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Equilibrium and first-best city with endogenous exposure to local air pollution from traffic

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ABSTRACT

Exposure to urban traffic-induced air pollution is a major health concern of cities. This paper analyzes the urban structure when localized pollution exposure arises from commuting traffic and investigates the feedback effect of endogenous pollution on residential choices. The presence of stronger traffic-induced air pollution exposure reduces the geographical extent and the population of cities. Land rents fall with distance from the city center while population densities may be non-monotonic. Cleaner vehicle technologies reduce pollution exposure everywhere, increase population and density everywhere and do not affect the spatial extent of the city. The paper compares the urban equilibrium with the first-best. The first-best structure is a less expanded city with higher densities at the center and lower densities at the fringe.

1. Introduction

Despite technological improvements and reduction in air pollution emissions over the last years (WHO, 2014), air pollution remains a major concern. More than 400,000 Europeans still die prematurely each year because of air pollution (EEA, 2014). It is a particular concern for urban areas where population is highly concentrated and traffic is the major source of primary pollutants (EEA, 2014). In China, 87% of major cities were recently declared to exceed the guidelines set by the World Health Organization in terms of air pollution concentrations (Zhang and Cao, 2015). Pollution from urban traffic is acknowledged to cause harmful effects not only on the environment but also on human health. Besides their concerns for accessibility and housing space, residents are preoccupied by the health impact of air pollution in their close neighborhood (Chay and Greenstone, 2005; WHO, 2014) and display higher willingness to pay to live in less polluted neighborhoods (e.g. Smith and Huang, 1995; Bickerstaff and Walker, 2001; Lera-López et al., 2012).

As residents have incentives to relocate to less polluted urban areas, they may make longer commuting trips to their workplaces, thereby generating additional pollution and exposing other residents further. As a result, the spatial distribution of both residents and urban pollution is strongly intertwined. This endogeneity between the choice of residence and pollution patterns calls for a dedicated study of the spread of pollution and residences. While urban compaction policies might address environmental concerns linked to total urban emissions, more dispersed urban development might well be beneficial in terms of reducing the impact of localized pollutants, improving local households' well-being and health (e.g. Borrego et al., 2006; Manins et al., 1998; Martins, 2012; De Ridder et al., 2008; Marshall et al., 2005; Schindler and Caruso, 2014). In order to design appropriate urban environmental policies, one requires a detailed understanding of how households' choices and urban structures interact and impact emission generation and health. This is the purpose of this paper.

We extend the standard monocentric city model (Alonso, 1964) with an endogenous local pollution externality that arises from the traffic passing at each location. Our central issue is the endogenous link between pollution exposure and residential choices. We investigate the effects of localized traffic pollution. Allowing for an analytical solution, the model offers a detailed investigation of the feedback effect of endogenous local pollution externalities on residential choices. We show that the stronger the aversion and exposure to traffic-induced pollution are, the smaller are the geographical extent and the population of the city. Households tend to reside further away from the CBD to reduce their exposure to pollution, which creates a tension on the land market near the city border. Land rents fall with distance from the CBD while population densities may be non-monotonic. We also show that cleaner vehicle technologies reduce pollution exposure every-

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where, increase the city population and its density everywhere and do not affect the spatial extent of the city. They induce higher and steeper land rents everywhere and non-monotonic population density profiles are possible for a smaller set of parameters. Compared to previous urban economics literature with aggregate city-wide pollution (e.g. Verhoef and Nijkamp, 2003), we show that lower local traffic-induced air pollution differs from a lower city-wide pollution in terms of its effects on the city extent, the population density and the land rent gradient. Finally, the socially optimal city structure is a less expanded city with smaller population and may also hold non-monotonic population densities. The first-best has higher densities at the center and lower densities at the fringe. The first-best can be decentralized through a localized lump-sum tax.

In contrast to this paper, the urban economic literature mostly focuses on urban air pollution generated by exogenous sources (e.g. Henderson, 1977; Arnott et al., 2008; Rauscher, 2009; Kyriakopoulou and Xepapadeas, 2013) or by endogenous industrial sources (Regnier and Legras, 2014). A few urban economic contributions consider traffic-induced pollution (e.g. Fisch, 1975; Robson, 1976; Proost and Dender, 1998; Van Marrewijk, 2005; Marshall et al., 2005; Lange and Quaas, 2007; Boadway et al., 2011; Gaigné et al., 2012). Fisch (1975) introduces traffic-induced pollution as a cost (for analytical tractability) in a close city and discusses numerical simulations about pollution taxes. Robson (1976) introduces traffic-induced pollution as a disutility also in a closed city model. In contrast to our paper, however, he does not introduce the standard trade-off between residential and commuting choices (again for analytical tractability). McConnell and Straszheim (1982) discuss automobile pollution and congestion and provide numerical assessments of pricing and emission policies. Close to this paper, Verhoef and Nijkamp (2003) discuss numerical simulations of an urban model where residents are homogeneously harmed by the 'total pollution' generated by commuters. However, pollution externalities are spatially differentiated: while some pollutants like ozone are undoubtedly of a regional nature, primary emissions like CO, $PM_{2.5}$ and PM_{10} vary locally (e.g. Colvile et al., 2001; Jerrett et al., 2005; Kingham et al., 2000). To our knowledge, the impact of local pollution exposure from urban commuting has not been studied in an open city framework. This paper, thus, departs from previous literature and provides a general framework to study technological and societal impacts on urban and pollution patterns. It offers a rejoinder to results by Robson (1976) and Verhoef and Nijkamp (2003) but takes on a per-distance pollution perspective. Urban properties are derived, comparative statics are performed and the optimal urban policy is analyzed.

