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Learning Marginal-Cost Pricing via Trial-and-Error Procedure with Day-to-Day Flow Dynamics

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Abstract

This paper investigates the convergence of the trial-and-error procedure to achieve system optimum by incorporating day-to-day evolution of traffic flows. The path flows are assumed to follow a so-called ‘excess travel cost dynamics’ and evolve from dis-equilibrium states to the equilibrium day by day. With this consideration, the observed link flow pattern during the trial-and-error procedure is in disequilibrium. With certain assumptions on the flow evolution dynamics, we prove that the trial-and-error procedure is capable of learning the system optimum link tolls without requirement of explicit knowledge on the demand functions and flow evolution mechanism. A methodology is developed for updating the toll charges and choosing the inter-trial periods to assure convergence of the iterative approach towards the system optimum. Some numerical examples are conducted to support the theoretical findings.

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1. Introduction

As rational road users selfishly minimize their own travel cost, the user equilibrium (UE) flow patterns usually deviate from the system optimum (SO), which describes the status of minimal total travel time in a traffic network. To achieve this system optimum state, researchers have dedicated to design appropriate mechanisms, among which is the well-known first-best road pricing scheme. It is increasingly believed that road pricing may offer an effective and efficient instrument to relieve traffic congestion, reduce vehicular emissions, manage travel demand and achieve transportation sustainability. The initial idea of road pricing can trace back to Pigou (1920) and the followers such as

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Walters (1961), Beckmann (1965) and Vickrey (1969). In the context of a congested network, various mathematical models and algorithms have been proposed to determine the SO link tolls. Comprehensive reviews can be found in Yang and Huang (2005), and de Palma and Lindsey (2011). In comparison with the booming development in the academia, the implementation of congestion pricing is only limited in a dozen of cities, the rejected proposals are far more than the cases in use. Besides the political reasons, from the perspective of practical implementation, there may be other barriers that impede the promotion of congestion pricing from a purely economic concept to a comprehensive and practical traffic regulation policy.

Exact calculation of the first-best tolls requires explicit and analytical demand functions, which are difficult to establish in practice (Walters, 1961), and the commonly-used linear or exponential demand functions are usually too arbitrary and not convincing (Li, 2002). Fortunately, this issue can be circumvented and the congestion pricing can still proceed on a trial-and-error basis without demand functions. This enlightened idea was proposed by Vickrey (1993) and Downs (1993) and accomplished for the first time when Li (1999, 2002) gave an iterative bi-section algorithm that can be applied to a homogeneous traffic stream along a single expressway. The trial-and-error method allows a traffic planner to estimate or update the tolls easily by using readily available traffic count data while requiring the travel cost functions only. In the same spirit, Yang et al. (2004) suggested an algorithm based on the method of successive average (MSA) (Powell and Sheffi, 1982) and presented a rigorous theoretical proof of its convergence in a general network, which was later modified by Han and Yang (2009) with a faster convergence. Yang et al. (2005) developed a sequential bi-level programming approach for iteratively estimating traffic demand information (demand matrix or demand functions) and optimizing link tolls to deal with the second-best road pricing problem with unknown demand functions. Meng et al. (2005) and Yang et al. (2010) employed the trial-and-error method in the traffic-restrained road pricing problems. Wang and Yang (2012) and Wang et al. (2013) fixed a non-convergence issue of the bisection method in Li (2002) and further adapted it to implement the tradable travel credit schemes for network mobility management. Xu et al. (2013) developed a trial-and-error pricing scheme on a network with multiple interacted vehicle types and multiple time periods with interdependent demands. Zhou et al. (2014) proposed a unified framework of the trial-and-error congestion pricing scheme for achieving capacity restraint and system optimum.

The trial-and-error method obviates the requirement for analytical demand functions and has been proved to be efficient and promising. A critical underlying assumption in most of the above-mentioned trial-and-error methods is the existence and immediate appearance of user equilibrium for any given toll charges (Yang et al., 2004), which is idealized and in some degree too restrictive in practice. The incontestable fact is that traffic flow on a certain road or path changes from day to day. Once a pricing scheme is imposed or altered, travelers take time to learn and adjust their trip-making decisions in a new pricing environment. More realistically, even if the road users can be quickly informed of altered toll charges and a new equilibrium is reachable, the network flows may tend to temporarily evolve towards a new stable state in response to the adjustment of road pricing schemes. As a result, it is very likely that the link flows observed by the planner may not be in equilibrium at any arbitrary time. In this situation, even if the trial-and-error procedure can also be adopted, its convergence should be reexamined. Thus there is a great need for the development of efficient road pricing methods in networks taking into account day-to-day flow dynamics. Yang and Zhang (2009) summarized a type of fixed-demand day-to-day dynamics as ‘rational behavior adjustment process’, which comprises some previous path-based models. The recent development on the day-to-day flow dynamics can be found in Watling and Cantarella (2013) and Ye and Yang (2013).

Yang and Szeto (2006) adopted a dynamic toll scheme in the network with the ‘rational behavior adjustment process’ to achieve SO by charging the marginal-cost tolls (Button, 1993) based on the instantaneous link flows. Yang et al. (2007) suggested that, imposing the tolls corresponding to the steepest descent direction of the total system cost could accelerate the system’s convergence to SO. Sandholm (2002) recommended a dynamic pricing mechanism to achieve the SO tolls without knowing the exact demand information in the network with the excess payoff dynamics. Guo (2013) proposed a toll strategy to achieve the target flow pattern in a network with boundedly rational user equilibrium. Yet, the above-mentioned limited number of dynamic pricing schemes under flow evolution either requires that the tolls can be adjusted (continuously or daily) in response to the change in road flows or that (at least part of) the explicit mechanisms of the networks flow evolution are known to the social planner. These assumptions are restrictive in actual implementation. A piecewise constant dynamic pricing scheme is a better

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