Transportation Research Part C 79 (2017) 178–195

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Tradable network permits: A new scheme for the most efficient use of network capacity

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ARTICLE INFO

Article history:
Received 10 November 2016
Received in revised form 6 March 2017
Accepted 14 March 2017

Keywords:
Bottleneck congestion
Dynamic traffic assignment
Time-space network
Tradable permit
ITS

ABSTRACT

Akamatsu et al. (2006) proposed a new transportation demand management scheme called "tradable bottleneck permits" (TBP), and proved its efficiency properties for a single bottleneck model. This paper explores the properties of a TBP system for general networks. An equilibrium model is first constructed to describe the states under the TBP system with a single OD pair. It is proved that equilibrium resource allocation is efficient in the sense that the total transportation cost in a network is minimized. It is also shown that the "self-financing principle" holds for the TBP system. Furthermore, theoretical relationships between TBP and congestion pricing (CP) are discussed. It is demonstrated that TBP has definite advantages over CP when demand information is not perfect, whereas both TBP and CP are equivalent for the perfect information case. Finally, it is shown that the efficiency result also holds for more general demand conditions.

1. Introduction

Recent advances in information and communication technology (ICT) have led to rapid changes in the "virtual" world represented by the internet. The increasing capabilities and decreasing cost of ICT is now becoming the impetus for changing the "real" world. The effects of ICT on transportation systems are no exception. The broadly defined "Intelligent Transportation Systems (ITS)" that exploits ICT has a large potential for dramatically improving efficiency of road transportation systems if the systems are implemented together with appropriate transportation demand management (TDM) schemes.

As an example of such futuristic TDM schemes making the most of ICT/ITS, Akamatsu et al. (2006) proposed the "tradable bottleneck permit" (TBP) system. Their proposed scheme is designed for resolving the problem of congestion during the morning rush hour at a single bottleneck, and consists of the following two parts:

(*a*) the road manager issues a right that allows a permit holder to pass through the bottleneck at a pre-specified time period ("bottleneck permits"),
(*b*) a new trading market is established for bottleneck permits differentiated by a pre-specified time.

Note here that both parts (*a*) and (*b*) of this scheme are feasible for implementation from a technical point of view, even at the present time. The system for handling part (*a*) may be constructed as an application of the dedicated short range communication (DSRC) system that is used in the current electric toll collection (ETC) system; the trading markets in part (*b*) also

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http://dx.doi.org/10.1016/j.trc.2017.03.009
0968-090X/

can be realized inexpensively by using internet auction markets. It is, therefore, reasonable to assume that implementing this scheme will become technically easier when we take into account the future advances of ICT/ITS.

Part (*a*) of this scheme is almost the same as the concept of "advance highway booking" (reservations or quotas) that is one of the *quantity-based regulation schemes* and has been previously proposed by several authors (e.g., Akahane and Kuwahara, 1996; Wong, 1997; Teodorović and Edara, 2005; Liu et al., 2015). Under this scheme, the arrival flow at a bottleneck at any time period is, from the definition of the scheme, equal to the number of permits issued for that time period. This implies that we can completely eliminate the occurrence of queuing congestion by setting the number of permits issued per unit time to be less than or equal to the bottleneck capacity. However, there may be cases in which road users cannot choose their desired time for using the road if the permits are assigned according to some unrefined rule (e.g., a simple "quota" scheme). Such an infringement on freedom of choice necessarily causes economic losses and should not be socially acceptable. In order to circumvent this problem that arises in employing only part (*a*) of the scheme, we need to add an appropriate mechanism in which each user can choose his or her desired permit. It is part (*b*) of the scheme that gives the foundation for this "choice mechanism" by a market system for buying and selling permits.

With the complementary properties of parts (*a*) and (*b*) in the combined scheme above, we can expect that this is the most efficient scheme of using the limited resource of road capacity. Indeed, for a departure-time choice equilibrium problem with a single bottleneck (Vickrey, 1969), Akamatsu et al. (2006) showed that the proposed system has the following desirable properties: (1) comparing equilibrium states with and without the proposed system, we can achieve Pareto improvement for both the road manager and all road users, (2) the equilibrium with the proposed system achieves the most efficient (i.e., Pareto optimal) resource allocation, (3) the "self-financing principle" holds for the equilibrium with the proposed system—that is, the total revenue (market value) of selling the permits is equal to the investment cost required for increasing the bottleneck capacity to a socially optimal level.

These properties of the tradable permit system are proved only for a road with a single bottleneck. Specifically, the proof is based on the isomorphism between the commuters' departure-time choice equilibrium in a single bottleneck model and an equilibrium model of an urban residential location (see, for example, Fujita, 1989). Since such isomorphism cannot be extended to a case with multiple bottlenecks, the properties of the tradable permit system for general networks are largely unknown.

The purpose of this paper[1] is to explore some of the properties of a system of tradable bottleneck permits for general networks (we call this a system of "tradable network permits."). To attain this purpose in a clear manner, we consider ideal situations[2]; whereas practical and implementation issues for the tradable network permits are discussed accordingly. Specifically, after defining the system of a tradable network permit, we present a mathematical model that describes the equilibrium that arises under the tradable permit system. We then prove that the equilibrium resource allocation under the system is efficient in the sense that the total transportation cost in a network is minimized: formulating a dynamic system optimal assignment, we show that the equilibrium assignment coincides with the optimal assignment. We also prove that the "self-financing principle" holds not only for the single bottleneck case but also for the general network case. We further show the theoretical relationship between the tradable permit system and congestion pricing: we demonstrate the definite advantages of the tradable permit system over congestion pricing when the demand information is not perfect, whereas they are equivalent for the perfect information case.

The organization of this paper is as follows. In Section 2, we briefly review related works. In Section 3, we outline the framework of the tradable permits system analyzed in this paper. In Section 4, we present a model of the equilibrium under the tradable network permit system with a single OD pair. In Section 5, we analyze the efficiency of the equilibrium allocation. We also show that the self-financing principle holds for the tradable network permits system. In Section 6, we discuss the theoretical relationship between the tradable permit system and congestion pricing. Section 7 extends the model to the case with general demand conditions. Finally, Section 8 concludes the paper.

2. Related works

In general, there are two types of regulation schemes to eliminate economic inefficiency due to market externalities: *price-based* and *quantity-based* regulation schemes. For the choice of regulation schemes, "asymmetric information" between a regulation authority and firms is an essential issue that should be taken into account. The general discussion on this issue was given by Weitzman (1974) and Laffont (1977); a well-known application of this theory is the environmental policy choice between a tax and a quotas (or a tradable permits scheme[3]). The theory, however, cannot apply to traffic congestion problems directly because mechanisms of externalities for environmental problems are different from bottleneck congestion. For the dynamic traffic congestion problem, the detailed comparisons between congestion pricing and tradable network permits are given in Section 6.

Dynamic traffic assignment literature has been only focused on the price-based regulation scheme "dynamic congestion pricing" for eliminating bottleneck congestion. For simple networks such as single bottleneck or parallel link networks, the

[1] This paper is an enhanced version of the working paper (Akamatsu, 2007).

[2] This is a natural first step when progressing the theory. For example, although the congestion pricing in the first best case (e.g., general networks in which congestion tolls are imposed on every link) may be impractical, the theory has been well systematized thanks to such an ideal assumption.

[3] See, for example, Montgomery (1972) and Tietenberg (1980), for tradable permits schemes for environmental protection.