Journal of Urban Economics 80 (2014) 51–61

Contents lists available at ScienceDirect

Journal of Urban Economics

www.elsevier.com/locate/jue

Dynamic bottleneck congestion and residential land use in the monocentric city

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ARTICLE INFO

Article history:
Received 4 January 2013
Revised 10 July 2013
Available online 1 October 2013

JEL classification:
D62
R21
R41
R48

Keywords:
Bottleneck model
Monocentric model
Road pricing
Congestion
Urban sprawl

ABSTRACT

We consider a monocentric city where a traffic bottleneck is located at the entrance of the central business district. The commuters' departure times from home, residential locations, and lot sizes, are all endogenous. We show that elimination of queuing time under optimal road pricing induces individuals to spend more time at home and to have larger houses, causing urban sprawl. This is opposite to the typical results of urban models with static congestion, which predict cities to become denser with road pricing.

1. Introduction

Peak-hour traffic congestion is a hardly avoidable burden in the morning routines for many residents in modern cities. Many commuters usually depart from home earlier than they would otherwise prefer to, in anticipation of the time they will spend in congestion. Time at home could have been spent on more sleeping, working, exercising, or other activities. Some of these would either require additional floor space or are better enjoyed in a more spacious environment. Long looked-for alleviation of congestion might thus, when leading to more time spent at home, affect not only the time allocation decisions of an inhabitant, but her spatial behavior as well. In this paper, we show that first-best time-dependent road pricing not only relieves congestion but may also cause urban sprawl.

Congestion in an urban setting, where both spatial and travel behavior are endogenous, has proven to be a challenging topic for economic analysis (Ross and Yinger, 2000). By far the most common way of modeling congestion in such a setting is in terms of static flow congestion, where the timing of travel is not a choice variable, and where traffic flows and speeds are constant over time. For example, Solow and Vickrey (1971) relate the per-unit-of-distance cost of traveling at a certain location to the total number of drivers passing that point. That specification of travel cost does not allow the consideration of potential benefits of avoiding the peak by traveling earlier or later. But congestion in reality is a dynamic phenomenon, with time-varying speed and traffic flows. This has inspired transportation economists to develop dynamic models of traffic congestion, in which the choice of departure times is endogenous, and where dynamic patterns of travel delays are key features. As Vickrey showed in 1969, such models may produce insights that diverge substantially from those traditional static models.

To develop a model that accounts for the dynamic nature of travel in a city, we integrate two workhorse models in the urban and transportation economics literature. A classic Alonso–Muth–Mills monocentric city model, in some important respects probably "the most successful model in urban economics" (Glaeser, 2008, p. 18), defines the spatial equilibrium, in which no individual can

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http://dx.doi.org/10.1016/j.jue.2013.09.001

unilaterally relocate within a city to gain a higher utility. Vickrey's dynamic bottleneck model of peak period congestion, very likely the most widely used dynamic model of traffic congestion in transportation economics, allows for the analysis of a dynamic traffic equilibrium, in which no driver can gain a higher utility by unilaterally changing the departure time (see, for example, the exposition in Small and Verhoef, 2007). We aim to integrate those two models in order to study the relationship between spatial allocation and travel time decisions.

In our model, homogeneous inhabitants[1] with a common preferred time of arrival at work, commute from their homes to a workplace located in the central business district of a city (hereafter, the CBD). The city is congestion-free, apart from a road bottleneck right at the entrance to the CBD. One might think of a bridge or a junction that a driver has to pass to get to the workplace. Starting in a queue-free situation, when the inflow of cars first exceeds the bottleneck's capacity, a queue starts growing in front of the bottleneck and evolves at a rate determined by the difference between queue-entries (at the back of the queue) and queue exits (the bottleneck's capacity). By adjusting the timing of departure from home, a driver can incur different queuing times, and arrive at work at times with different levels of scheduling inconvenience. For instance, a driver can depart very early in the morning and avoid the queue altogether, or arrive at the most desirable moment but not after having spent quite some time in the queue. Following the framework of Vickrey (1973), and later Tseng and Verhoef (2008) and Fosgerau and Engelson (2011), we explicitly define the utility that an individual derives from spending time at home, at work, and in a car. That will later allow us to incorporate the spatial aspect of the model in a structured manner.

