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A hybrid implementation mechanism of tradable network permits system which obviates path enumeration: An auction mechanism with day-to-day capacity control ☆

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ABSTRACT

Akamatsu (2007a,b) proposed a new dynamic traffic congestion control scheme called *tradable network permits*, and demonstrated its efficiency properties for general road networks. To implement tradable permit markets, this paper proposes a novel auction mechanism with capacity control. This mechanism employs an evolutionary approach to achieve a dynamic system optimal allocation of network permits in a computationally efficient manner. We prove that the proposed mechanism has the following desirable properties: (i) truthful bidding is a dominant strategy for each user on each day and (ii) the permit allocation pattern under the mechanism converges to a dynamic system optimal allocation pattern.

1. Introduction

Congestion pricing is considered an effective economic instrument for managing traffic congestion, and various types of pricing schemes have been proposed since the pioneering work of Pigou (1920) (see Yang and Huang, 2005; Tsekeris and Voß, 2009; de Palma and Lindsey, 2011, for comprehensive reviews and other references). Although these schemes work effectively in ideal situations, almost all of them fail to take into consideration the important fact that *asymmetric information* exists between road managers and road users. For instance, in standard congestion pricing, the road manager requires accurate and detailed demand information (e.g., the desired arrival time and value of time) to calculate optimal toll levels, but it is almost impossible for the manager to obtain such private information. This lack of information may distort toll levels and inevitably result in economic losses.

As an alternative to price-based regulation such as congestion pricing, there is another economic instrument called *tradable permits* scheme, which is a generalization of quantity-based regulation.[1] This scheme directly regulates traffic flows by assigning priority-service permits to road users, which has great potential for not only reducing traffic congestion but also resolving the asymmetric information problem. As an example of such a scheme, Akamatsu et al. (2006) and Akamatsu (2007a,b) proposed a new dynamic traffic congestion control scheme called *tradable network permits*, which does not require

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[1] See, for example, Weitzman (1974) and Laffont (1977) for general discussions on the comparison between price-based and quantity-based regulation in the field of economics.

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detailed user information. This scheme consists of two parts: (a) the road manager issues a right (network permit) that allows the permit holder to pass through a bottleneck during a prespecified time period and (b) a trading market is established for network permits differentiated by prespecified time. Under this scheme, queuing congestion can be completely eliminated for each bottleneck by issuing a number of network permits that is less than its capacity. For allocating the permits to users, there are two representative schemes: the *market selling scheme* and the *free distribution scheme*. In the market selling scheme, the road manager sells all the permits to users through the trading markets. In the free distribution scheme, the road manager initially distributes all the permits to users for free according to methods that consider the equity among users. In this scheme, the permits allocated for each user does not necessarily match one's own desired permit. For that case, users can mutually trade permits in the trading markets. With both schemes, the asymmetric information problem is resolved through the trading markets. Furthermore, Akamatsu et al. (2006) demonstrated that under both permit-allocating schemes the equilibrium achieves the most efficient (i.e., Pareto optimal) resource allocation for a single bottleneck, and Akamatsu (2007a,b) extended this property to general networks.[2]

Although the efficiency of the tradable network permits was established by assuming that a competitive equilibrium can be achieved in the trading markets, no concrete trading mechanism that attains the equilibrium was demonstrated in the above studies. In other words, trading processes were treated as a black-box. Thus, in order to implement tradable network permits, it is necessary to establish a micro-mechanism for the trading markets. It should be noted that in terms of efficiency of resource allocation, the above two permit-allocating schemes are essentially identical. Therefore, as the first step in trading markets design, this paper focuses on the market selling scheme to achieve an efficient allocation as simply as possible.[3] In this regard, Wada and Akamatsu (2010) and Wada et al. (2010) designed an auction mechanism for a trading market for a single bottleneck and showed the following: (i) the network permit allocation pattern achieved under the mechanism is efficient and (ii) the mechanism is strategy-proof, which means that a dominant strategy employed by each user is truthful revelation of the value of permits. However, extending the auction mechanism to general networks is not a trivial problem, because a naïve formulation of the problem leads to NP-hardness owing to the complex relationship between link and path.

This paper proposes a novel auction mechanism to implement trading markets on general networks with multiple origin–destination (OD) pairs. Assuming that each user makes a trip from an origin to a destination via a certain path and in a specific time period, we design an auction mechanism that enables each user to purchase a bundle of network permits corresponding to a set of links on the user's preferred path. We first briefly discuss how the Vickrey–Clarke–Groves (VCG) mechanism, which is a benchmark mechanism in auction theory (e.g., Milgrom, 2004), cannot possibly be applied to the trading markets because the combinatorial optimization problem of finding a network permits allocation pattern is NP-hard. To avoid such computational infeasibility, we propose an auction mechanism that is readily implementable. This mechanism employs an evolutionary approach that decomposes the combinatorial optimization problem into two phases, an auction phase and a path capacity adjustment phase, which are repeated on a day-to-day basis. The path capacity is defined as the number of bundles of permits for the path. In the former phase, the manager fixes each path capacity and sells the bundles to users through an ascending auction. In the latter phase, the road manager adjusts each path capacity to an appropriate level by exploiting bundle prices determined in the auction phase. We then prove that the proposed mechanism has the following desirable properties: (i) truthful bidding is a dominant strategy for each user on each day and (ii) the permit allocation pattern under the mechanism converges to an approximate dynamic system optimal allocation pattern in the sense that the social surplus reaches its maximum value when the number of users is large. Finally, we show that the proposed mechanism can be extended to obviate path enumeration by introducing a column generation procedure.

The rest of this paper is organized as follows: Section 2 discusses related work. Section 3 outlines the framework of the tradable network permits scheme and describes assumptions used throughout the paper. Section 4 defines a dynamic system optimal allocation of network permits and discusses the impossibility of applying the VCG mechanism to the trading markets due to NP-hardness. Section 5 presents ideas for a novel auction mechanism that is readily implementable for general networks. Section 6 gives details of the proposed mechanism and clarifies its properties. Section 7 presents an extended mechanism which obviates path enumeration by exploiting a column generation procedure. Section 8 demonstrates the convergence properties of the proposed mechanism through a numerical example. Section 9 concludes the paper.

2. Related work

Our study is mainly concerned with dynamic traffic assignments (DTA), some types of transportation demand management (TDM) schemes (i.e., dynamic congestion pricing schemes and tradable permits schemes), and combinatorial auctions. The first two areas provide an analytical framework for modeling and managing traffic congestion in transportation networks, whereas the third area provides a foundation for constructing an auction mechanism to implement trading markets. In particular, auctions for bundled items with network structure are relevant to our study.

[2] We can also generalize the theory to include supply side conditions. Specifically, Wada and Akamatsu (2012) proposed a distributed signal control policy based on the tradable network permits, which adjusts a green time proportion by exploiting permit prices.

[3] To implement the free distribution scheme, it is necessary to design a micro-mechanism for a double auction market in which trading strategies of users are more complex than those of one-sided auction.