Journal of Environmental Economics and Management 107 (2021) 102443

Contents lists available at ScienceDirect

Journal of Environmental Economics and Management

journal homepage: www.elsevier.com/locate/jeem

On the design of sustainable cities: Local traffic pollution and urban structure☆

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ARTICLE INFO

Article history:
Received 23 May 2020
Revised 11 February 2021
Accepted 2 March 2021
Available online 19 March 2021

JEL classification:
Q53
R14
R49

Keywords:
Local pollution
Urban structure
Commuting

ABSTRACT

This paper investigates the impact of local traffic pollution on the formation of residential and business districts. While firms benefit from local production externalities, households commute to their workplaces with private vehicles and exert a local pollution externality on the residents living along the urban transport networks. The spatial location of firms and residents endogenously results from the trade-off between the production and pollution externalities and the commuting costs. The analysis shows that in monocentric cities the benefits associated with a fall in per-vehicle pollution are absorbed by rents paid to absentee landlords. When a city includes business and residential districts as well as a district mixing both agents, a lower per-vehicle pollution enlarges the residential districts and shifts the business districts closer to the geographical center of the city. The paper finally studies the optimal city structure. The first-best policies that fully internalize the externalities still foster business agglomeration.

1. Introduction

In the 2030 Agenda for Sustainable Development, the United Nations promote efforts to ensure the successful management of rapid urban growth (United Nations, 2018). While 55% of the world's population live today in urban areas, 68% are expected to reside in urban areas by 2050 (United Nations, 2018). Such a rapid urban development offers a unique opportunity to design sustainable urban planning and reform land-use policies. Key challenges include the management of environmental quality in urban areas, in particular, the air quality. The current urban trends point toward higher car dependence and longer commuting distances (OECD, 2018), which clearly leads to higher levels of air pollution.

According to the World Health Organization (WHO, 2016), air pollution represents the biggest environmental risk to health. Around 3 million deaths are attributed to ambient air pollution annually. In 2012, one out of nine deaths was caused by air pollution-related conditions (WHO, 2016). In China, 87% of major cities are exposed to pollution levels in excess of the WHO guidelines. In Austria, France, and Switzerland, air pollution is estimated to cause 6% of total mortality and about half of these

☆ We thank the Associate Editor, Martin Quaas, and two anonymous reviewers for their helpful comments on a previous version of this paper. We also thank participants in the 9th European Urban Economics Association Conference, EAERE-ETH Winter School 2020, ITEA 2019, Workshop on International Trade and Urban Economics 2019 (St. Petersburg), 24th EAERE Conference for helpful comments and suggestions. Kyriakopoulou acknowledges financial support from the Swedish Environmental Protection Agency (Project title: To buy or not to buy. Vehicle demand and policy for sustainable transport).

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https://doi.org/10.1016/j.jeem.2021.102443

mortalities are attributed to motorized traffic (Künzli et al., 2000). Traffic is shown to be the most important contributor of urban air pollution (Karagulian et al., 2015). For example, in Paris, road transport accounts for 73% of primary emissions of NOx and 42% of particulate matter PM10, while in London it accounts for 50% of both pollutants (Font et al., 2019). Importantly, those pollutants have a strong impact on the locations around the emitting vehicles because of their low diffusion properties.[1]

The study of traffic pollution is important to understand the impact of the past growth of combustion vehicles on urban structure in the last century. But it is also important for the understanding of the potential effects of current and future technologies and policies curbing urban traffic pollution. Traffic pollution will likely decrease due to technological innovations like better fuel efficient combustion, lower-sulfur gasoline, and electric cars. It should also significantly drop with current and future investments in bike lanes, metro infrastructures, and transit-parking as well as with urban access policies like urban tolls and low emission zones. A wider use of car pooling and tele-working may also diminish it. Finally, current and future policies curbing urban congestion are also likely to reduce traffic pollution as congested traffic implies about a threefold increase in CO, HC, and NOx emissions compared to non-congested traffic (Sjodin et al., 1998).

The objective of this paper is to study the impact of local traffic pollution on the attractiveness and internal structure of cities when firms and residents compete for land. Firms agglomerate in space due to production externalities, which imply benefits to any firm from the existence of other firms nearby (Marshall, 1890). Residents incur a cost not only from commuting to work but also from the pollution generated by the local traffic around their residences. We discuss spatial equilibria where firms and residents compete for land in closed cities with exogenous population sizes. In particular, we focus on three urban configurations: monocentric, partially integrated, fully integrated cities. Those configurations emerge respectively for large, intermediate and small population sizes.

We find that the pollution externality affects the urban structure by changing the sizes of residential, business and integrated areas in the city. It also changes the land rents and the discrimination power of landowners depending on the equilibrium urban configuration. In the case of monocentric cities, we find that lower per-vehicle pollution benefits the landlords by increasing the land rents while it *harms* residents because of the interaction between the land and labor markets. In the case of cities that include pure residential and business areas as well as mixed areas, lower per-vehicle pollution benefits the residents. This is because the latter have the option to leave the mixed areas and pay lower land rents in the residential districts that have become cleaner. Therefore, lower per-vehicle pollution expands residential areas, shifts business activities to the city center, and shrinks the mixed areas. We then compare the market equilibrium to the optimal structure and show that the consideration of production and pollution externalities fosters the agglomeration of firms. Finally, we discuss how the effects of local traffic pollution differ from pollution that diffuses across the city. To the best of our knowledge, this is the first paper that studies how local traffic pollution affects the land market for office and residential space and how it changes the internal structure of a city.

