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Mode choice and railway subsidy in a congested monocentric city with endogenous population distribution

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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

The objective of this paper is to provide new insights into commuters' mode choice behavior in a monocentric closed city with endogenous population distribution, where a congested highway and a crowded railway provide commuting services for residents on a linear urban corridor. We first explore the typical equilibrium mode-choice patterns with exogenous city boundary and population distribution, and then incorporate the residents' mode choice into an urban spatial equilibrium model, in which the residents' household consumption, the residential location choice and the property developers' housing production are also explicitly modeled. Using comparative static analysis, we find that the urban corridor expands with the increase of railway fare if there is no congestion in the bimodal transportation system, but it's not necessarily the case if highway congestion and transit crowding cannot be ignored. We provide numerical evidence to show that the urban corridor possibly shrinks with the increase of railway fare once congestion effects are considered. We also discuss the changes of urban form, utility level of residents and social welfare with different railway fare and subsidy policies. Numerical results show that the distance-based fare policy with low subsidy should be preferred because it can realize the Pareto-improved social welfare and utility level of residents.

1. Introduction

In recent decades and accompanying the economic growth and technological advances, we have seen rapid expansions and complex changes in developing cities around the world, such as that taking place in Beijing and Shanghai, China. Urban expansion results in commuters living further away from work places, which in turn dramatically increases the demand for motorized vehicles. For instance, a report by Beijing Municipal Bureau of Statistics stated that the total number of motorized vehicles has reached 5.6 million at the end of 2014 from a level of 4.8 million just four years ago, even though new car registrations via a lottery system have been introduced since 2011 (BMBS, 2015). Meanwhile, rapid developments of urban subways and railway networks such as mass transit systems in these cities have broadened travel mode choices to commuters (Yang et al., 2016; Peng et al., 2017), and governments and transit agencies are putting in vast sum of investments and subsidies to provide a reasonable level of transit operations throughout the cities (Wang et al., 2015; Xu et al., 2017). These rapid and complex developments in cities raise challenging research questions, especially on the agenda of sustainable urban development.

In principle, distribution and migration of population, frequent changes in work place and residential location and so on, may all have marked effects on the travel decisions of the residents (e.g. on travel mode, time of day and route choices). Likewise,

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developments (and expansions) of multimodal transportation networks (such as new metro lines) and the accompanying pricing policies may lead to changes in residential location choice, land-use pattern, housing market and so on (e.g., Bravo et al., 2010; Ma and Lo, 2012; Mohammad et al., 2013; Efthymiou and Antoniou, 2013; Dubé et al., 2013; Wang and Du, 2016b; Ng and Lo, 2015, 2017). It is, therefore, of great importance to address the inter-relationship between transportation and residential location choices, and the impacts of pricing policies, land use and housing developments on these choices.

Transport planners have long since recognized the need to consider the interactions between transport and land use in making their long-term transport planning for urban areas. For cities of relatively small sizes and with stable transportation and land-use markets, traditional four-stage travel demand models have been established to analyze trip generation, trip distribution, modal split and trip assignment. However, it has long been recognized that there are inconsistencies across different levels of four-stage modeling, due in part to their sequential and independent processes and the lack of feedback loops between stages. There have been large efforts in developing combined (with feedback loops) transportation equilibrium models to overcome some of the inconsistencies in the traditional four-stage modeling (e.g. Evans, 1976; Boyce and Southworth, 1979; Safwat and Magnanti, 1988; Huang and Lam, 1992; Tam and Lam, 2000; Zhou et al., 2009). For a historical overview of combined equilibrium models, readers can refer to Boyce and Williams (2015).

