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Pricing and mode choice based on nested logit model with trip-chain costs

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ABSTRACT

Commuters can complete their "home-work-home" trips by three options: subway-only mode, auto-only mode, and park-and-ride mode on a bottleneck-constrained corridor. The purpose of this paper is to enhance the insights into pricing mechanism for subway and parking and corresponding mode choice behavior on the corridor with elastic demand. A nested logit-based stochastic user equilibrium model is proposed to characterize the commuters' modal choice. Dispersion parameters in the nested logit model reflect the risk or uncertainty of mode choice. It is found by sensitivity analysis that the impacts of subway fare and parking fee on the commute pattern are not always monotonous. Optimal strategies of subway fare and parking fee are discussed, respectively, under four market schemes by assuming that the subway and the parking lot at workplace are operated by either the government or a private owner. A numerical example is presented to illustrate how the pricing policies affect demand implementation, mode choice behavior and benefits of private owners and the whole transportation system.

1. Introduction

As the result of urban revitalization, many metropolitan areas have witnessed explosive growth of traffic demand. Due to the limited road supply, various traffic demand management strategies have been proposed by researchers, such as congestion toll (de Palma and Lindsey, 2004; Shiftan et al., 2012), parking policy (Inci, 2014; Shiftan and Burd-Eden, 2001), auto restraining (Shiftan and Golani, 2005) and etc., and some of them have been implemented in practice. One of the adopted strategies is to encourage park-and-ride (P&R) travel, namely guiding auto commuters to park at highway bottleneck, and then take the high-capacity public transit to finish the rest of the trip (Lam et al., 2001; Wang et al., 2004). For example, during Beijing's Twelfth Five-Year Plan period, 26 large-sized P&R facilities are expected to be built in the vicinity of new subway lines. Meanwhile, parking fees are expected to be differentiated according to parking regions, positions, time intervals and forms. On April 1, 2011, the differentiated parking fee policy started to be formally implemented in Beijing by keeping lower charges in P&R parking lots and raising parking fee at the city center. Since then, the volume of passengers on the public transits substantially increases, and the traffic congestion indexes of some major roads within the 5th ring fall significantly.

Parking pricing strategies are important tools for rebalancing the modal split between private car and transit systems in urban areas (D'Acierno et al., 2006). However, it should be recognized that the high price of parking fee raises the travel cost by car, which will certainly intensify the conflicts among government, parking lot owners and commuters. Therefore, the nature of differentiated pricing policy needs to be further discussed and the multimodal trip distribution under the influence of the policy should be reasonably forecasted (Huang et al., 1998; Gkritza et al., 2011; Inturri and Ignaccolo, 2011).

The classical traffic bottleneck model studies the commuting congestion on a highway with a single bottleneck between a residential area and a workplace (Vickrey, 1969). Tabuchi (1993) first studied such a bi-modal competitive system containing transit and highway modes. However, in many large cities, P&R services are provided for auto commuters to choose at highway bottleneck, for example, in Beijing and Hong Kong. Unlike the auto mode, the P&R mode mainly depends on its fare level, parking fee and service quality for attracting commuters. Usually, the parking fee is lower at P&R facilities than that at the city center. Also different from the transit mode, the P&R mode could make use of high velocity of car for attracting commuters, although the trains of railway or subway normally arrive on time no matter how crowded their carriages may be. Obviously, the analysis of this multi-modal system with a P&R option will be significantly different from that of a bi-modal system. Hence, the greatest need perhaps is the development of an

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integrated transport pricing system that enables the coordination of parking fee at different positions and transit fares for optimal modal split.

Usually, a commuter complete his/her "home-work-home" trip chain by two single trips that "home to work" and "work to home". In most academic research, a trip chain is conventionally defined as a sequence of trips that starts at home, involves one or more intermediate stops, and ends back at home (Ye et al., 2007). As Currie and Delbosc (2011) pointed out, the trip chain is an important aspect of travel and has the significant impact on changing travel patterns. McGuckin et al. (2005) found a 9% increase in chained work trips between 1995 and 2001.

Considering the "home-work-home" trip-chain costs, a nested logit-based stochastic user equilibrium (SUE) model is developed in this paper to investigate subway fare, parking fee and corresponding modal split under different market schemes with elastic demand[1]. The transportation system studied here is a subway/highway parallel corridor with a P&R option. Commuters first decide to travel by car or subway, and then those by car will choose either parking their cars and riding a train at highway bottleneck or continuing driving to the workplace. The four market schemes are further explored by assuming that the subway and the parking lot at the workplace are operated by either the government or a private owner. Specifically, in the market scheme I, both the subway and the parking lot at the workplace belong to the government; in the market scheme II, the parking lot at the workplace still belongs to the government, but the subway is operated by a private owner; in the market scheme III, contrary to scheme II, the subway belongs to the government whilst the parking lot at the workplace is operated by a private owner; and in the market scheme IV, both the subway and the parking lot at the workplace are operated by different private owners. Without loss of generality, it is assumed that, the government hopes to maximize the net social benefit in the whole transportation system, and the private owners want to set the charges for profit maximization.