From a methodological viewpoint, the paper extends Fujita and Ogawa's (1982) framework by considering the presence of local traffic pollution. We select this model for its analytical simplicity. In particular, Fujita and Ogawa's model permits the theoretical analysis of land bid-rent functions which allows us to study the precise effect of local pollution on the different urban configurations. Recent alternative approaches use quantitative models of endogenous urban structure that include more effects and are closer to reality (e.g., Ahlfeldt et al., 2016). However, these quantitative models rely on simulation exercises, calibration or estimations that are often specific to the considered city and do not make possible the theoretical discussion of land prices and urban structure.

The paper is organized as follows. Section 2 relates the paper to the literature. Section 3 presents the model while Section 4 discusses the spatial equilibrium with local traffic pollution. Section 5 is devoted to the first-best city structure and the policy instruments needed to implement it. Section 6 briefly discusses the case of diffused pollution and Section 7 concludes. Appendices include mathematical details.

2. Related literature

The increasing number of people moving to urban areas creates a number of challenges, as a larger percentage of the world population is exposed to high pollution levels. The poor air quality in the majority of big cities has motivated the study of pollution externalities in a spatial context. In most papers, pollution is assumed to be emitted from stationary sources – such as the industrial activity – so that households locate in cleaner areas at the expense of higher land rents. In particular, Henderson (1977) studies air pollution externalities in a specific urban setting with predetermined land use, and discusses optimal environmental policies that include Pigouvian taxes and regulations. He finds that optimal taxes should be combined with zoning policies to prevent polluting firms from locating to residential areas. Verhoef and Nijkamp (2002) use a general spatial equilibrium model of a monocentric city to study the pollution effect of industrial activity on residential areas. They investigate first- and second-best policies and find that environmental goals can be promoted at the expense of agglomeration economies, but can also stimulate these economies. New Economic Geography models have also been used to study how the concentration of economic activity across two regions is affected by environmental pollution associated with the production process (e.g. Lange and Quaas, 2007; Zeng and Zhao, 2009).

[1] Both pollutants pose serious threats to human health. With an average lifetime of 3.8 h, NO_2 can be considered as a very *local* pollutant especially in summer and urban environments (Liu et al., 2016). Particulate matter have a life time of about a day (National Academies et al. 2010, p. 67) and in the absence of wind, they diffuse very *locally* around the polluting vehicles.

When commuting is costly, workers trade off between shorter commutes and worse air quality. This leads to the emergence of different spatial structures, depending on the size of the agglomeration and dispersion forces. In this context, Arnott et al. (2008) show how pollution diffusion and costly commuting affect the optimal and equilibrium urban patterns. They find that the optimal spatial allocation leads to monocentric cities when the commuting costs are low and to multiple center cities when the cost of pollution is very high. Kyriakopoulou and Xepapadeas (2013) study how pollution from the industrial activity interacts with two agglomeration forces, namely production externalities and a first nature advantage site. They find that when the social cost of pollution is taken into account, sites with first nature advantages can lose their comparative advantage. Kyriakopoulou and Xepapadeas (2017) study a general equilibrium model embedding pollution from stationary forces, production externalities, and commuting costs and discuss the optimal and equilibrium location of industrial and residential clusters across space. At the optimum, firms are shown to cluster in districts smaller than in the equilibrium city structure, while firms and households locate in pure industrial and residential clusters, respectively. In contrast, in equilibrium, mixed areas are formed. Finally, Regnier and Legras (2018) study the case where households are harmed by industrial pollution but not by traffic pollution and show how the equilibrium spatial structures affect the emissions of greenhouse gases generated from commuting. They show that industrial pollution shrinks the mixed area of a partially integrated city, while the larger specialized areas have a negative impact on the greenhouse gas emissions.

There are also some papers in this literature that consider pollution generated by urban traffic (non-point source pollution). Verhoef and Nijkamp (2004) point out the importance of analyzing urban air pollution in a spatial framework since aggregate pollution depends on the total amount of commuting within a city and not on the absolute number of commuters. This implies that changing the location of workers (and not their number) results in either higher or lower levels of aggregate pollution. They also show that when first-best policies are implemented, there is a simultaneous stimulation of agglomeration effects and a reduction of environmental externalities. In a similar context, Schindler et al. (2017) investigate the effect of urban traffic-induced air pollution on residential choices. Their findings suggest that higher pollution levels reduce the geographical extent and the population of the city. Cleaner vehicles reduce pollution, increase the population and the density everywhere, but they do not affect the size of the city. Denant-Boemont et al. (2018) study the effects of urban design on pollution and welfare. They find that the polycentric cities are desirable from both a welfare and an ecological perspective. Borck and Brueckner (2018) use a monocentric city model to analyze the socially optimal urban form when both housing and commuting generate emissions. They show that the combination of three taxes (land, housing and commuting tax) can generate a more compact city with taller buildings and less commuting. Finally, Schindler and Caruso (2018) use an agent-based model with traffic pollution to analyze the effect of household aversion to pollution on urban and pollution patterns.

