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A dynamic cordon pricing scheme combining the Macroscopic Fundamental Diagram and an agent-based traffic model

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ABSTRACT

Pricing is considered an effective management policy to reduce traffic congestion in transportation networks. In this paper we combine a macroscopic model of traffic congestion in urban networks with an agent-based simulator to study congestion pricing schemes. The macroscopic model, which has been tested with real data in previous studies, represents an accurate and robust approach to model the dynamics of congestion. The agent-based simulator can reproduce the complexity of travel behavior in terms of travelers' choices and heterogeneity. This integrated approach is superior to traditional pricing schemes. On one hand, traffic simulators (including car-following, lane-changing and route choice models) consider travel behavior, i.e. departure time choice, inelastic to the level of congestion. On the other hand, most congestion pricing models utilize supply models insensitive to demand fluctuations and non-stationary conditions. This is not consistent with the physics of traffic and the dynamics of congestion. Furthermore, works that integrate the above features in pricing models are assuming deterministic and homogeneous population characteristics. In this paper, we first demonstrate by case studies in Zurich urban road network, that the output of a agent-based simulator is consistent with the physics of traffic flow dynamics, as defined by a Macroscopic Fundamental Diagram (MFD). We then develop and apply a dynamic cordon-based congestion pricing scheme, in which tolls are controlled by an MFD. And we investigate the effectiveness of the proposed pricing scheme. Results show that by applying such a congestion pricing, (i) the savings of travel time at both aggregated and disaggregated level outweigh the costs of tolling, (ii) the congestion inside the cordon area is eased while no extra congestion is generated in the neighbor area outside the cordon, (iii) tolling has stronger impact on leisure-related activities than on work-related activities, as fewer agents who perform work-related activities changed their time plans. Future work can apply the same methodology to other network-based pricing schemes, such as area-based or distance-traveled-based pricing. Equity issues can be investigated more carefully, if provided with data such as income of agents. Value-of-time-dependent pricing schemes then can also be determined.

1. Introduction

To alleviate traffic congestion in cities, congestion pricing has been proposed by researchers and policy makers as an effective traffic management policy, with direct applications to cities, e.g. London, Singapore and Stockholm. The intention of pricing is to change travelers' behavior choice, such as departure time, route or mode choice and to reduce congestion by

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charging users for the external costs they create. A comprehensive literature summary of congestion pricing models can be found in Yang and Huang (2005). The theoretical background of pricing has relied on the fundamental concept, first introduced by Pigou (1920) and followed by Vickrey (1963) and other researchers: if on each link of a network a toll is charged, which equals to the additional congestion cost imposed on other users by an extra traveler, the sum of consumer surplus and total revenue is maximized. In the traffic assignment literature tolls of this type belong to the first-best pricing and have been proposed to drive a user equilibrium pattern (Wardrop, 1952) towards a system optimum. Despite their idealized theoretical basis, first-best pricing models have been impractical and difficult to implement. Merchand (1968) investigated second-best tolls using a general equilibrium model. According to the second-best pricing models, e.g. Arnott et al. (1990), Small and Yan (2001), Verhoef (2002), tolls are charged in a subset of selected links where the bottlenecks are. Demand pattern changes, e.g. departure time choice or mode choice, as the "utility" of travelers changes for a given toll. For example, in Vickrey's model (1969) a traveler experiences a utility cost of waiting in the queue and a penalty, "schedule delay", which is the difference between the actual time passing the destination and the desired time; accordingly. The traveler may adjust his departure time to avoid high schedule delay. Equilibrium is obtained when no individual has an incentive to alter his departure time. Arnott et al. (1988) extended the schedule delay concept with heterogeneous travelers, however applied at a single bottleneck only and without pricing. The common inadequacies of the existing models include: (i) user heterogeneity is not well dealt with, e.g. "utility" is identical for all travelers, while in reality utilities varies in trip purpose, desired arrival time, willingness to pay, etc., (ii) demand elasticity is limited to departure time and route choice where in reality mode choice and travel or not travel are also important components and (iii) Pigouvian-type tolls assume a network supply curve (desired or input demand vs. average travel cost) which is not consistent with the physics of traffic (Geroliminis and Levinson, 2009).

