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Tradable OD-based travel permits for bi-modal traffic management with heterogeneous users

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ABSTRACT

A tradable origin-destination (OD) based travel permits scheme is proposed to manage mobility in a bi-modal transportation network with heterogeneous users in value of time. The travel permits are OD-specific, initially allocated to eligible users by city authority, and then traded in a free market. The optimal permits supply is determined by solving a bi-level programming problem for minimizing the system's total cost. The market-clear conditions are formulated as a complementary problem, which in turn guarantees the modal split equilibrium. Extensions are made to the OD-independent permits, flexible car owning and heterogeneous transit crowding cases.

1. Introduction

Congestion, mainly caused by the mismatch between supply and demand, is becoming an increasingly serious problem worldwide. Due to the unrestricted use of private cars, the travel demand exceeds the capacity largely, resulting in more queue time wasted in the traffic network. How to relieve traffic congestion has become a hot issue for economists and transportation scholars. Intuitively, two ways can be used to resolve this issue: one is to enlarge network capacity (supply) to satisfy travel demand and the other is to maintain road space availability by guiding travel demand. However, the former has been proved to be self-defeating in the congested area because the newly enlarged capacity will soon be occupied by the induced demand (Goodwin, 1996; Hansen and Huang, 1997; Yang and Huang, 2005). Thus, more attentions have been turned into the latter one, guiding the demand for travel.

Nowadays, many large cities around the world are using simple quantity control policies to directly reduce road traffic. For example, the end-number license plate restriction has been introduced in Beijing since 2008. Under this restriction, vehicles are not allowed to drive on public roads (inside the 5th Ring Road of Beijing) for one day per week from 07:00 am to 20:00 pm. Owing to the coercive force of city authorities, these simple policies to a certain extent relieve traffic congestion. However, if we examine them from the perspective of economics, there may be much loss of social welfare under the quantity controls, which limit users from the use of their private properties, resulting that the road resource be not utilized by people who want most. Therefore, more efficient and equitable urban transport policies need to be developed to achieve sustainable development targets, such as road pricing and tradable travel credits/permits.

Road pricing has been studied for decades since the introduction of marginal theory by Pigou (1920), in which the optimal amount of pricing is defined as the difference between the marginal social cost and the marginal private cost (Beckmann, 1965; Dafermos and Sparrow, 1971). Yang and Huang (1998) analyzed the principle of marginal-cost pricing in a general traffic network

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and found that it still works when congestion tolls are charged for homogeneous travelers on all roadway links. Yang (1999) further extended this analysis to the case of stochastic user equilibrium. However, the marginal-cost pricing theory cannot be applied directly to real world because road users are heterogeneous in many aspects (Small and Yan, 2001; Brownstone and Small, 2005; Small et al., 2005; Cirillo and Axhausen, 2006). One of aspects is value of time (VOT). The VOT signifies the amount of money per hour that people are willing to pay in time saving. In a network with a discrete set of VOTs for several user classes, Yang and Huang (2004) found that a uniform link toll pattern based on marginal cost pricing can drive a multi-class network equilibrium to a system optimum in cost units. However, Marcotte and Zhu (2009) argued that the marginal cost pricing corresponding to link usage would be no longer valid when the VOT continuously varies across the population. Using the time difference-based pricing instead of marginal cost pricing, Wu and Huang (2014) derived anonymous path tolls to realize a system optimum flow pattern in a network with continuously distributed VOTs.

The marginal cost pricing or the time difference-based pricing aims at achieving a system optimum flow pattern, which implies all used roadway links or paths would be charged. Obviously, it is unpractical or much loss of privacy in reality even if all vehicles' trip trajectories are recorded through their GPS devices. In contrast, cordon pricing or zone-based pricing, which charges a fee to enter or drive within a congested area, has been practiced in Singapore and London due to its simplicity and feasibility (Nie, 2017). One of the alternatives lying in between is the OD-based pricing proposed by Ohazulike et al. (2013), which charges travelers based on their origin-destination (OD) information. Under this alternative, all travelers between the same OD pair will pay the same toll computed according to the minimal travel cost irrespective of their respective paths. When the OD-based pricing is implemented, the monitoring devices are installed at the origin and destination areas (entrance and exit of traffic network) to identify travelers' OD information by scanning electronic toll cards. This alternative can be regarded as a generalization of freeway network tolling or urban rail transit pricing, under which tolls or fares are mainly computed based on the shortest travel distance between entry and exit nodes.