All the above papers that study the effect of the transport-related pollution on the size of the cities and on aggregate pollution levels assume (a) spaceless business center(s). Our paper extends these models by assuming that both households and firms compete for land. They form residential and business clusters of different sizes depending on the strength of agglomeration and dispersion forces. In this study, we aim to investigate the trade-off between production externalities, commuting cost and traffic pollution, derive the equilibrium and the optimal urban configurations, and discuss policies that decentralize the optimal structure as an equilibrium outcome. In our analysis, we use a model à la Fujita and Ogawa (1982) which is analytically tractable and allows us to derive closed-form solutions for the different urban configurations. Our results can be compared to Regnier and Legras (2018), who use the same model to study the impact of *industrial pollution* on urban patterns and find that more specialized urban configurations are *more* likely to be an equilibrium outcome when industrial pollution is taken into account. Our paper explores the effect of *traffic pollution* on urban patterns and shows that more specialized urban configurations are *less* likely to become a spatial equilibrium when the pollution per vehicle increases. We should also point out that even though Denant-Boemont et al. (2018) consider pollution externalities arising from commuting, their framework is different to ours since (i) firms do not compete for land in their model (urban land is exclusively devoted to residents), and (ii) they study the effect of urban design on pollution. On the contrary, our main question is what is the effect of pollution on urban design, i.e., where firms and households would like to locate under the presence of traffic pollution. Our results have important policy implications for the design of sustainable cities.

3. Model

We consider a linear city model with homogeneous firms, homogeneous residents-workers, and absentee landlords. The city expands on the unit-width segment where firms and workers interact through competitive labor and land markets. There are three forces that promote the formation of business and residential areas: business production externalities, workers' commuting cost, and local traffic pollution. More precisely, firms tend to locate closer to each other because geographical proximity increases their productivity, for instance, through the better exchange of information and ideas. On the other hand, workers face a trade-off: locating closer to firms relaxes their commuting costs but exposes them to higher pollution because of the higher number of commuters in more central locations. The balance between those forces determines the land use.

Following Fujita and Ogawa (1982), we assume a mass N of workers who work and reside in the city and an endogenous mass M of firms that produce in the city.[2] Workers consume an (inelastic) unit of land and a quantity c of composite good, available in the national market at a price normalized to 1.[3] Workers are harmed by their exposure to local pollution P at their place of residence. They are endowed with a utility function given by

$$U(c, P) = c - \theta P. \tag{1}$$

The parameter θ captures the pollution aversion (utility units per ton of pollutant). It is larger in urban areas where atmospheric conditions (temperature or air pressure) augment the negative impact of local pollution.[4] Our main assumption is that residents are harmed by the local pollution induced by commuters ($PM_{2.5}$, $PM_{10,}NOx$) in the locales where they live:

$$P(x) = \varepsilon N(x), \tag{2}$$

where $N(x)$ is the mass of commuters crossing location x. The parameter ε measures the *per-vehicle pollution*, that is, the local pollution emitted by each vehicle at a specific location (e.g., ton of pollutants per vehicle). This parameter captures technology and policy features. It falls with improvements in fuel efficiency, imposition of catalytic converters, ban of diesel engines, introduction of electric cars, etc. It also captures the urban developments of bike lanes, metros, and peri-urban transit parking, to the extent that those reduce the share of car vehicles independently of the workers' residences. The parameter can also express the exposure to road noise.[5]

Firms hire workers who commute from home to workplace with private vehicles. Each worker gets a salary $w(y)$ at a firm located at y and incurs a commuting cost given by $t|x-y|$ where t is the cost per unit of distance. A worker residing at x and working at y has a budget constraint given by

$$c(x) + R(x) + t|x-y| \leq w(y) \tag{3}$$

where $R(x)$ is the land rent.

Firms have equal sizes and produce the composite good that is shipped and sold at unit price in the national market. For the sake of exposition, each firm uses a unit of land and a unit mass of workers.[6] Its production function depends on spillover, communication, and economic interactions summarized by

$$A(y) = \int (\alpha - \tau|z-y|)m(z)\mathrm{d}z \tag{4}$$

where $m(z)$ is the density of firms at location z, α is a parameter scaling productivity and τ reflects the cost of interaction with firms that are located at the spatial point z.[7] The term $(\alpha - \tau|z-y|)$ can be interpreted as knowledge or information spillovers enjoyed by a firm at y when interacting with another firm at z. In the context of production, it can be interpreted as the contribution of firms at z in the production of firms at y. Importantly, the higher the mass of firms in nearby areas, the higher the productivity of a firm located at y. Empirical research in urban and regional economics provides ample evidence of such type of agglomeration forces (Ciccone and Hall, 1996; Rosenthal and Strange, 2008). We assume that all firms have a positive interaction in the sense that $\alpha - \tau|z-y| > 0$ for any feasible distance in the city.[8] Firm profits are given by

$$\pi(y) = A(y) - R(y) - w(y) \tag{5}$$

where $R(y)$ and $w(y)$ denote the land rent and labor costs, respectively.

[2] Fujita and Ogawa's (1982) model offers several advantages. First, it neatly focuses on the main trade-off between production and pollution externalities. Second, it leads to sufficiently simple land bid-rents that permit a theoretical analysis of land market equilibrium and first-best conditions. Third, absent traffic pollution externalities, the model is known to have a unique equilibrium city structure (see Fujita and Thisse, 2002), which avoids the discussion of multiple equilibria (e.g., Ogawa and Fujita, 1980; Commendatore et al., 2017).

[3] For simplicity, we assume that the consumption of land is equal to one. Fixed land consumption by both households and firms is assumed in Fujita and Thisse (2002, chapter 6.3) and Regnier and Legras (2018).

[4] The aversion parameter θ could also depend on socio-demographic variables of residents, such as average age and health status.

[5] We distinguish the parameters ε and θ that represent respectively the vehicle pollution technology and the degree of pollution aversion. The former depends on the adoption of clean air technologies and policies, while the latter relates to individuals' perception about pollution. Changes in the value of one of the parameters do not necessarily affect the other. For instance, ε falls with the advent of electric cars while θ may have risen after the climate strikes that started in 2018 and the increasing awareness for environmental problems. This distinction is important in terms of policy implications.

[6] The firms' land and labor demands can trivially be extended to any scalars. See Fujita and Ogawa (1982).