The remainder of the paper is organized as follows: Section 2 presents the model and the competitive land market equilibrium with housing choice and traffic-induced air pollution. Conditions for the existence of equilibrium and equilibrium properties are analyzed. Section 3 presents comparative statics on the exogenous model parameters. In Section 4, the first-best policy allocation and optimal city structure are presented and compared to the equilibrium ones. Section 5 discusses and concludes. Appendices A and B contain the proofs.

2. Urban equilibrium

In the tradition of Alonso (1964), we use a linear monocentric urban model with a spaceless CBD at distance r=0, identical households and absentee landlords. The city is open and households migrate into the city as long as they gain a higher utility than the utility obtained in the rest of the world, $\bar{u}$. Each household is endowed with a Cobb–Douglas utility function[1] that includes the exposure to the local pollution $P(r)$ induced by the commuting traffic passing through the location at distance r to the CBD, in addition to a general basket of goods $Z(r)$ and housing space $H(r)$

$$U = \kappa H(r)^{\alpha} Z(r)^{1-\alpha} P(r)^{-\beta} \tag{2.1}$$

where α and $(1-\alpha)$ represent the preference for each good respectively $(0<\alpha<1)$, and β the aversion to pollution exposure $(0<\beta<1)$. For convenience, we use $\kappa \equiv (1-\alpha)^{\alpha-1}\alpha^{-\alpha}$ as a simplification constant.

Besides the housing and composite consumptions, households spend their income Y on a commuting cost $t\ r$, which is linear with distance from the CBD and there is no congestion. They maximize utility subject to the following budget constraint:

$$H(r)R(r) + Z(r) + tr \leq Y \tag{2.2}$$

where $R(r)$ is the rent per acre at location r.

Each household residing at location r undergoes a negative externality from being exposed to air pollutants generated by commuters who live at further distances from the CBD, up to the urban boundary r_f, and pass by r on their trip to work. We assume that there is one commuter per household as in previous models (e.g. Anas and Xu, 1999). Exposure to local pollution[2] $P(r)$ is increasing with the traffic volume passing by r

$$P(r) = 1 + a + b\int_r^{r_f} n(r)\,\mathrm{d}r \tag{2.3}$$

The parameters $a>0$ and $b>0$ measure the impacts of the regional and traffic-induced pollution in the city. Regional pollution originates from sources other than commuting traffic and is assumed to be the same over the city (Fowler et al., 2013). Traffic-induced pollution depends on the traffic volume $\int_r^{r_f} n(r)dr$ and the vehicle technology b which is expressed in terms of pollution emission per vehicle and unit of traveled distance.[3] Since most industrial or agricultural pollutants are largely independent from population growth (Cramer, 2002), a is exogenous in our model, i.e. not related to the total city population. In the absence of pollution ($a=b=0$), the pollution profile $P(r)$ is equal to one and does not affect the utility level.

In equilibrium, all households get the same reservation utility level $\bar{u}$, no matter their residential location since they are identical and migration is free. The equilibrium is defined by the functions $Z(r)$, $H(r)$, $P(r)$ and $R(r)$ and the scalar r_f that satisfy the pollution exposure property (2.3) and the land allocation property $R(r) = \max\{\Psi(r),\ R_A\}$, where $\Psi(r)$ is the unit land bid rent given by

$$\Psi(r) = \max_{Z(r),H(r)} \frac{Y - tr - Z(r)}{H(r)} \quad \text{s. t.} \quad U(Z(r), H(r), P(r)) \geq \bar{u} \tag{2.4}$$

The unit land bid rent expresses the maximum land rent that the household is willing to pay given its outside utility $\bar{u}$ and income Y. Households take the pollution profile as given.

In the following, we drop the reference to r for Z, H, P and R for conciseness whenever possible.

2.1. Consumption

The household's demand function for housing H and composite good Z are derived from the maximization problem (2.4). As noted in Fujita and Thisse (2002), households have no incentives to get a surplus over their utility $\bar{u}$ so that the constraint (2.4) binds. Defining $\widehat{H}(Z,\bar{u})$ as the unique solution of $U(Z,H,P)=\bar{u}$, we can find the consumption of the composite good Z that maximizes the bid rent $\widehat{\Psi}(r,Z) \equiv (Y - tr - Z)/\widehat{H}(Z,\bar{u})$. Equating $d\widehat{\Psi}(r,Z)/dZ$ to zero we find the equilibrium demand functions for the composite good Z and then

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[1] The Cobb–Douglas is also chosen by Fisch (1975) and Robson (1976).

[2] The functional form for the externality follows from Robson (1976). It does not include a spatial diffusion component (e.g. Kyriakopoulou and Xepapadeas, 2013) in order to analyze only direct local effects of location choice and because our aim is an analytical model solution and analysis.

[3] Distance effects on engine temperature and emissions have been considered in simulations by Schindler and Caruso (2014) but would add terms within the integral of the pollution equation here, which is an unnecessary complication at this stage.