Although congestion pricing has been implemented in a small number of cities, there are still some political resistances to its implementation worldwide. One of major concerns is that congestion pricing involves the financial transfer from travelers to city authority, which is thought as being less efficient in distributing or refunding toll revenue to travelers than the competitive market (Yang and Wang, 2011). Considering this, tradable travel permits or credit schemes, together with quantity control policies, have been recently advocated by transportation scholars (Verhoef et al., 1997; Zhang et al., 2011; Wada and Akamatsu, 2013; Akamatsu and Wada, 2017; Yang and Wang, 2011; Wang et al., 2012; Tian et al., 2013; Nie and Yin, 2013; Zhu et al., 2015; Jia et al., 2016; Miralinaghi and Peeta, 2016). Under these schemes, the city authorities predetermine the number of permits or credits for each roadway link or time period, and permits or credits can then be traded freely in a competitive market. In most situations, each city authority enacts only a role of supervisor in the whole trading process. One of the main differences between tradable permits and tradable credits is that travelers have to acquire all link permits (the number of permits on a link is mostly set in accordance with its capacity) along their respective chosen paths, and the trading prices of permits are link-specific, whilst they are charged different amount of credits for each roadway link under the single price of credits formed in the competitive market (Yang and Wang, 2011).

The successful implementation of tradable travel permits or credit schemes is closely related to advances in information technology and privacy protection. Although they probably have bright future, these schemes are still unadopted by city authorities and public till now. One of major reasons might be that they must be implemented on all used links in a road network, which are similar to link-based marginal cost pricing at this point. Certainly, it is possible to propose a second-best permits or credit scheme by adding some realistic constraints. For example, only part of roadway links or time periods are used to charge travelers in the second-best case, as done in Nie and Yin (2013). Following but different from Ohazulike et al. (2013), we propose an alternative tradable OD-based travel permits scheme to manage mobility in a bi-modal traffic network with heterogeneous users in VOT. Under this scheme, each car owner is unallowed to commute by auto until owing an OD-based permit. Thus, travelers with different VOTs can only restrictedly choose respective travel modes to complete their trips with the given OD (or entrance-exit) information, driving a car or riding by public transit. The proposed scheme is a little practical but second-best, since all travelers between the same OD pairs are charged the same permit, independent of their respective used paths and links. Fortunately, it can surely erase the negative effects induced by the OD-based tolling policy, under which the financial transfer from travelers to city authority is involved.

Generally, the implementation of tradable OD-based travel permits scheme includes three major stages. (1) With the objective of the system's total cost minimization, including the crowding cost by transit, the city authority initially determines the target vehicle flow for each OD pair, then equally or by a fair rule distributes the equivalent travel permits to all travelers with the same OD property. (2) The OD-based travel permits are allowed to be traded freely in a bidding market, thus their prices are OD-dependent. (3) A typical traveler owning an OD-based permit through distributing or trading can choose the solo-driving mode, whilst for others who do not own the permits, the transit is the only choice. In the process of the three stages, the city authority has no financial revenue from travelers, thus being revenue-neutral. However, as pointed by Nie (2012), the administrative burden of city authority under this scheme cannot be ignored, and might be nearly the same with that under the conventional congestion pricing, since all travelers' VOT information must be collected to determine the optimal amount of permits for minimizing the system's total cost. To investigate the impact of transaction costs or administrative burden of city authority is beyond the scope of this paper. We are more interested in determining the endogenous price and optimal amount of tradable OD-based permits with the resultant equilibrium bi-modal flow pattern.

To reveal the nature of tradable OD-based travel permits scheme, we first characterize a mode-choice equilibrium in a bi-modal traffic network with the fixed amount of OD-based permits, thus determining the endogenous OD-specific prices of the permits through trading in a bidding market among travelers between the same OD pairs. All travelers are grouped into two types, i.e., car owners and non-car ones. If having no travel permit, car owners with different VOTs are willing to bid different prices for the OD-