[7] The combination of linear commuting cost functions and quadratic production externality functions are often used in urban economics literature because of their analytical tractability. Under linear commuting costs, workers arbitrage between different workplaces (see Eq. (11) below). The implications of linear and nonlinear commuting costs are presented in Berliant and Tabuchi (2017). Quadratic production externality functions have been applied by Ogawa and Fujita (1980) and Mossay and Picard (2011). These functions provide a good benchmark and remarkable analytical tractability. Non-quadratic production externality functions have been used by Fujita and Ogawa (1982) and Lucas and Rossi-Hansberg (2002) and also in recent quantitative urban models (Ahlfeldt et al., 2016). In most cases, such production functions do not permit the analytical characterization of spatial equilibria.

[8] A sufficient condition is that $\alpha > 2\tau M$. We assume that α is high enough or τ is low enough for this inequality to be satisfied.

4. Spatial equilibrium

In this section, we define the equilibrium in the urban labor and land markets. We then study specific urban structures when firms and residents separate or mix in the same geographical areas of a closed city. In particular, we study three city structures: (i) monocentric cities where businesses sort out in a central district, (ii) partially integrated cities where firms and residents co-locate in a central district but also form specialized clusters in the rest of the city, and (iii) fully integrated cities where businesses and residents co-locate in the whole urban area.

4.1. Equilibrium definition

Workers are homogeneous and able to relocate at no cost within the city. For this reason, in equilibrium, they must reach the same utility level U^* independently of their workplaces and residences. If it were not the case, they would have incentives to move to the urban location that offers the highest utility. Workers' consumption is given by their binding budget constraint: $c(x) = w(y) - t|x-y| - R(x)$. The maximum land rent that they can offer in order to locate at the spatial location x while working at y is given by the following residential bid-rent function:

$$\Psi(x, U^*) = \max_y \; w(y) - t|x-y| - U^* - \theta P(x) \tag{6}$$

Firms are free to enter and produce in the city. Free entry pushes their profits to zero so that $\pi(y) = A(y) - R(y) - w(y) = 0$. Therefore, the maximum land rent that a firm can offer is given by the following business bid-rent function:

$$\Phi(y) = A(y) - w(y) \tag{7}$$

Let X be the set of locations where only residents locate, Y the set of locations where only firms locate, and Z the set of locations where both residents and firms co-locate. The density of residents and firms are denoted by $n(x)$ and $m(x)$, respectively. A spatial equilibrium satisfies the following conditions:

1. Land market equilibrium:

$$\begin{aligned}
\Psi(x, U^*) \geq max\{\Phi(x), R_A\} \quad & x \in X \\
\Phi(x) \geq max\{\Psi(x, U^*), R_A\} \quad & x \in Y \\
\Phi(x) = \Psi(\mathrm{x}, \mathrm{U}^*) \geq \mathrm{R_A} \quad & x \in Z \\
R_A \geq max\{\Phi(x), \Psi(x, U^*)\} \quad & x \notin X \cup Y \cup Z \\
n(x) + m(x) = 1 \quad & x \in X \cup Y \cup Z
\end{aligned}$$

2. Labor market equilibrium: $\int_{X\cup Z} n(x)\mathrm{d}x = \int_{Y\cup Z} m(x)\mathrm{d}x$.
3. Firms' and workers' population constraints: $\int_{Y\cup Z} m(x)\mathrm{d}x = M$ and $\int_{X\cup Z} n(x)\mathrm{d}x = N$.
4. No commuting in an integrated district: $|R'(x)| < t$, where $x \in Z$ and R is the land rent.

The first set of land market equilibrium conditions imply that each location is occupied by the agent who offers the highest bid-rent. They also require that the demand for land by residents and firms and the supply for land by absentee landlords balance in every location of the city. The second condition says that labor demand is equal to labor supply in the interior of the city. The third condition links the densities to total population. Conditions 2 to 3 imply that the mass of firms and the mass of workers are equal: $M = N$. The fourth condition expresses that there is no incentive to commute in a district where both firms and workers co-locate. This is true when the commuting cost per unit of distance is larger than the land gradient in any district where residents and businesses co-locate. Intuitively, a worker co-locating with her firm at location x and paying a land rent $R(x)$ should have no incentive to relocate at $x \pm dx$, $dx > 0$ and pay a land rent $R(x \pm dx)$ and commuting cost tdx. Finally, as in Ogawa and Fujita (1980), there is no cross-commuting even in the presence of local pollution.[9]

Following the literature, we study spatial equilibria in cities that are spatially symmetric around $x = 0$. We can therefore focus on the land use starting from the city center to the city edge ($x > 0$). We postulate a general urban configuration with three types of urban districts. The first one has an integrated area in the middle of the city $Z \equiv [0, b_0]$ where firms and workers locate next to each other and workers do not need to commute. The second one has a business area in $Y \equiv [b_0, b_1]$, which hosts only firms and to which workers commute. The last one has a residential area $X \equiv [b_1, b_2]$, in which workers have residences and from which they commute to the business area. The scalars (b_0, b_1) are the boundaries between districts with different land use while b_2 is the city border, separating the residential area from the outside area that is assumed to be used for agricultural purpose. We study urban configurations as special cases of this general urban configuration. For instance, a monocentric city emerges if $b_0 = 0 < b_1 < b_2$ as the city only includes a business and residential area. A fully integrated city emerges for $b_0 = b_1 = b_2 > 0$

[9] See Proof in Appendix A.