The second issue of pricing is that charging individual links is difficult to implement. Instead, pricing schemes of aggregated links and networks have been developed and applied in different cities (Zhang et al., 2008). Recently, Maruyama and Sumalee (2007) compared the performance of cordon- and area-road pricing schemes regarding their efficiency and equity. Anderson and Mohring (1997) examined congestion on the Twin Cities road network having drivers face marginal rather than average costs to reflect optimal prices using a user equilibrium assignment for a single period. Yang and Huang (1998) examined the principle of marginal-cost pricing in a road network. The basic ambiguity in most of these models is that traffic conditions are considered stationary. Furthermore, the traditional network supply curve for congestion pricing modeling, relating input demand to average travel cost, is not consistent with the physics of traffic. This is because (Geroliminis and Levinson, 2009) for a given desired demand over a period of time, the total cost expressed in delay terms (i) is sensitive, during congested conditions, to small variations of flow within the given period and (ii) depends on the initial state of the system and the level of congestion. On the other hand, it has been broadly shown through simulation and field experiments (e.g., Munoz and Daganzo, 2003; Helbing et al., 2009; Geroliminis and Daganzo, 2008) that the linkage between pertinent variables flow, speed and density on a spatially disaggregated level (one link) is very scattered and does not follow a well-defined curve. One of the reasons is that traffic systems are not in steady-state conditions at a link level. Thus, the estimated congestion toll based on idealized versions of these curves may not be optimal and the system may be either still congested if under-priced or very uncongested if overpriced. According to the same research, a Macroscopic Fundamental Diagram (MFD) model can better capture traffic behavior on an aggregated level, say an urban network, without the detailed knowledge of conditions in individual links. It was recently observed from empirical data that by spatially aggregating the highly scattered plots of flow vs. density from individual loop detectors in networks (roughly) homogeneously loaded with traffic, the scatter almost disappeared and a well-defined Macroscopic Fundamental Diagram exists between space-mean flow and density. The homogeneity of traffic conditions assumed in each aggregated network is also consistent with the homogeneity that applies to flow and density when dealing with road congestion in urban economic models (Small and Chu, 2003; Arnott, 2007; Arnott and Inci, 2010).

Recently, Geroliminis and Levinson (2009) combined Vickrey's theory with a macroscopic traffic model to identify the equilibrium solution for a congested network in the no-toll case. A dynamic model of cordon-based congestion pricing (such as for the morning commute) for networks was also developed consistent with the physics of traffic. In comparison to the bottleneck model, in the network case the optimal length of the toll period was found to be smaller than the congestion period in the no-toll case and the total delay savings to be higher than the total toll paid. The above work assumes deterministic and homogeneous population characteristics. This might result in non-optimal estimated tolls. Agent-based models are possible solutions for representing demand elasticity and heterogeneity. This is because (i) activity-based demand generation is utilized. Change in travel cost does not only influence travel behaviors of an agent but also his daily plan, which is a more realistic and accurate representation, (ii) agents have different value of utilities when they perform different activities, which introduce heterogeneity among agents, (iii) one agent's behavior affects other agents' decisions (Zhang et al., 2008) and (iv) lots of efforts have been made on realizing individual heterogeneity, e.g. different value-of-times and schedule-delays to agents. If the output of an agent-based model shows the property of the MFD, we can develop a dynamic network-wide congestion pricing schemes controlled by a macroscopic tool. This approach is more robust since tolls are determined based on traffic flow dynamics, rather than the traditional models based on demand–supply curves and marginal cost, which are sensitive to demand fluctuations and non-stationary conditions.

Empirical and simulation studies have been carried out to test and evaluate the effectiveness of different congestion pricing schemes at network level. For example Seik (2000) investigated the advantages of Singapore's Electronic Road Pricing, in term of efficiency, flexibility, equity, practical convenience, reliability, etc. De Palma et al. (2005) investigated the welfare gains and the resulting behavioral changes (such as departure time shift) of first-/second-best pricing schemes in METROP-