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Pareto-improving policies for an idealized two-zone city served by two congestible modes

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Abstract

We study urban structure and traffic congestion of a monocentric city by idealizing its suburb and its core as two zones and then exploring what would happen when they are connected by a congestible highway and a crowded railway system. We introduce dynamic congestion effect into commuters' departure-time and mode choice behaviours, and analyse the endogenous interactions between their travel and residential relocation choices. Studies ignoring dynamic departure-time behaviour show an ambiguous effect of transit improvements to the city. However, we find that transit improvement has a definitive impact on city structure: it increases the residents' equilibrium utility, at a cost of increased suburb land use. We show that it is possible to design Pareto-improving land-use and transit policies which benefit the residents without causing urban sprawl. We provide analytically the existence conditions of such policies and suggest that a high return of land use tax to subsidize transit improvement is required.

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Keywords: Monocentric city model; Dynamic congestion; Land use tax; Transit subsidy; Urban sprawl; Pareto improving.

1. Introduction

A city's transportation system is intrinsically linked to its geographic structure and its economic activities. Rapid urbanization seen in cities around the world has led to investments in rail transit systems as ways to alleviate traffic congestion. On the one hand, the developments of such systems and the accompanying traffic management policies

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(e.g. pricing, transit subsidy) have a direct impact on where people choose to live and how they travel to work (McDonald and Osuji, 1995; Li et al., 2012; Ma and Lo, 2012). On the other hand, residential locations influence and determine the commuters' travel decisions (e.g. on travel mode, departure time, etc) (Boyce and Southworth, 1979). Thus, understanding the interplays between urban economic activities and transportation developments, and the role rail transit plays on travel behaviour and on urban land use, is important in shaping the city's development.

The standard model of urban structure and urban traffic congestion provide a powerful framework to explore these complex interrelationships, and the most basic form is the monocentric city model where all jobs are located in the Central Business District (CBD). The model describes the spatial structure of the city as the result of a trade-off between land rents and commuting costs (Alonso, 1964; Mills, 1967; Muth, 1969). The differences in commuting cost across the city are compensated by the differences in land price or housing price. This compensatory price variation, which reconciles suburban residents to long and costly commuting trips, is shown to have a profound effect on the spatial structure of the city.

When a public transit system is introduced to a city, it naturally alters the transportation landscape of the city and the cost of travel, which in turn affects the spatial structure of the city. Capozza (1973) was the first to integrate public transit into urban economic analysis and established a general spatial equilibrium model in a monocentric city with two transportation modes. He found that the addition of a subway system to a city reduces the overall transportation costs and the city size. Building on Capozza's work, Sasaki (1989) showed that reducing the public transport cost also leads to a contraction in city size. Su and DeSalvo (2008) further identified an inverse relation between transit subsidy and urban sprawl, and a direct relation between auto subsidy and urban sprawl. A common limitation however in the above studies of the two-mode city is that they ignored the transport congestion effects.

A feature in modern cities is the peak-hour traffic congestion. Modelling congestion in an urban economics setting, where both commuters' spatial distribution and travel behaviour (in their mode and departure time choices) are endogenous, raises challenges to urban economic analysis. Most existing cities models tend to assume a static travel cost function which varies only with distance. Strotz (1965) was the first to raise the congestion effect on the economy of urban communities. This is followed by studies of city models with travel costs which vary not only with distance but also with traffic density (e.g. Solow, 1972; Anas and Xu, 1999; Li et al. 2012). Congestion tolls are usually proposed as an effective way to internalize congestion externality, and their effect on a monocentric city is found to centralize the population towards the city centre (e.g. Wheaton, 1998; Verhoef, 2005). These studies, however, are concerned with monocentric cities served by only a single travel mode.

Few by far have examined congestion externality on urban spatial equilibrium with alternative transport modes, with the exceptions of Haring et al. (1976) and Buyukeren and Hiramatsu (2016). Haring et al. (1976) showed that increasing public transport capacity reduces the land rent differentials between the CBD and the city fringe, and lowers the equilibrium commuting costs. Using a discrete core-suburb monocentric model, Buyukeren and Hiramatsu (2016) found that modal substitution effect can limit the centralizing force of anti-congestion policies (such as road pricing) and lead to the acceleration of urban sprawl. In the above studies, the dynamic congestion effect on commuters' departure time choice is not considered.

In reality, congestion phenomena is highly dynamic and sensitive to traffic flow levels. Likewise, commuters are sensitive to congestion levels and they may choose to use the less congested mode to travel and/or to choose to depart early or late in order to avoid congestion. Thus, their generalized travel cost is determined not only by which mode they choose, but also by their trip timing and schedule delay costs. The classic bottleneck model first proposed by Vickrey (1969) provides a framework for analysing commuters' departure time choices as they vary endogenously with the dynamic nature of congestion. The bottleneck model has also been employed to examine the dynamic congestion effect on a combined residential location and departure time choice. Arnott (1998) incorporated the Vickrey's bottleneck model into a model of a discrete core-suburb monocentric city connected by a road with a bottleneck. Contrary to the standard urban economics model which suggests that congestion tolling results in a more concentrated city, Arnott showed that when departure time decisions are considered, congestion tolling may have less pronounced effects on urban structure. In fact, imposing an optimal congestion toll without redistributing its revenues will have no effect on commuting costs and residential locations of the commuters. Using a spatially continuous monocentric city with a bottleneck at the entrance to the CBD, Gubins and Verhoef (2014) found that congestion tolling causes residents to spend more time at home and to have larger houses, thereby leading to urban