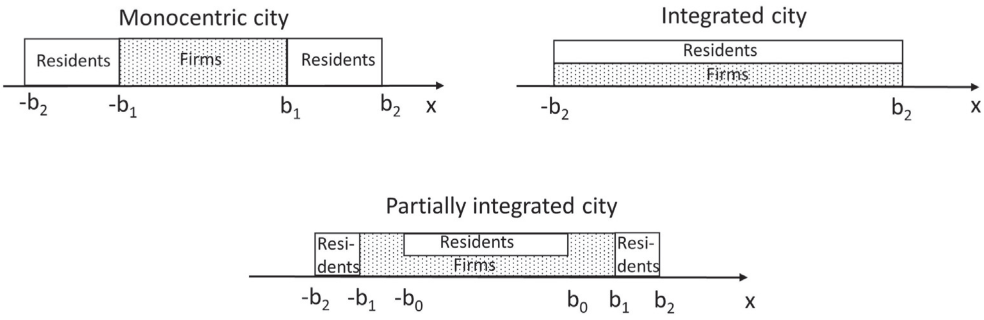

Fig. 1. Three city configurations.

as firms and workers locate next to each other in the whole urban area. A partially integrated configuration takes place if $0 < b_0 < b_1 < b_2$. Fig. 1 displays the three city configurations.

We consider spatial equilibria in closed cities with an exogenous city size M. Below, we study the different urban patterns that emerge as the population size M decreases (monocentric, partially integrated, fully integrated city).

4.2. Monocentric city

A monocentric city includes only a business district on $[0, b_1]$ and a residential one on $[b_1, b_2]$ $(0 < b_1 < b_2)$. The firm density $m(y)$ is equal to one in the business district and zero in the residential district while the opposite holds for the residential density. The borders between residential district, business district, and farming land are respectively given by $b_1 = M/2$ and $b_2 = M$. Because of land market arbitrage, the bid-rents equalize between residential and business districts and between residential and agricultural land:

$$\Psi(M/2, U^*) = \Phi(M/2) \tag{8}$$

$$\Psi(M, U^*) = R_A \tag{9}$$

Also, there is arbitrage between labor and commuting in the employment basin $[0, M]$. Namely, workers should not get a higher utility by changing their workplaces within the same employment basin. This implies that they get the same utility level U^* for any workplaces y and y' on the left-hand side of their residences x so that

$$U^* = w(y) - t(x-y) - R(x) - \theta P(x) = w(y') - t\left(x - y'\right) - R(x) - \theta P(x) \tag{10}$$

After simplification, this yields the labor-commuting arbitrage relationship

$$w(y) + ty = w(y') + ty', \quad y, y' \in [0, M/2] \tag{11}$$

In other words, to attract workers, firms must compensate workers for their commuting cost. The spatial equilibrium is reached if bid-rents satisfy the following conditions:

$$\Phi(y) \geq \Psi(y, U^*) \geq R_A \quad \text{if} \quad y \in [0, M/2] \tag{12}$$

$$\Psi(x, U^*) \geq \Phi(x) \geq R_A \quad \text{if} \ x \in [M/2, M] \tag{13}$$

Conditions (12)–(13) mean that firms should outbid households in the center $[0, M/2]$, while the opposite is true in the residential area $[M/2, M]$. Fig. 2 displays the equilibrium land bid-rent in monocentric cities.

In a monocentric city, traffic pollution is given by the mass of commuters flowing through location $x > 0$. In other words, at each spatial point x, the number of commuters is equal to the number of people living at any location on the right-hand side of x and working on the left-hand side of x, i.e.:

$$N(x) = \begin{cases} x & \text{if} \quad x \in [0, M/2] \\ M - x & \text{if} \quad x \in [M/2, M] \end{cases} \tag{14}$$

Firms' production function in the monocentric city (A_m) is given by

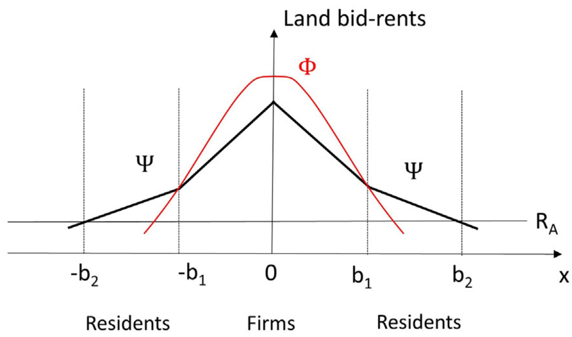

Fig. 2. Equilibrium land rents in monocentric cities.

$$A_m(y) = \int_{-M/2}^{M/2} (\alpha - \tau|z-y|)\mathrm{d}z = \begin{cases} M\alpha - \tau\left(\frac{1}{4}M^2 + y^2\right) & \text{if} \quad y \in [0, M/2] \\ M(\alpha - y\tau) & \text{if} \quad y \in [M/2, M] \end{cases} \tag{15}$$

which is concave in M.

