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Congestion pricing effects on firm and household location choices in monocentric and polycentric cities

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ABSTRACT

This paper develops a spatial general equilibrium model to explore the land use effects of three roadway congestion pricing strategies in both monocentric and polycentric city settings, where household and firm locations and wage rates are endogenously determined. Simulation results show how marginal cost pricing (MCP) of travel in the polycentric setting can cause many jobs (16% in this example) to leave the central business district (CBD) and relocate to a relatively dense but suburban ring. To achieve city-wide welfare gains, efficient land use regulations should permit such job decentralization. Simulations also illuminate how simple, distance-based tolls generate lower welfare improvements, but stimulate similar land use effects. A cordon toll imposed in monocentric cities may agglomerate all firms in a smaller CBD or re-agglomerate parts of firms in a sub-center ring of development. Overall, results highlight how an urban economic model enabling endogenous business and household decisions can illuminate various travel, congestion pricing, and land use connections.

1. Introduction

The use of congestion tolls around the world is rising, in the form of cordon charges, area-wide pricing, and variable-rate highway tolling. Pioneering examples include Singapore's Area Licensing Scheme in the early 1970s and its Electronic Road Pricing (congestion pricing) policy in 1998 and London's 2003 start of an area-wide toll (Santos, 2005). By 2011, ten U.S. metropolitan areas had introduced 12 high-occupancy toll (HOT) facilities on freeways, and 13 new HOT lanes were under construction or extension (GAO, 2012). Congestion pricing (CP) schemes in these regions are expected to reduce congestion, moderate negative congestion externalities (like traffic delays, air pollution, and greenhouse gas emissions), and offer revenue to help fund transport system improvements, including public transit. Much literature has focused on the short-term impacts of CP on traffic conditions and mode choices, and CP's long-term effects on travel preference and climate change (see, e.g., Olszewski and Xie, 2005; Beevers and Carslaw, 2005; Bhatt, 2011). Less attention has been paid to CP's effects on land use patterns, urban form, and environmental justice, all of which merit further exploration (Levinson, 2010; Urban Land Institute, ULI, 2013).

CP strategies differ from many other sources of transport funding (e.g., fuel, sales, and property taxes), and can influence land use decisions rather directly, since trip charges affect travel routes, destinations, timing, and ultimately home and business location decisions. Tolls can affect firms' labor costs, productivity, and customer access. Many experts believe that a tax on vehicle-miles traveled (VMT) may accelerate new development of compact, mixed-use, walkable neighborhoods, and may modestly affect commercial land uses, especially retail (Urban Land Institute, ULI, 2013). Gupta et al.'s (2006) simulations of Austin, Texas suggest that CP may catalyze land development around tolled roads, while London's area-based charge has had a somewhat negative effect on the city center's economy, particularly in retail (Santos and Shaffer 2004). Associations between congestion tolls and land use patterns in Singapore and Stockholm remain ambiguous (Bhatt, 2011; Litman, 2011).

This paper develops modeling improvements for analyzing CP's land use effects. Many studies (e.g., Pines and Sadka, 1985; Wheaton, 1998; Brueckner, 2007; Kono and Joshi, 2012) provide theoretically rigorous frameworks to explore land use patterns under marginal cost pricing (MCP) strategies in monocentric settings, with firms' location decisions exogenously given (i.e., all jobs are placed in the central business district, or CBD). In a city or region with only congestion externalities, MCP is a

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first-best policy to reflect the gap between marginal social and marginal private costs of each trip. In a closed-form monocentric model, MCP raises residential densities near the CBD, while slightly lowered edge densities (Pines and Sadka, 1985; Wheaton, 1998; Kono and Joshi, 2012). A well-executed lot-size zoning policy can replace such MCP policies and still reach the first-best optimum, including an upward adjustment of central densities and downward adjustment of edge densities. However, these findings largely rely on the monocentric assumption and hardly reflect most regions' polycentric reality, with firm location decisions endogenous and dependent, to some extent, on household choices.

Several studies have explored the effects of first-best CP strategies in polycentric cities and their land use effects on both firm and household location choices. For example, Anas and Xu (1999) developed a spatial general equilibrium model without predetermined firm locations to explore the locational effects of MCP in a linear city with discrete zones. They found that the addition of MCP policies could disperse producers away from the regional center while centralizing households, thus bringing jobs and workers closer together. However, their model did not treat the Marshallian agglomeration economies that can cause firms to locate close to one another, arising from nonmarket interactions, and thus can somewhat misestimate CP's effects on job dispersion.[1]

Several other studies have built models for continuous space, allowing more direct comparison of results to those of the traditional monocentric setting. For example, Wheaton (2004) extended a monocentric model to involve both congestion and center-agglomeration externalities, and found that higher congestion levels may cause greater job decentralization.[2] Though his model did not test the toll policy's efficiency, his results suggest that land use-congestion studies of this sort should not overlook interactions between congestion and agglomeration externalities. Recently, Zhang and Kockelman (2014) developed a spatial general equilibrium model that permits such interactions, and compared socially optimal land use patterns to those under a free-market equilibrium. They found that the MCP strategy may lead to job decentralization and residential densification. These non-monocentric studies focus less on other, second-best CP policies, such as a VMT tax and a cordon toll, which are much more practical for application than is MCP.[3]