Combined equilibrium models based on multi-modal discrete networks have been formulated and analyzed extensively in the past decade (e.g. Lo et al., 2004; García and Marín, 2005; Liu et al., 2015). Discrete network models are generally developed for their realism in representing the behavior of city; however such models tend to have a large number of parameters to be estimated. On the other hand, the continuum modeling approach has been shown to be able to explore general trends and patterns of commuters' behavior and their changes in response to policy changes in transportation systems at a more aggregated macroscopic level (Ho and Wong, 2006). In many continuum equilibrium traffic assignment models, densely spaced roads are treated as a continuum over which commuters are continuously distributed in a two-dimensional space (e.g., Sasaki et al., 1990; Yang et al., 1994; Wong, 1998; Jiang et al., 2011). Due to the difficulty of obtaining exact solutions and analytical properties in a two-dimensional space, a simplified one-dimensional urban corridor with a continuum of entry points and a single exit point has often been adopted. Jehiel (1993) was the first to verify the existence of the simple solution of equilibrium states under the condition that the capacities of two congested modes are constant. In a transport system with a congestible highway and a congestion-free railway, Wang et al. (2004) investigated the characteristics of equilibrium mode choice patterns before and after the introduction of a park-and-ride (P&R) service. Following the thinking of Wang et al. (2004), Liu et al. (2014) further investigated the effects of rationing and pricing on morning commuters' travel cost and modal choice behavior in each location. Taking into account the in-vehicle crowding effects of railway service and assuming a continuous P&R provision on the urban corridor, Liu et al. (2009) explored the continuum equilibrium properties by analyzing commuters' mode choice and P&R transfer decisions. Li et al. (2012) investigated the intermodal equilibrium, road toll pricing, and bus system design issues on the congested urban corridor with two alternative modes of auto and bus, which share the same roadway. These studies on the continuum equilibrium are limited in their consideration of transportation systems and rely on one key assumption that the spatial distribution of households and the length of urban corridor, i.e., the city boundary, are given exogenously. As we mentioned before, transportation systems are linked closely with urban economics. Especially in those cities with rapid spatial expansions, urban land-use and housing developments as well as residents' consumer behavior frequently interact with residents' residential location and mode choices in the long term. Therefore, it is necessary to analyze the continuum equilibrium properties of mode choice patterns in an urban spatial equilibrium modeling framework.

On the basis of the stylized monocentric city model (Alonso, 1964; Muth, 1969; Mills, 1967, 1972; Brueckner, 1987), this paper develops a bimodal urban spatial equilibrium model in which the interplays among household consumption, residential location, mode choice and housing production are explicitly modeled. Furthermore, we analyze the impacts of railway fare changes on the city boundary with the consideration of endogenous population distribution, and numerically discuss the changes of urban form, utility level of residents and social welfare with different railway fare and subsidy policies.

The remainder of this paper is organized as follows. Section 2 reviews the urban economics studies on mode choice and subsidy issues associated with monocentric cities. Section 3 describes the basic assumptions and the overall modeling framework. Section 4 explores equilibrium mode-choice patterns with exogenous city boundary and population distribution. Section 5 presents an urban spatial equilibrium model by integrating household consumption, residential location choice and housing production with mode choice. The effects of railway fare changes on the city boundary are examined in detail. Section 6 provides a numerical comparison of urban system performance with different railway fare and subsidy policies. Concluding remarks are provided in Section 7.

2. Related studies

Much urban economic analysis is made based on a particular model of urban spatial structure, the monocentric city model pioneered in the 1960s by Alonso (1964), Muth (1969) and Mills (1967). In this section, we focus on reviewing related studies on mode choice and subsidy issues associated with monocentric cities in the urban economics literature.

The earlier literature emphasized the integration of mode choice into urban economic analysis and ignored the effects of either traffic congestion or in-vehicle crowding. Capozza (1973) was the first to develop a spatial general equilibrium model of a monocentric city with two transportation modes, i.e., a land-intensive road service and a land-economizing subway service. By assuming that the subway is less expensive than roads from the Central Business District (CBD) to some location on the urban corridor, Capozza found numerically that the addition of a subway system to a city with only roads would reduce transportation costs and city size. The reason for this is such that the construction of a subway permits land to be transferred from road use to housing, thereby dominating the reduction of city size. Without the use of land in transportation, Arnott and MacKinnon (1977) used a spatial general equilibrium