Note that there is no traffic at the city border, which means that $P(M) = 0$. However, all commuters cross the location $b_1 = M/2$, which is the border between the business and the residential cluster. This spatial point has the highest number of commuters and as a result, pollution reaches its peak value, $P(M/2) = \varepsilon M/2$. Solving for (8) and (9), we obtain the utility as a function of the city size:

$$U^*(M) = A_m(M/2) - tM - 2R_A + \varepsilon\theta M/2 \tag{16}$$

Because A_m is a concave function, the utility is also a concave function of the city size. In the absence of pollution, each worker's utility is given by the value of her employer's production, minus her commuting cost, minus the opportunity cost of the land used by her residence and her workplace. Considering pollution, the equilibrium condition (16) shows that *the per-vehicle pollution parameter ε and the pollution aversion parameter θ have a positive effect on utility*. This is because those parameters flatten the equilibrium residential bid-rent in the residential district, which successively computes as

$$\begin{aligned} \Psi(x, U^*) &= R_A + t(M-x) + \theta P(M) - \theta P(x) \\ &= R_A + t(M-x) - \varepsilon\theta(M-x), \quad x \in [M/2, M] \end{aligned} \tag{17}$$

and has a gradient equal to $-(t - \varepsilon\theta)$. Indeed, the commuting advantage of a residence closer to the business district is balanced with the drawback of higher pollution. Because spatial differences between residents are attenuated, *landlords are limited in their ability to discriminate and extract the surplus of residents*. In other words, cleaner vehicles (smaller ε) increase the residential land rent ($\partial\Psi(x,U^*)/\partial\varepsilon = -\theta(M-x) < 0$), which is received by the landlord, while residents pay higher land rents and get lower utility levels.

This result comes as a surprise because the per-vehicle pollution parameter ε negatively affects individuals but has the opposite effect in the context of urban land and labor market. More precisely, the per-vehicle pollution parameter has three effects. The first one is the negative direct effect on the utility by $\theta P(x)$. The second one is an indirect effect through the land market. In equilibrium, landlords must make their land as attractive to residents as the land plots located at the city border b_2. Since there is no pollution at this border ($P(b_2) = 0$), residents ask to be compensated for the local pollution damage $\theta P(x)$ by landlords, who decrease their land rent by the same amount. In equilibrium, this yields a flatter residential land rent that keeps utility constant across space. In Fig. 2, for $x > 0$, this means that the residential bid-rent Ψ counterclockwise rotates around the point $b_2 = M$. By this second effect, the direct utility loss is fully shifted to landlords. In addition, for a given utility level, the land rent in the internal border b_1 falls by the amount of $\theta P(b_1) = \varepsilon\theta M/2$. This implies that the land rent must also fall by the same amount on the left-hand side of b_1 so that firms pay a lower land rent in the business center.

The third effect is also indirect and stems from the labor market arbitrage in the business district. Absent of free entry, firms would make a profit because of the above lower land rents. However, under free entry, firms compete to attract workers and raise their wages until they make zero profit. Hence, the decrease in the land rent in the business area is fully passed to workers. All workers incur a wage increase by the amount $\varepsilon\theta M/2$. Since the first and second effects cancel out, this third effect increases the equilibrium utility by the amount $\varepsilon\theta M/2$. In brief, workers-residents are compensated twice for the same pollution damage.

Such a mechanism takes place in this model because firms compete for (a non-zero amount of) land. In particular, it is not present in models where businesses do not use any land (e.g., Schindler et al., 2017; Denant-Boemont et al., 2018). In addition, this mechanism is important for forecasting the effect of current and future technological and policy changes that *reduce* the per-vehicle pollution ε: in a monocentric city configuration, *such policies will increase the residential land rent and benefit the landlords at the expense of the residents.*

The monocentric city exists only under certain conditions. In equilibrium, firms must overbid residents in the business district, and in particular at $y = 0$:

$$\Phi(0) \geq \Psi(0, U^*) \tag{18}$$

Using (7), (8), (11), and (17), the condition becomes

$$A_m(0) - A_m(M/2) \geq tM + \theta \left[P(M/2) - P(0)\right] \tag{19}$$

According to this condition, firms overbid residents at the city center $y = 0$ if the productivity benefits from locating in the center (left-hand side of inequality) exceed the commuting cost (first term on the right-hand side) plus the utility gain from a lower level of traffic pollution in the city center (second term on the right-hand side). After substituting for A_m and P, we get

$$M \geq \frac{4t + 2\varepsilon\theta}{\tau} \tag{20}$$

Hence, monocentric structures are spatial equilibrium only for sufficiently big cities, low enough commuting costs and low levels of externalities from local traffic pollution. When (20) gets binding, there exist incentives for workers to combine their residence and workplace at the city center, which will be further discussed in subsection 4.3. The monocentric city configuration is therefore supported by a smaller set of parameters when $\varepsilon\theta$ rises. Conversely, *the technologies and policies that reduce the parameter bundle $\varepsilon\theta$ sustain the monocentric city configuration for larger parameter sets*. For example, electric vehicles produce very little local air pollution; hybrid cars also have a better gas mileage than other fuel cars; better fuel efficiency implies gas savings which helps the environment; cleaner combustion engines or lower-sulfur gasoline work in the same manner. All these technological advances decrease ε and favor the formation of a monocentric city.

Finally, since the residential bid-rent Ψ is equal to the land rent R_A at the city border $x = M$, it lies above R_A only if $\mathrm{d}\Psi/\mathrm{d}x \leq 0, x \in [M/2, M]$. Because $\mathrm{d}\Psi/\mathrm{d}x = -t + \varepsilon\theta$, the residential bid-rent Ψ lies above R_A if and only if $\varepsilon\theta \leq t$. This is intuitive. In the absence of pollution, the residential land gradient is negative because landlords reap the benefits of lower commuting distance at locations closer to the city center. In the presence of local traffic pollution, those locations are less attractive. If pollution is too high ($\varepsilon\theta > t$), proximity to the business district harms residents who are now willing to pay lower land rents. This makes the land gradient positive and the land rents lower than the farming land rent R_A, which is a contradiction according to the equilibrium condition (1).

