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Trading mechanisms for bottleneck permits with multiple purchase opportunities☆

Pengfei Wang[a,b,*], Kentaro Wada[c,*], Takashi Akamatsu[d], Takeshi Nagae[e]

[a] Beijing Key Laboratory of Transportation Engineering, Beijing University of Technology, 100 Pingleyuan, Chaoyang District, Beijing 100124, China
[b] College of Urban Construction, Hebei Normal University of Science and Technology, 360 Western Section of Hebei Avenue, Haigang District, Qinhuangdao, Hebei 066004, China
[c] Institute of Industrial Science, The University of Tokyo, Komaba 4-6-1, Meguro-ku, Tokyo 153-8505, Japan
[d] Graduate School of Information Sciences, Tohoku University, Aramaki Aoba 6-3-09, Aoba-ku, Sendai, Miyagi 980-8579, Japan
[e] Graduate School of Engineering, Tohoku University, Aramaki Aoba 6-6, Aoba-ku, Sendai, Miyagi 980-8579, Japan

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ABSTRACT

This paper extends the theory of tradable bottleneck permits system to cases with multiple period markets and designs its implementation mechanism. The multiple period markets can achieve more efficient resource allocation than a single period market when users' valuations of tradable permits change over time. To implement the multiple period trading markets, we propose an evolutionary mechanism that combines a dynamic auction with a capacity control rule that adjusts a number of permits issued for each market. Then, we prove that the proposed mechanism has the following desirable properties: (i) the dynamic auction is strategy-proof within each period and guarantees that the market choice of each user is optimal under a perfect information assumption of users and (ii) the mechanism maximizes the social surplus in a finite number of iterations. Finally, we show that the proposed mechanism may work well even for an incomplete information case.

1. Introduction

1.1. Background and purpose

Transportation demand management schemes can be roughly divided into two types: "price-based regulation" and "quantity-based regulation." As a representative of the former, congestion pricing is theoretically desirable for reducing traffic congestion in a distributed manner. However, in order to calculate the optimal toll levels, the road manager requires detailed and accurate demand information of all users. It is almost impossible for the road manager to obtain such private information due to an asymmetric information between road managers and road users. Therefore, it is difficult to guarantee the effect of the road pricing scheme.

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* Corresponding authors at: Beijing Key Laboratory of Transportation Engineering, Beijing University of Technology, 100 Pingleyuan, Chaoyang District, Beijing 100124, China (P. Wang). Institute of Industrial Science, The University of Tokyo, Komaba 4-6-1, Meguro-ku, Tokyo 153-8505, Japan (K. Wada).

E-mail addresses: wpf_plan_civil@163.com (P. Wang), wadaken@iis.u-tokyo.ac.jp (K. Wada), akamatsu@plan.civil.tohoku.ac.jp (T. Akamatsu), nagae@m.tohoku.ac.jp (T. Nagae).

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As a representative of the latter scheme, we can take highway booking/reservation for examples (e.g., Akahane and Kuwahara, 1996; Wong, 1997; Akahane et al., 2000; Teodorović and Edara, 2005). This type of schemes can achieve a quantitative policy target without requiring detailed user information. However, there may be cases in which road users cannot select their desired choice if the permits (or allocations) are assigned according to unrefined rules. Such an infringement on freedom of choice necessarily causes economic losses. However, with the progress of communication technology and the popularization of information and communication technology/intelligent transportation systems, it is not difficult to establish the mechanism in which the users can select his/her desired choice free.

As one possible way to eliminate bottleneck congestion and to resolve the above information and choice problems simultaneously, Akamatsu et al. (2006) proposed a novel system of "tradable bottleneck permits." Their proposed scheme comprises two parts: (a) the road manager issues a right (bottleneck permits) that allows the permits holders to pass through a bottleneck during a pre-specified time interval, (b) a trading market is established for bottleneck permits that are differentiated on the basis of a pre-specified time. Under this scheme, the queuing congestion can be completely eliminated by setting the number of permits issued per unit time interval to be less than or equal to the bottleneck capacity. In addition, because of the part (b), users can select their desired permit freely. Furthermore, the equilibrium under the scheme is efficient and achieves Pareto improvement for both the road manager and all users. The properties of the scheme for general networks have been explored in Akamatsu (2007) and Akamatsu and Wada (2017).

