo and Lehe (2015) further introduced trip length heterogeneity and proposed an optimal usage-based toll. A fundamental study on NFD-based pricing in large-scale real-world networks was only recently conducted where the NFD was used to describe the level of congestion at the network level (Zheng et al., 2012). The authors applied an integral (I-type) controller for toll adjustment within an agent-based simulation environment. The I-type controller was later extended to a proportional-integral (PI) controller whereby users' adaptation to pricing was considered (Zheng et al., 2016). A similar simulation framework based on the NFD was also proposed by Simoni et al. (2015) but without using feedback control theory. The authors developed the toll adjustment rule by integrating the NFD (and also the 3D-NFD) with the MCP.

1.2. Objectives and contributions

NFD-based pricing in large-scale networks has so far mainly focused on the cordon-based regime. Given that a cordon toll undercharges long journeys and overcharges short trips, a distance toll was considered as an alternative (May and Milne, 2000; Meng et al., 2012). Although theory on distance-based pricing is well established, it is largely constrained within the traditional second-best pricing framework. Investigating distance-dependent pricing using the NFD therefore becomes theoretically interesting and also practically promising.

The overall toll design problem consists of a toll level problem and a toll area problem (Ekström et al., 2012). In this paper, we assume a predefined toll area and only aim to solve the optimal toll level problem. Since we are solving an area-based pricing problem, the NFD becomes a handy entry point to the solution due to its macroscopic nature. Similar to the existing studies on NFD-based network-wide control and management (Aboudolas and Geroliminis, 2013; Keyvan-Ekbatani et al., 2012; Simoni et al., 2015; Zheng et al., 2016; Zheng et al., 2012), the objective is to price and keep the network from entering the congested regime of the NFD.