Proposition 1. *A monocentric city is an equilibrium if $\varepsilon\theta \leq t$ and $M \geq (4t + 2\varepsilon\theta)/\tau$. Utility increases with higher per-vehicle pollution ε and pollution aversion θ.*

Proof. *We finally need to show that bid-rents Φ and Ψ are ranked as in (12)–(13). One can indeed show that the firm bid-rent $\Phi(y)$ is an affine function of $A_m(y)$ and is therefore a concave function while the worker bid-rent $\Psi(x, U^*)$ is a piece-wise linear and convex function of x. Given (8) and (18), this implies that bid-rents Φ and Ψ are ranked as in (12).* ∎

We now turn to the partially integrated urban configuration.

4.3. Partially integrated city

The partially integrated city includes a mixed area at the center of the city $[-b_0, b_0]$, surrounded by business areas, $[-b_1, -b_0]$ and $[b_0, b_1]$ and then by residential areas, $[-b_2, -b_1]$ and $[b_1, b_2]$, where $0 < b_0 < b_1 < b_2$. The city is symmetric so that we can focus on the right-hand side of the city ($x > 0$). The inelastic land use and the organization of urban areas impose a series of conditions on firms' and residents' densities. Indeed, the densities of residences and firms should be equal in the integrated area because each worker is employed in a firm at the same location. So, we get $m(x) = n(x) = \frac{1}{2}$ for $x \in [0, b_0]$. The business area hosts only firms so that $m(x) = 1$ and $n(x) = 0$ for $x \in [b_0, b_1]$. The residential area hosts only residents so that $m(x) = 0$ and $n(x) = 1$ for $x \in [b_1, b_2]$. Given this, it becomes clear that the mass of commuters crossing location $x > 0$ is given by:

$$N(x) = \begin{cases} 0 & \text{if} \quad x \in [0, b_0] \\ x - b_0 & \text{if} \quad x \in [b_0, b_1] \\ b_2 - x & \text{if} \quad x \in [b_1, b_2] \end{cases} \tag{21}$$

The mass of commuters is zero at $x = b_0$ and $x = b_2$, as there is no commuting and no pollution both at the boundary between the mixed area and the business area (b_0) and at the border of the city (b_2). It is positive in business and residential areas which implies that local traffic pollution is also positive and equal to $P(x) = \varepsilon N(x)$.

The inelastic land use and labor requirement yield the city structure where the border of the city and the border between business and residential districts are given by $b_2 = M$ and $b_1 = \frac{1}{2}(M + b_0)$. Using these values for the borders, the production

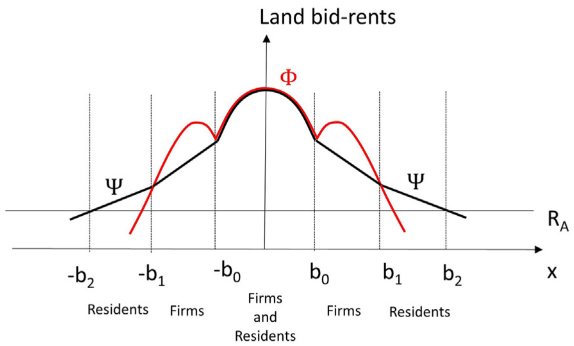

Fig. 3. Equilibrium land rents in partially integrated cities.

function (4) is easily computed as:

$$A_p(x) = \begin{cases} \alpha M - \dfrac{\tau}{2}(x^2 - b_0^2 + 2b_1^2) & \text{if} \quad x \in [0, b_0] \\ \alpha M - \tau(x^2 - b_0|x| + b_1^2) & \text{if} \quad |x| \in [b_0, b_1] \\ \alpha M - \tau M|x| & \text{if} \quad |x| \in [b_1, b_2] \end{cases} \tag{22}$$

which is symmetric around $x = 0$, concave in the integrated area and business district, and linearly decreasing in the residential district.

At a given city size, the equilibrium is defined by the conditions presented in subsection 4.1. Fig. 3 presents the land bid-rents when this urban configuration is a spatial equilibrium. Residents' and firms' bid-rents are equalized in the central district, while residents outbid firms in the peripheral residential district and are outbidden by firms in the business district.

Combining the above procedures for partially integrated and monocentric cities we prove the following proposition.

Proposition 2. *The partially integrated city is a spatial equilibrium if $\varepsilon\theta \le t$ and $(2t + \varepsilon\theta)/\tau < M < (4t + 2\varepsilon\theta)/\tau$. The district borders are given by*

$$(b_0^*, b_1^*, b_2^*) = \left(\frac{(4t + 2\varepsilon\theta)}{\tau} - M, \ \frac{(2t + \varepsilon\theta)}{\tau}, \ M \right) \tag{23}$$

Utility is given by

$$U^*(M) = A_p(b_0^*) - 2t\left(M - b_0^*\right) - 2R_A \tag{24}$$

Proof. *See* Appendix B. ■

The proposition calls for three remarks. First, the internal borders of the partially integrated city change with the population size, the commuting cost and the traffic pollution parameter bundle $\varepsilon\theta$. A larger population fosters the entry of firms and enhances business interactions, which raises firms' productivity and bid-rents. As a result, more residents find it harder to reside close to their employers, relocate to the residential district, and commute from there. As a consequence, a larger population enlarges the residential and the business areas and shrinks the integrated area. Importantly for our study, *higher per-vehicle pollution and pollution aversion (higher $\varepsilon\theta$) enlarge the central integrated district, shift the business district away from the city center, and shrink the residential district (larger b_0 and b_1 and smaller $b_2 - b_1$).*

The mechanism behind this result includes four effects. The first three effects are similar to the ones in the monocentric city. The first effect of higher per-vehicle pollution ε lies in the direct harm caused by local pollution. The second effect works through the land market. In the residential district, the higher per-vehicle pollution induces a smaller and flatter residential bid-rent, so that utility losses from local traffic pollution are transformed to lower land rents to landlords. The land rent falls on the right-hand side of the district border b_1. Here, lower land rents help firms to overbid workers on this side of b_1 and entice them to spread the business area over the residential area beyond b_1. The third effect results from the labor market as in the monocentric city. Land market arbitrage propagates the lower land rents to the left-hand side of b_1 so that firms are forced to raise wages due to free entry. Labor market competition does not only spread the wage increase over all workers in the business district but also propagates it into the central integrated district $[-b_0, b_0]$. Workers then have higher income and are better equipped to match firms' land rents in this district. As a consequence, this district grows and its border b_0 shifts to the right. Overall, the business districts shrink and spread apart.

