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Park-and-ride service design under a price-based tradable credits scheme in a linear monocentric city

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A R T I C L E I N F O

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A B S T R A C T

This study conducts a multimodal analysis in a competitive railway/highway system along a linear traffic corridor. A price-based tradable credits scheme is introduced into the park-and-ride (P&R) design in which the credit price is determined by the government. The C-logit model is used to analyze the linear monocentric city's route choice behavior. A bi-level programming model is proposed to study the P&R location problem. The upper level minimizes the social cost by optimizing the quantity and location of P&R stations and the price-based tradable credits scheme. The lower level is to determine the equilibrium assignments on the multi-mode network. Finally, a numerical example is used to investigate the effects of the price-based tradable credits scheme, bodily congestion in transit carriages and P&R facilities' investment on social cost, traveler behavior and P&R locations. It is found that besides the price-based tradable credits scheme, bodily congestion and P&R facilities investment also have an important influence on the P&R location design and the social cost.

1. Introduction

In recent years, the rapid growth of motor vehicles has caused serious traffic congestion in most big cities of China. Some researchers and planners have advocated the further development of public transportation when big cities are faced with the problem of congestion. One of the most effective methods is constructing the subway lines. In some cities of china, such as Tsingtao, Lanzhou, Dalian, Xiamen, Suzhou, Wuxi and Nanchang, subway lines are complete or are under construction. In such an environment, park-and-ride (P&R) is viewed as a traffic mode to encourage commuters to combine auto and railway modes and help alleviate traffic congestion. This idea can be traced back to 1930s (Noel, 1988). Later studies found that P&R is certainly an effective way to reduce congestion (e.g. Flint, 1992; Bolger et al., 1992; Parkhurst, 1995; Roberts et al., 1998; Parkhurst, 2000; Lam et al., 2001; Bos et al., 2003; Garcia and Marin, 2005; Li et al., 2007). Considering the merits of P&R for alleviating congestion, various tools have been developed by some researchers to determine the optimal locations for P&R facilities, such as the hybrid knowledge-based pert system and geographic information system (Horner and Grubesic, 2001; Faghri et al., 2002; Farhan and Murray, 2003). Some other researchers have focused on optimization approaches. For example, Wang et al. (2004) studied the optimal location and pricing of a P&R facility in a linear city and Liu et al. (2009) developed a deterministic continuum equilibrium model to enhance insights into commuters' travel choice behaviors and P&R transfer behavior in a linear monocentric city.

Besides P&R services, market-based instruments for mobility management (Mamun et al., 2016) have been put forward for over several decades. As is well known, congestion pricing (Pingo, 1920; Viegas, 2001; Tsekeris and Voss, 2009; de Palma and Lindsey, 2011; Xu and Gao, 2017) and tradable credits (Goddard, 1997; Verhoef et al., 1997; Raux and Marlot, 2005) are two of the most famous market-based instruments in traffic management. Compared to the former, the latter is a more equitable and transparent option for travelers and government, which dates back to Dales (1968) for the purpose of attaining water quality targets.

Recently, Yang and Wang (2011) made a significant development in tradable credit schemes analysis which proved the existence and uniqueness of the equilibrium link flow pattern under a tradable credits scheme in a general network context. Later, extensions were made in different aspects. Wang et al. (2012) analyzed the tradable credits scheme by considering heterogeneous users with different values of

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travel time. Nie (2012) considered the effects of transaction costs. Wu et al. (2012) designed a more equitable congestion pricing and tradable credits scheme by considering the effect of income on travelers. Xiao et al. (2013) and Tian et al. (2013) extended the credits scheme to bottleneck congestion. He et al. (2013) examined the effects of credit schemes on mixed equilibrium behaviors. Ye and Yang (2013) studied price and flow dynamics within a tradable credits scheme. Nie and Yin (2013) developed a new tradable credit scheme for managing commuters' rush hour choices. Fan and Jiang (2013) presented a review on tradable mobility permits in roadway capacity allocation. Grant-Muller and Xu (2014) had a review on the role of tradable credit schemes in road traffic congestion management. Wang et al. (2014a, 2014b) analyzed the effects of tradable credits on continuous network design. Bao et al. (2014) studied loss aversion behavior on travelers under a tradable credits scheme. Zhu et al. (2014) explored the properties of multiclass traffic network equilibria under a tradable credits scheme. Xu and Grant-Muller (2016) discussed trip mode and travel pattern impacts of a tradable credits scheme.

Different from the quantity-based tradable credits scheme, in this paper, we propose a new tradable credits scheme in which the credit price is determined by the government instead of the credit market. In the market, travelers could trade with each other freely under the government supervision. The speculators cannot reap profits by controlling a high credit price. Meanwhile, compared with conventional tradable credits schemes, advantages, such as fairness and transparency are still achieved in the price-based tradable credits schemes.