An important assumption that we introduce is that the marginal utility of spending time at home depends on the size of the house,[2] which is endogenously determined in the model. Ceteris paribus, the larger the house one lives in, the more utility one derives from spending additional time in it. This assumption seems consistent with the observed preferences for larger housing, as shown by countless hedonic price studies (see, e.g., Bajari and Kahn, 2008). We impose a time aspect by stating that an individual derives utility from a house by spending time in it. While a house might yield utility via various channels, e.g., as a storage place, a status symbol, or an investment asset, we believe it is safe to assume that at least some part of the utility from having a house depends on the amount of time an individual spends in it.[3] The usual pattern in the monocentric city model, with land consumption increasing the further away one lives from the CBD, thus produces variation in scheduling preferences across drivers, as a driver who lives closer to the CBD values time spent at home at a lower rate than one who lives at the city fringe. As we show later, depending on the size of the house, a driver chooses a certain time of departure from home, and vice versa. In this manner, we connect the transport model of bottleneck congestion, that has a dynamic equilibrium condition, with the urban model of a monocentric city, which gives a spatial equilibrium condition.

Arguably, the most striking result of this paper is that first-best time-dependent road pricing in this context leads to a lower density, and hence a larger city, even without redistributing the collected road toll revenues back to the city inhabitants. The intuition is that first-best time-dependent road pricing induces drivers to spend more time at home, as road tolling eliminates queuing time by shifting departure times from home to later moments. More time spent at home provides stronger incentives for having a larger house, and thus the city expands. In a similar fashion, an expansion of bottleneck capacity leads to the same effect. Our outcome is the opposite of the typical result of spatial urban models with static flow congestion. There, the Pigouvian toll, the typical first-best remedy for the negative congestion externality, increases the generalized transportation costs, and therefore reduces the city's geographical extent (e.g., Wheaton, 1998; Anas et al., 1998). Nevertheless, our result is consistent with other results in the sense that improved transportation causes urban sprawl (see, for example, the paper by Glaeser and Kahn (2004) on the invention of cars, and the study by Baum-Snow (2007) on highways construction).

There are few economics papers that model dynamic congestion in urban space. Arnott and DePalma (2011) report on their progress to solve the so-called "corridor problem", in which inhabitants of a monocentric city might experience congestion at each point on the road, as opposed to the single point congestion considered in our paper. Finding a complete solution to the dynamic equilibrium of flow congestion without a toll appears prohibitively difficult, even in a setting with an exogenously distributed population. A paper by Arnott (1998) is the only one that considers both dynamic congestion in the form of Vickrey's bottleneck and a (discrete) locational choice endogenously. The specified preference for the lot size though does not relate to the scheduling behavior and, as noted by Fosgerau and de Palma (2012), space in the model by Arnott (1998) has been "essentially [...] assumed away" (p. 274). Fosgerau and de Palma (2012) consider a continuous space city with a central Vickrey bottleneck, with time-varying marginal utilities of spending time at home and at work and without considering spatial equilibrium. Contrary to what we will find, they show that inhabitants located near the bottleneck tend to lose from optimal pricing. To the best of our knowledge, our study is the first to consider both locational choice (that leads to commuting) and scheduling choice (that affects residential location) of city inhabitants endogenously.

The paper is organized as follows. Section 2 presents the model setup, and Section 3 discusses how to find the market equilibrium. Section 4 then shows the resulting equilibrium patterns of land consumption, population density and rents over space; as well as the dynamic travel patterns by location. Section 5 considers first-best time-varying road pricing. Section 6 studies the robustness of the numerical outcomes by performing sensitivity analyses. Section 7 concludes.

2. Model setup

Consider a closed linear rectangular city of n homogeneous, atomistic, car owning, utility-maximizing inhabitants. All inhabitants earn an identical wage m in a spaceless CBD which is located in the city center. Assuming symmetry, we may consider half a city with the CBD being at the spatial edge of our single dimension. The inhabitants, with a common preferred time of arrival at work t^*, commute in the morning by car from their homes to the CBD, on a single road at a constant free-flow speed. At the entrance of the CBD, the road has a traffic bottleneck with a fixed capacity s. When the inflow of cars at any moment exceeds s, a "first-in first-out" traffic jam builds up at the bottleneck. Without queuing, the total commuting (free-flow) travel time of a driver is proportional to the distance from her home to the CBD, as in the conventional uncongested monocentric model. With queuing, the total travel time of a driver is the sum of her free-flow travel time to the CBD, plus the waiting time that she incurs in the queue.

To model scheduling behavior, we apply the model proposed by Vickrey (1973), and later by Tseng and Verhoef (2008) and Fosgerau

[1] All city inhabitants are drivers, and we use both these terms to indicate the same individuals.

[2] Throughout the paper we use the consumption of "land" as equivalent to that of "housing" and therefore use both the words "land" and "house" consumption to indicate the same good.

[3] We check sensitivity of our results with respect to this assumption later in the paper.