In order to implement the trading markets for the bottleneck permits, Wada and Akamatsu (2010, 2011, 2013) designed an auction mechanism for single bottleneck/general networks. Then, they showed that (i) the bottleneck permits allocation achieved by the mechanism is efficient and (ii) the mechanisms are strategy-proof (a dominant strategy employed by each user is the truthful revelation of the value of the permits).

However, the previous studies do not explicitly treat that when road users would participate in trading markets or when the transaction would be established before their trips (they implicitly assumed that all of the users would gather in the markets on the day before making trips). This single purchase opportunity assumption would be reasonable for the first step of analyzing "efficient" implementation mechanisms of the trading markets. Meanwhile, the travel flexibility and convenience for an individual also have to be considered for implementations. One of the examples in this direction is to design the multiple period markets enhancing the flexibility of users' decision making.[1] Furthermore, if the users' valuations for the permits change over periods for some reasons, the multiple period markets can achieve more efficient resource allocation than a single period market.

The purpose of this study is to design an implementation mechanism of tradable bottleneck permits scheme with multiple purchase opportunities for a single bottleneck network. Firstly, assuming that the users' valuations for permits change depending on the purchase periods, we present the framework of the multiple periods scheme. Under this scheme, the road manager sets the number of permits in each market, while the users select the purchase period and time interval of permits (arrival time). We then propose a mechanism to implement the multiple periods markets. In this mechanism, the adjustment of the number of permits (adjustment phase) and permits allocation phase (auction phase) are repeated. We prove that the proposed evolutionary mechanism has the following desirable properties: (i) the dynamic auction for multiple period markets is strategy-proof within each period and guarantees that the market choice of each user is optimal under a perfect information assumption of users and (ii) the mechanism achieves the optimal social allocation in a finite number of iterations. Finally, we show that the proposed mechanism may work well even for an incomplete information case.

1.2. Literature review

The scheme considered in this research corresponds to introducing a reservation system to the conventional tradable bottleneck permits scheme. Reservation systems have been widely studied in the field of revenue management for many years (see Talluri and vanRyzin, 2004 and Chiang et al., 2007, for comprehensive reviews of the literature). Moreover, in the transportation field, much research has been performed on the theory and practice of reservation systems (e.g., airline seat reservations, see Kobayashi et al., 2008). Almost all of the above studies have aimed at maximizing revenue or social surplus by market segmentation and discriminatory pricing. However, as we previously stated, it is difficult to determine an optimal price because there is an asymmetric information between suppliers (road managers) and buyers (road users).

One of the approaches to resolve the asymmetric information problem is to employ auction mechanisms. In the transportation field, for example, Teodorović et al. (2008) proposed a concept of a new demand management scheme called auction-based congestion pricing. Lam (2016) and Hara and Hato (in press) found that the simple Vickrey-Clarke-Groves (VCG) mechanism (Vickrey, 1961; Clarke, 1971; Groves, 1973) is an effective approach to achieve the optimal resources allocation for the transportation system. In addition, some simulation studies have demonstrated the quantitative impacts of the auction-based tolling system such as revenue generation and total travel time saving (see Peng and Park, 2015; Basar and Cetin, 2017). However, these studies did not deeply discuss the efficient trading mechanism under the multiple trading opportunities.

Recently, in the field of mechanism design/auction theory, much effort has been put into extending the theory to dynamic settings (Parkes, 2007; Bergemann and Said, 2011). Cavallo et al. (2006) and Bergemann and Välimäki (2010) considered the time-varying users' valuations and generalized the static VCG mechanism to a dynamic setting (*dynamic pivot mechanism*). They proved that the mechanism achieves the efficient resource allocation and satisfies the ex-post incentive compatibility. However, they did not consider an adjustment problem of the number of items for each period (i.e., the number is fixed in advance). Hence, a trading mechanism that combines a dynamic auction and an adjustment rule is a major contribution of this study.

Another stream of research relevant to the tradable bottleneck permits is about the "tradable travel credit" scheme proposed by

[1] Another example is to design cancelation rules (see Nagae and Gai, 2009 for example).