This study makes a general multimodal analysis in a competitive railway/highway system along a linear traffic corridor. Firstly, a price-based tradable credits scheme is proposed in which the credit price is used to regulate the link flow condition. Secondly, a bi-level programming model is proposed to study the P&R location problem. The upper level minimizes the social cost by optimizing the quantity and location of P&R stations and the price-based tradable credits scheme. The lower level is to determine the equilibrium assignments on the multi-mode network. Thirdly, the C-logit model is used to analyze the linear monocentric city's route choice behavior. Finally, a numerical example is presented to investigate the effects of the price-based tradable credits scheme, body congestion and P&R investment on social cost, traveler behavior and P&R locations.

For the remainder, in Section 2, the characteristics of a linear monocentric city and the price-based tradable credits scheme are given. Travelers' costs, mode choice behavior and credit market trading behavior are analyzed in Section 3. A b-level programming is proposed in Section 4, while Section 5 gives the algorithm to solve the model. Numerical results and analysis based on an example network are presented in Section 6. Finally, Section 7 concludes the paper and gives some extensions for future study.

2. Linear monocentric city and the tradable credits scheme

2.1. Characteristics of the linear monocentric city

We consider a linear monocentric city with a subway and highway system providing three travel modes: auto (represented by a), subway (represented by b), and Park and Ride (represented by c). The city contains one Central Business District (CBD). Residential density is uniformly distributed along the city corridor. The highway that runs parallel to the subway, suffers from congestion on some links. Some of the subway stations are P&R stations. Commuters choose their preferred travel modes and routes solely based on the generalized travel cost. The city boundary is L, and x_i is the distance from the i-th residential community (subway station/highway node) to the CBD. There are h subway stations along the subway line. The h-th subway station lies in the CBD. The illustration of the linear monocentric city is shown in Fig. 1.

In order to show the relationship among highway node, subway station and residential community, Fig. 1 is expanded into Fig. 2.

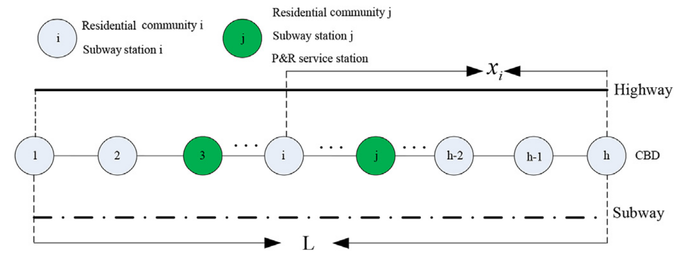

Fig. 1. A linear monocentric city with a highway and a subway line.

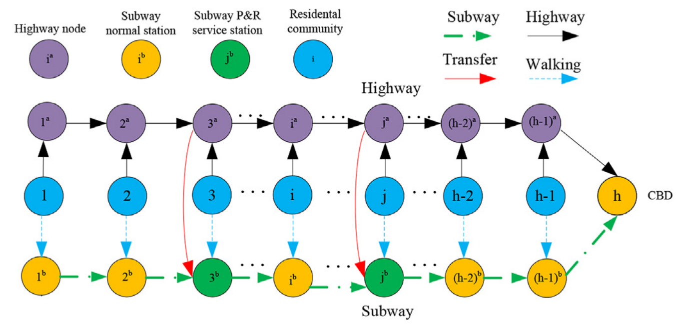

Fig. 2. Extended network of Fig. 1.

In Fig. 2, $i$denotes the i-th residential community. i^adenotes the i-th highway node and i^b is the i-th subway station.

2.2. A price-based tradable credits scheme

In this paper, the tradable credits scheme is described as follows:

- **Initial distribution of credits**

The planner distributes tradable credits to all taxpayers uniformly and freely. The total amount of credits is predetermined. The initial distribution of credits satisfies the following condition:

$$k\cdot\sum_i D_i = K,\quad i = 1,2,\ ...,h \tag{1}$$

In Eq. (1), $k$is the amount of credit distributed to each traveler. D_i denotes the level of demand from resident community $i(i = 1,2,\ ..,\ h)$ to the CBD and $K$is the total amount of credits in circulation.

- **Credits charges**

All credit charges are non-negative. The Government charges credits on highway link $(i^a,\ \ (i+1)^a)(i = 1,2,\ ..,\ h-1)$, in P&R parking lot and CBD parking lot to encourage travelers to use the subway. There is no credits charge on the subway. $\tau^a_{(i^a,(i+1)^a)}$denotes the credit charge for using highway link $(i^a,\ \ (i+1)^a)$. $\tau^c_{j^b}(j = 1,2,\ ..,\ h)$ denotes the credit charge for using P&R station j^b. $\tau^c_{h^b}$ represents the credit charge in the CBD parking lot.

- **Credit price**

In this article, the credit price is determined by the planner instead of the credit market. The credit price is unique. Nobody could change the credit price except the planner. However, users' behavior (mode choice behavior, route choice behavior and credits trading behavior) could affect the credit price.

- **Credits trading**