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A novel permit scheme for managing parking competition and bottleneck congestion

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ABSTRACT

Morning commuters may have to depart from home earlier to secure a parking space when parking supply in the city center is insufficient. Recent studies show that parking reservations can reduce highway congestion and deadweight loss of parking competition simultaneously. This study develops a novel tradable parking permit scheme to realize or implement parking reservations when commuters are either homogeneous or heterogeneous in their values of time. It is found that an expirable parking permit scheme with an infinite number of steps, i.e., the ideal-scheme, is superior to a time-varying pricing scheme in the sense that designing a permit scheme does not require commuters' value of time information and the performance of the scheme is robust to the variation of commuters' value of time. Although it is impractical to implement the ideal-scheme with an infinite number of steps, the efficiency loss of a permit scheme with finite steps can be bounded in both cases of homogeneous and heterogeneous commuters. Moreover, considering the permit scheme may lead to an undesirable benefit distribution among commuters, we propose an equal cost-reduction distribution of parking permits where auto commuters with higher value of time will receive fewer permits.

1. Introduction

Parking policy has been known for long as a powerful and efficient tool for transportation management (Young et al., 1991). In a static stochastic traffic assignment model, Bifulco (1993) introduced parking search times, types and fees for the evaluation of various parking policies. Arnott and co-authors have developed a series of economic analyses of downtown parking over the years (e.g., Arnott et al., 1991; Arnott and Rowse, 2009; Arnott and Inci, 2010). Besides, many researchers have investigated parking fee as an instrument to help manage traffic. (e.g., Glazer and Niskanen, 1992; Verhoef et al., 1995; Anderson and de Palma, 2004; Zhang et al., 2008; Qian et al., 2012; Fosgerau and de Palma, 2013).

Qian et al. (2011) pointed out that parking availability will affect commuters' choices of travel mode, route and departure time. In the same spirit of tradable mobility credits proposed by Yang and Wang (2011), Zhang et al. (2011) proposed a parking permits distribution and trading scheme for managing the morning commute when parking supply in the downtown is insufficient. More recently, Yang et al. (2013) proved that, when the parking supply is inadequate to accommodate the potential auto demand, retaining some parking spaces open for competition while keeping others for reservation can smooth out commuters' arrivals to the highway bottleneck and thus reduce the total system cost. For the same problem, an

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accompanying paper, Liu et al. (2014), proposed a more elaborate parking reservation scheme where reservations may expire at pre-determined times. They showed that if differentiated expiration times are properly designed, the morning peak will be further smoothed out and the total social cost can be further reduced.

In this paper, we propose a novel tradable parking permit scheme to realize parking reservations of commuters, and thus to manage both parking competition and bottleneck congestion. The proposed permit scheme is different from that in Zhang et al. (2011) on several aspects: first, parking reservations considered here can be either expirable or non-expirable, thus the corresponding parking permits for reservation would also be either expirable or non-expirable. Secondly, this study considers the socially optimal supply of parking permits (as well as parking reservation) while Zhang et al. (2011) only considers reserving all available parking spaces to commuters. Also, we extend the studies by Yang et al. (2013) and Liu et al. (2014) by taking into account commuters' heterogeneity in their value of time (VOT). In reality, people's VOT varies, and commuters with different VOT may respond to the parking space constraint and the parking permit scheme differently. Lastly, since commuters are heterogeneous, a parking permit scheme may lead to an undesirable distribution of benefit among the commuters. Such equity issues has been observed in previous studies when considering congestion pricing with both static models (e.g., Glazer, 1981; Evans, 1992) and dynamic models (e.g., Cohen, 1987; Arnott et al., 1994; Xiao and Zhang, 2013). Efforts have been made to achieve better equity (e.g., Wu et al., 2012; Xiao et al., 2013). In this study, we would also explore the distribution of parking permits to achieve a more equitable benefit distribution among commuters.

We consider that two competing modes, a highway and a parallel transit line, connect a residential area to the Central Business District (CBD). For the highway, bottleneck congestion is considered in order to make our model more tractable. Vickrey (1969) firstly introduced the bottleneck model of congestion dynamics. Smith (1984) and Daganzo (1985) then established the existence and uniqueness of the time-dependent equilibrium distribution of arrivals at a single bottleneck respectively. Arnott et al. (1990) provided a thorough economic analysis of the bottleneck model and showed that congestion tolls can generate efficiency gains by altering the frequency distribution of departure times. The bottleneck model has been adopted to study various issues. For recent comprehensive reviews, see, e.g., Arnott et al. (1998) and de Palma and Fosgerau (2011).

The remainder of this paper is organized as follows. Section 2 considers the bi-modal equilibrium with homogeneous commuters, and examines tradable non-expirable and expirable parking permit schemes. In Sections 3, commuters' heterogeneity in VOT is introduced, and then the effects of tradable non-expirable and expirable parking permit schemes are discussed. In addition, welfare effects are explored and the equal cost-reduction permit distribution is introduced. Section 4 discusses road pricing to eliminate bottleneck congestion and deadweight loss of parking competition, and then compares it with the tradable expirable parking permit scheme. Finally, Section 5 concludes the paper and provides some discussions.

2. The case with homogeneous commuters

2.1. Basic setting

Suppose a fixed number of N commuters travel from home to the CBD every morning, and there are two competing modes: a bottleneck-constrained highway and a parallel transit line. We assume that all parking spaces are located at the CBD, and the walking time from parking spaces to workplace is ignored without loss of generality. The numbers of auto and transit commuters are denoted by N_a and N_b respectively, and $N = N_a + N_b$.

The generalized travel cost of an auto commuter consists of his or her fixed money cost, travel time cost and schedule delay cost. Departing at time t, the travel cost is given by

$$c_a(t) = p_a + \alpha \cdot T_a(t) + \beta(t^* - t - T_a(t)), \tag{1}$$

where p_a is the fixed money cost; $T_a(t)$ is the travel time; t^* is the desired arrival time at the destination, and α and β are the value of travel time and the marginal cost of early arrival respectively. Without loss of generality, the free-flow commute time is assumed to be zero, and thus $T_a(t)$ only contains the queuing time, i.e., $T_a(t) = q(t)/s$, where $q(t)$ is the queue length at the highway bottleneck at time t, and s is the service capacity of the bottleneck. In addition, according to empirical evidences and for the existence and uniqueness of the equilibrium, it is assumed that $\alpha > \beta > 0$. Also note that in this study, we assume late arrivals of commuters are not allowed and a discussion on the relaxation of this assumption will be presented in the last section.

For transit commuters, the travel cost consists of travel time cost and transit fare. The generalized travel cost of commuters by transit can be expressed as

$$c_b = p_b + \alpha T_b, \tag{2}$$

where p_b is the transit fare and T_b is the constant travel time on transit. Note that since we assume zero free-flow time on highway, T_b indeed represents additional travel time on transit compared with highway. It is assumed that $p_a - p_b > 0$, which means the fixed money cost of the auto mode is higher than the transit fare. Note that the schedule delay cost of transit commuters is ignored for simplicity since we want to focus on commuters' responses to the insufficient parking supply and auto mode.