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Analysis of multimodal two-dimensional urban system equilibrium for cordon toll pricing and bus service design

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ABSTRACT

This paper presents a multimodal urban system equilibrium model to address cordon toll pricing and bus service design issues in a two-dimensional monocentric city. Commuters are assumed to travel by auto or bus from their home locations to their workplace located in the city center through a ring-radial routing system. Auto users must pay tolls when passing through the cordons installed on the radial major roads. The multimodal two-dimensional urban system equilibrium is first formulated and its properties are analytically explored. A social welfare maximization model that simultaneously determines the optimal cordon toll location, toll level, bus service frequency and fare on each radial major road is then proposed. The effects of different tolling schemes (uniform and differential cordon-based, first-best, and no toll) on the multimodal urban system are also examined and compared.

1. Introduction

In the past decade, rapid urbanization and economic growth in China have led to a sharp increase in the size of some large Chinese cities, such as Beijing, Shanghai, and Wuhan. It has been reported that at the end of 2016, China's urbanization rate hits 57.35%, which is over three times higher than that (17.9%) in 1979 (NBSC, 2016). Such rapid urban expansion has provoked serious traffic congestion, excessively high house prices, and expensive living costs. Congestion tolling schemes have been widely suggested as a viable measure to address these problems (Lindsey, 2010) because of its potential in alleviating traffic congestion by changing travel choices of road users, such as route and mode choices.

Among the congestion tolling schemes, the cordon tolling scheme, in which each auto user passing through a specified cordon is charged a fixed toll, is popular due to its ease of implementation in practice. Such a scheme has been successfully implemented in many modernized cities in the world, such as Singapore, London, Hong Kong, Oslo, Stockholm, and Bergen (Zhang and Yang, 2004; Wong et al., 2005; Yang and Huang, 2005; Rouwendal and Verhoef, 2006; Anas and Lindsey, 2011). Recently, some large Chinese cities, such as Beijing, Shanghai, Hangzhou, and Shenzhen, are intending to introduce such a scheme. Project certification works on the cordon tolling scheme have been implemented in these cities. This raises some intriguing and important issues: How to specify the cordon toll location and toll level for each radial major road linking to the city center so as to maximize the efficiency of a multimodal urban system with both private and public transport modes in terms of social welfare? What effects does the cordon tolling scheme bring to the commuter's modal shift and

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Table 1
Contributions to cordon toll pricing research in urban economics field.

Citation	Decision variable	Travel mode	Urban form	Modeling method	Considering household relocation behavior
Eliasson and Mattsson (2001)	Toll location and toll level	Auto, public transit, and a non-motorized mode	Symmetric, two-dimensional, polycentric	Numerical simulation (discrete)	Yes
Mun et al. (2003)	Toll location and toll level	Auto only	Linear, monocentric	Continuum	No
Mun et al. (2005)	Toll location and toll level	Auto only	Linear, polycentric	Continuum	No
Ho et al. (2005)	Toll level	Auto only	Asymmetric, two-dimensional, monocentric	Continuum	No
Ho et al. (2013)	Toll level	Auto only	Asymmetric, two-dimensional, polycentric	Continuum	No
Verhoef (2005)	Toll location and toll level	Auto only	Linear, monocentric	Continuum	Yes
Chu and Tsai (2008)	Toll location and toll level	Auto only	Linear, monocentric	Continuum	No
Anas and Hiramatsu (2013)	Toll level	Auto, public transit, and a non-motorized mode	Asymmetric, two-dimensional, polycentric	Empirical simulation (discrete)	Yes
Li et al. (2012a)	Toll location, toll level, bus fare and frequency	Auto and bus	Linear, monocentric	Continuum	No
Li et al. (2014)	Toll location and toll level	Auto only	Symmetric, two-dimensional, monocentric	Continuum	No
Li and Guo (2017)	Cordon pricing timing, toll location, and toll level	Auto only	Symmetric, two-dimensional, monocentric	Continuum	Yes
This paper	Toll location, toll level, bus fare and frequency	Auto and bus	Asymmetric, two-dimensional, monocentric	Continuum + discrete	Yes

the urban spatial structure in terms of household's residential location choice and housing market? The present study will address these important issues. It is expected that the proposed methodology in this paper can provide some new insights into the cordon toll pricing issues in a competitive multimodal urban system.

Recently, significant progress has been made in the design issues of cordon tolling scheme. For the convenience of readers, we have summarized in Table 1 some principal contributions to the studies on continuum cordon tolling problems, in terms of decision variable, travel mode, urban form, modeling method, and household relocation behavior. Table 1 shows that the previous related studies have mainly focused on the optimization of cordon toll location and/or toll level in an auto-only urban system, and the interaction and substitution effects between auto and transit modes (e.g., bus) were usually ignored. There also exist some studies where public transport services are assumed to be pre-given and fixed regardless of the implementation of congestion tolling scheme (e.g., Eliasson and Mattsson, 2001; Anas and Hiramatsu, 2013). In reality, auto and transit modes usually share the same roadway, and thus have impacts on each other. The congestion interaction between them directly affects the cost of travel by a particular mode and thus the travelers' mode choices, which in turn influence the optimal toll location and toll level and the bus services (frequency and fare). Conversely, a change in the toll location/level or bus services can cause a change in the modal split of auto and bus. It is, therefore, of great importance to incorporate congestion interaction and substitution effects between modes and the demand-responsive bus service strategy in the multimodal decision-making models (Small, 2004; Pels and Verhoef, 2007; Tsekeris and Voß, 2010; Li et al., 2012a).

Table 1 also shows that the existing relevant studies usually assumed that the spatial distribution of households in the city was exogenously given and fixed. Nonetheless, some studies have shown that the cordon tolling scheme can cause changes in urban land-use pattern, land value and the housing market in terms of housing price and space (e.g., see Eliasson and Mattsson, 2001; Anas and Hiramatsu, 2013; De Lara et al., 2013; Li and Guo, 2017). Consequently, introducing a cordon tolling scheme may change households' residential location choices and thus residential distribution in the city, which can in turn affect the route and mode choices of commuters. It is, therefore, of great importance to consider the effects of cordon tolling scheme on the households' relocation decisions and the urban spatial structure.

In addition, Table 1 also shows that the previous cordon toll pricing studies in the urban economics literature usually adopted continuum modeling approach, where the urban transportation system was assumed to be a perfectly divisible dense system consisting of an infinite number of radial roads. However, in the cordon tolling practice (e.g., London's and Hong Kong's toll schemes), the cordons are installed on the discrete radial major roads linking to the city center. The classic continuum unimodal linear urban models cannot be used to address the cordon toll pricing issues (including determination of toll location and toll level) in a multimodal radial circular urban system with discrete radial major roads, as shown in Fig. 1. One has thus to turn to a model that considers the urban structure as a sparse system with discrete radial roads. In this regard, Anas and Moses (1979) conducted a pioneering work. They first proposed a circumferential-radial or ring-radial travel method for a multimodal two-dimensional monocentric urban system with auto and bus modes (see Fig. 1). In Fig. 1, the city's central business district (CBD) is connected to its suburban areas by some radial major roads. Commuters