There are three major contributions of this paper. Firstly, a nested logit SUE model is formulated to depict commuters' mode choice behavior with the consideration of the "home-work-home" trip-chain costs. Secondly, the sensitivity analysis is conducted to find the impacts of subway fare and parking fee on the travelers' commute pattern. Thirdly, optimal strategies of subway fare and parking fee are discussed under four different market schemes, respectively. It is proved that the impacts of subway fare and parking fee on the travelers' commute pattern are not always monotonous. Numerical examples are provided to give new managerial insights into the impacts of pricing policies on the demand implementation, modal choice and benefits of private owners and whole transportation system.

2. Related works

There are lots of studies concerning optimal transit fare, parking fee and their influences on the corresponding travelers' commute patterns. However, most of them are limited to the public transport or private car mode only. For example, in order to maximize the social welfare, Pedersen (2003) studied the optimal fare policies in a public transport market with capacity constraints. Sharaby and Shiftan (2012) focused on evaluating the impact of fare integration on transit ridership and travel behavior, using the city of Haifa, Israel, as a case study. Ottosson et al. (2013) investigated the sensitivity of on-street parking demand using the automatic transaction data from parking pay stations in Seattle. For more detailed discussions, Interested readers are referred to Li and Hensher (2011) and Inci (in press).

Some studies on the combined trip distribution on a multimodal corridor have been carried out. Tabuchi (1993) dealt with pricing and modal split in a competitive mass transit/highway system under the deterministic user equilibrium (DUE). Inspired by the seminal work of Tabuchi (1993), Huang et al. (1998) and Huang (2000) extended his study of modal choice by introducing crowding congestion on transit and by admitting the heterogeneity of commuters, respectively. Based on the assumption that the railway line is congestion-free, Wang et al. (2004) investigated the optimal location and pricing of a P&R facility in a linear monocentric city under the DUE. Supposing that P&R services are continuously distributed along a travel corridor, Liu et al. (2009) investigated the commuters' travel choice behaviors in a competitive railway/highway system under the DUE. Inturri and Ignaccolo (2011) investigated the effects of alternative or joint schemes of road pricing and parking pricing on an idealized urban multimodal traffic corridor under the DUE. Based on the multinomial logit-based SUE, Huang (2002) further analyzed the modal split problem under various pricing regimes. Following the work of Huang (2002), Tian et al. (2005) made an important extension by adding a P&R option at highway bottleneck, yet they still assumed commuters' multinomial logit-based mode choice behavior. According to Oppenheim (1995), the multinomial logit-based SUE model is more close to the reality than the DUE model. But due to the "independence of irrelevant alternatives" (IIA) assumption of the multinomial logit-based SUE model, i.e., all the alternatives should be irrelevant and independent; it is unsuitable for the case with a P&R option which is a combination of auto and subway. In contrast, a nested logit-based SUE model is more appropriate for mode split prediction when there are correlations among two or more transport modes.

Furthermore, traditional trip distribution models mainly focus on a single trip such as "home to work" or "work to home" trip. They may lead to inappropriate predictions of trip distribution or wrong evaluations of traffic demand management policies because of the separation of the "home-work-home" round journey (Strathman and Dueker, 1995). In fact, there exists a close connection between "to work" and "from work" travelers, especially for those by car. No matter whether his/her car is parked at the work area or a P&R station, the driver has to pick it up at the parking lot and then drives back home. Such the "home-work-home" round travel is one of the most simple and common trip chain (Ye et al., 2007).

3. Nested logit-based SUE model with trip-chain costs

The nested logit-based SUE model will be formulated in detail in this section, which is helpful for understanding further theoretical calculations and analysis.

3.1. Basic description

As shown in Fig. 1, Node H (a residential area or home) and node W (a workplace or central business district (CBD)) are connected by a simplified two-direction corridor with a parallel subway/highway system. Commuters leave their home to work at CBD, and after work, return to home along the corridor everyday. A P&R parking lot (P2) and a transfer station (TS) are located at the highway bottleneck (B). And also, a parking lot (P1) is located at

[1] A preliminary study has been conducted in Lu et al. (2011), in which the numbers of commuters using different travel modes, instead of subway fare or parking fee, are directly optimized. In general, it should be more natural to induce a reasonable modal split solution by adjusting those economic variables, which is that we expect to do in this paper.