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Time-dependent area-based pricing for multimodal systems with heterogeneous users in an agent-based environment

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ABSTRACT

In this paper, we investigate an area-based pricing scheme for congested multimodal urban networks with the consideration of user heterogeneity. We propose a time-dependent pricing scheme where the tolls are iteratively adjusted through a Proportional–Integral type feedback controller, based on the level of vehicular traffic congestion and traveler's behavioral adaptation to the cost of pricing. The level of congestion is described at the network level by a Macroscopic Fundamental Diagram, which has been recently applied to develop network-level traffic management strategies. Within this dynamic congestion pricing scheme, we differentiate two groups of users with respect to their value-of-time (which related to income levels). We then integrate incentives, such as improving public transport services or return part of the toll to some users, to motivate mode shift and increase the efficiency of pricing and to attain equitable savings for all users. A case study of a medium size network is carried out using an agent-based simulator. The developed pricing scheme demonstrates high efficiency in congestion reduction. Comparing to pricing schemes that utilize similar control mechanisms in literature which do not treat the adaptivity of users, the proposed pricing scheme shows higher flexibility in toll adjustment and a smooth behavioral stabilization in long-term operation. Significant differences in behavioral responses are found between the two user groups, highlighting the importance of equity treatment in the design of congestion pricing schemes. By integrating incentive programs for public transport using the collected toll revenue, more efficient pricing strategies can be developed where savings in travel time outweigh the cost of pricing, achieving substantial welfare gain.

1. Introduction

Research in transport economics have proposed road pricing as an effective policy to relieve traffic congestion in cities for many years. By charging road users the external costs they create, congestion pricing aims to trigger travel behavior changes (e.g. mode shift from cars to buses or departure time shift to outside of peak-hour) such that congestion is avoided. Despite the vast literature, a small number of cities have actually implemented congestion tolls due to social disagreement, political issues and myopic treatment of other modes of transport. Traffic mobility in multimodal systems is inherently a distributed and interconnected process, which should be modeled and managed as a whole to improve the global operational efficiency.

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The classical approach for determining pricing is based on economic theories. In the literature, there exists an extensive body of works on the first- and second-best pricing models. A comprehensive summary of these models can be found in Yang and Huang (2005) and de Palma and Lindsey (2011). Over the years, researchers have made significant effort in extending this type of models (either of a bottleneck or a small network) for studying the impact of pricing. Representative examples of this direction can be found in Verhoef (2002), Arnott (2007), and elsewhere, where Vikrey's bottleneck model (Vickrey, 1969) form the basis of their analysis; or in Lu et al. (2008), Lou et al. (2010) and Wu et al. (2011), where user equilibria of route choices were derived, given that the cost of pricing is taken into account. The treatment of user heterogeneity and equity should not be ignored when discussing congestion pricing. Regarding this research direction, similar types of models were proposed to capture the behavioral difference among travelers with have different value-of-times (see for instance in Lu et al., 2008; van den Berg and Verhoef, 2011; Qian and Zhang, 2013; Tian et al., 2013). Other well-established works on the design of equitable pricing schemes for multimodal networks include for example, Yang and Zhang (2002) and Yin and Yang (2004) who developed optimal pricing with social and spatial equity constraints. Others employed Pareto-improving approaches, such that all users are not worse off in the presence of pricing, see for example Lawphongpanich and Yin (2010), Nie and Liu (2010) and Xiao et al. (2013). Wu et al. (2012) and Xiao et al. (2013) share similar research interest with this paper, where the distributional effect of pricing on different income groups is captured and income-based pricing schemes are discussed. Zhu et al. (2013) developed a theoretical framework to address equity issues, though they did not touch directly how an equitable pricing scheme should be theoretically designed.

Existing traffic models in transport economics pose severe theoretical and empirical limitations in realistic applications. The main reason is because they employ link travel cost functions, which do not accurately describe the intra-day traffic dynamics and relate them to urban-scale network characteristics in a way that is computationally tractable and consistent with the physical properties of traffic. This failure constrains the ability of economic models to support efficient developments for network traffic management and diminish congestion externalities (Tsekeris and Geroliminis, 2013). With respect to the treatment of congestion dynamics (utilized traffic models), most of the aforementioned studies assume a steady-state traffic condition or demand-type of capacity-supply functions. Such models ignore the fact that the level of congestion is not a memory-less function of demand at a given time, but dependent on the history of the system, i.e. the same demand profile can influence differently the system if this was uncongested or congested at the current state (Geroliminis and Levinson, 2009).

With respect to the application level of the pricing schemes, pricing based on individual links is extremely difficult to implement in practice, and it is computationally complex for large-scale networks (Verhoef, 2002). With respect to the consideration of user heterogeneity, few studies quantitatively analyze the impact of pricing on different types of users, e.g. differences in mode shift behavior or distributional effect (as pointed out by Eliasson and Mattsson, 2006), while designing a pricing scheme capable of balancing the gain of all users is even rarely mentioned in the literature. While with respect to multimodality, alternative modes are not taken into account in most approaches. Integrating multimodality consideration in pricing is challenging and reserves further attention.

While the classical approaches focus on the link- or corridor-level of application, existing pricing schemes for macroscopic (large-scale) level have similar ambiguity. For example, in Maruyama and Sumalee (2007) and Zhang et al. (2008) traffic conditions are considered stationary; whereas in the well-known field implementation of congestion pricing, the Singapore scheme, it introduced a dynamic area-based type pricing system where the toll rates are time-dependent and adjusted based on regular surveys on travel speed (Liu et al., 2013). The valuable experience of the Singapore case significantly advanced the knowledge on congestion pricing, and had inspired the developments of speed-based toll schemes where a pre-defined optimal speed range serves as the base for toll optimization. According to the same reference mentioned above, the speed-based toll is regulated such that traffic flow rates can maintain at a speed ranging from 20 km/h to 30 km/h. Though it sounds reasonable, the issue is that traffic states can vary significantly at this speed range (see for example in the empirically observed fundamental diagram, e.g. in Geroliminis and Daganzo, 2008), therefore the determined pricing rates may not guarantee an optimum. Regarding the pricing schemes of other successful field implementations, for instance in Stockholm and London, the underlying method for determining the prices is unfortunately unavailable and remains as a black-box to the researchers.

To develop an effective congestion pricing scheme for urban networks, the aforementioned inadequacies need to be treated. Integrating a proper traffic model that captures congestion dynamics is critical in designing the optimal prices. It is even more challenging as the current urban management requires understanding at the network level. Recent findings on the Macroscopic Fundamental Diagram (MFD) shed light into this direction. The idea of macroscopic traffic model for car-only urban networks was initially proposed in Godfrey (1969) and followed in Mahmassani et al. (1987) and Daganzo (2007). The demonstration of the existence of the MFD with dynamic features from field data was firstly reported in Geroliminis and Daganzo (2008), showing that urban single-mode regions exhibit an MFD relating space-mean network flow (traffic throughput) to network density (traffic state). It has been showed by the same reference that (i) even though the flow-density plots for individual links in the network exhibit considerable scatter, the scatter nearly disappears once data of the individual links are spatially aggregated for the entire network, and (ii) the MFD is a property of the network itself (infrastructure and control) and not very sensitive to different demand patterns. An interested reader could refer to Yildirimoglu and Geroliminis (2014) and Leclercq et al. (2014) for a review of recent developments in MFD. Given the MFD of a network, monitoring and predicting the evolution of congestion is possible through the existing data technologies with fixed-location and mobile sensors (loop detectors and GPS of probe vehicles). It should be noted that the spread of