Several theoretical papers have investigated the land use effects of second-best pricing in a monocentric framework (see, e.g., Mun et al., 2003; Verhoef, 2005; De Lara et al., 2013). Some have sought to extend the monocentric model by involving non-monocentric features, like allowing flexible commute-trip destinations, instead of requiring that all such trips head to the CBD (Mun et al., 2005), or positing two CBDs, instead of one (De Lara et al., 2013). Such improvements still heavily rely on the assumption that firms' location choices are exogenously given, so they cannot anticipate CP's effects on job location patterns. Recent studies relying on discrete non-monocentric settings have examined the spatial redistribution of population and employment after levying a cordon toll or instituting area pricing. For example, Fujishima (2011) extended Anas and Xu's (1999) model to compare the cordon toll and area pricing impacts and found that both schemes can lead to population centralization and job dispersion in Osaka, Japan. Anas and Hiramatsu (2013) applied the RELU-TRAN model (Anas and Liu, 2007) to the Chicago region, to offer a more comprehensive evaluation of cordon tolling's land use and welfare effects. Their findings suggest that restrictive cordons around Chicago's CBD may decentralize jobs, while cordons around inner suburbs may centralize jobs. Related research is less common when using urban economic models with continuous space.

This paper extends Zhang and Kockelman's (2014) model by exploring the land use effects of three CP policies, including MCP, distance-based VMT taxes, and cordon tolls, after controlling for these policies' effects on firms' agglomeration economies. The resulting model is able to endogenously determine monocentric and polycentric structures, where the latter is a duo-centric urban form (i.e., a center plus an annulus). In this way, the work compares the effectiveness of the three CP policies in monocentric versus polycentric settings. The following sections define the model and its optimization problems under different CP schemes, present the simulation algorithm and its many parameters, discuss key simulation results, and offer several conclusions.

2. Model specification

The model developed and applied here assumes a region with continuous circular space. A city locates in this region with an endogenously determined city boundary, $\bar{x}$. The whole city area is assumed to be symmetrical, implying that people need travel only toward or away from the center, along radial street networks, and any circumferential travel is ignored.[4] Only identical households and homogenous firms exist in the city. For all locations x inside the city ($x \in (0, \bar{x}]$), land is used only for firms, households, and/or transport infrastructure. $\theta_f(x)$ and $\theta_h(x)$ represent the fractions of land area used by firms and households, while θ_t represents an exogenously given fraction of land for transportation use. Unlimited rural area exists outside the city boundary/edge, for agriculture use.

2.1. Firm behavior

Each firm is a price taker in the output and input markets, and decides how much labor and land to use for production, at each location x. Each firm's production per unit of land $p(x)$ at location x is determined by two functions: One is an ordinary, constant-returns production function (per unit of land), $f(n(x))$, that only relates to the labor per unit of land or employment density, $n(x)$. The other is a measure of external economies at location x, $A(F(x))$. Thus, $p(x)$ is defined as follows:

$$p(x) = A(F(x))f(n(x)) \tag{1}$$

where $F(x)$ represents a positive agglomeration externality for firms located at x. It is related to firms (or workers) at other locations r and the distance between x and r. A larger market may benefit more from the sharing of facilities and suppliers, a better matching between firms and workers, and the facilitation of social learning through knowledge transmission (Rosenthal and Strange, 2004; Puga, 2010). The setup used here mainly considers the agglomeration effects that come from sharing of facilities and social learning, by assuming that clustered firms benefit more from their workers' knowledge spillovers. Although the model is designed to deliver in a static, long-term spatial equilibrium, it is based on a dynamic agglomeration economy, which assumes that both current and historical economic activities at a given location affect agglomeration economies in production (Henderson, 2003; Rosenthal and Strange, 2004). Thus, $F(x)$ consists of two components:

$$F(x) = F^0(x) + F^1(x) \tag{2}$$

[1] Anas and Xu (1999) model endogenizes firm locations and so can treat the agglomeration benefits from firms located near their workers.

[2] Based on discrete spatial structure, an early model developed by Anas and Kim (1996) already reflects both congestion externalities and agglomeration externalities (on the producer and consumer sides). Firms are allowed to exchange inputs with each other and thus benefit from locating close to one another. Consumers are assumed to make more shopping trips to larger shopping centers, leading to retail-job agglomeration. They found similar results to these from monocentric models in that higher congestion levels may lead to larger numbers of job sub-centers.

[3] Other researchers tend to focus on second-best land use policies, instead of second-best pricing schemes. These include urban growth boundaries in monocentric regions (Kanemoto, 1977; Pines and Sadka, 1985; Brueckner, 2007) and polycentric regions (Anas and Rhee, 2006; Zhang and Kockelman, 2014), and building size/floor-area-ratio regulations in monocentric regions (Pines and Kono, 2012; Kono et al., 2012).

[4] In a two-dimensional urban model where firms can locate anywhere, the choice of transport network determines the distance and cost between any residences and workplaces. The model used here assumes a radial transport network, so workers only travel inward or outward, resulting in circumferential symmetry, rather than bounded sub-centers. This relatively strong assumption makes the model analytically tractable for continuous spatial settings.