The last effect stems from the changes in production externalities. Indeed, as the two business districts spread apart, firms become - on average - more distant from each other. As a result, their productivity decreases. This reduces their bid rents and mitigates their spatial expansion into the residential and mixed districts.

Do pollution parameters ε and θ decrease utility? Under (24), the equilibrium utility is a concave function of city size because the production function A_p is also a concave function. The utility is given by the production value at the border b_0^* minus twice the commuting cost between the business district and city borders $t(M - b_0^*)$. The utility is further decreased by the opportunity cost of the land used by the residence and firm associated with each worker. In equilibrium, the utility level is the same at all locations where individuals take residence. In expression (24), the utility level is measured at the border b_0 where no traffic pollution occurs. For this reason, the expression includes no term directly related to the pollution parameters ε and θ. The effect of pollution on utility depends on the size of the integrated district b_0^*. To explore this effect, we compute:

$$A_p(b_0^*) = \alpha M - \tau b_1^{*2} = \alpha M - \frac{1}{\tau}(2t + \varepsilon\theta)^2 \tag{25}$$

Larger parameter values ε and θ entice businesses to spread and shift to the urban edge (higher b_1^*) and therefore reduce the agglomeration effects and productivity levels. In addition, the commuting cost in (24) translates to

$$2t\left(M - b_0^*\right) = 4tM - \frac{4t}{\tau}(2t + \varepsilon\theta) \tag{26}$$

This falls with larger parameter values ε and θ, because b_0 rises with those parameters. Therefore, the effect of pollution depends on the trade-off between lower agglomeration effects and smaller commuting costs. It can be shown that (25) falls faster than (26) in $\varepsilon\theta$. The agglomeration effect therefore dominates the effect on commuting costs so that utility falls with a larger $\varepsilon\theta$. To sum up, *higher per-vehicle pollution or larger pollution aversion reduces equilibrium utility*.

Our last remark concerns the equilibrium conditions. On the one hand, as in the monocentric city, traffic pollution should not be too high to support an equilibrium with a succession of a mixed district, a business district, a residential district and agricultural land. This imposes that $\varepsilon\theta < t$. On the other hand, there should be no incentive for commuting in the central district $[0, b_0]$. This imposes that the land rent gradient in this district is not too high: $|\Phi'(y)| < t, y \in [0, b_0]$. Although there is no pollution in this district, the condition is restrictive under traffic pollution. Indeed, higher pollution parameters ε and θ increase the extent of the integrated district where land rent is a concave function of distance to the center, x. The bigger this district, the larger the (negative) land gradient at its border. Its residents therefore have stronger incentives to relocate to the periphery and begin commuting to their initial workplace.

4.4. Fully integrated city

A fully integrated city emerges when firms and workers locate next to each other so that workers do not have to commute ($b_0 = b_1 = b_2 > 0$). Because of the absence of commuting, there is no pollution ($P(x) = 0$) and the analysis is the same as in Fujita and Ogawa (1982). In Appendix C, we show that the fully integrated configuration is a spatial equilibrium only in the case of small population sizes, i.e. $M \leq 2t/\tau$. It is clear that this condition is independent of pollution technology and pollution aversion since integrated cities do not have traffic pollution.

4.5. Spatial equilibria

We now collect the results of the three previous subsections. We express city structures as a function of the population size and pollution parameters.

Proposition 3. *Suppose $\varepsilon\theta < t$ and consider closed cities with a fixed population size M. Then, the fully integrated city is a spatial equilibrium if $M \leq 2t/\tau$, the partially integrated city is a spatial equilibrium if $(2t + \varepsilon\theta)/\tau < M < (4t + 2\varepsilon\theta)/\tau$, and finally a monocentric city is a spatial equilibrium if $M \geq (4t + 2\varepsilon\theta)/\tau$.*

As the city population size M grows, *the urban structure moves from integrated to partially integrated and then to monocentric configuration* .[10] Fig. 4 depicts this urban structure as a function of the city size. Bigger cities have more business firms and therefore stronger production externalities. As a result, firms make higher profits and offer higher land bid-rents in the central area, which shifts residents to the suburbs. However, from the above proposition, it comes that *higher per-vehicle pollution ε or stronger pollution aversion θ enlarges the set of parameters* supporting *the partially integrated city structure*. Fig. 5 illustrates this property. All in all, Proposition 3 shows that stronger agglomeration economies in the form of production externalities (larger τ) promote the more specialized urban forms (monocentric), while commuting cost and pollution externalities work in the opposite direction.

What is the impact of local traffic pollution on the structure of the city? First, such pollution has no impact on the integrated city structure because residents do not travel in this structure. Second, an increase in the parameters bundle $\varepsilon\theta$ transforms a monocentric city into a partially integrated one as $(4t + 2\varepsilon\theta)/\tau$ passes over M. This is the case where $\varepsilon\theta > (\varepsilon\theta)^*$ in Fig. 5. Residents now have a lower willingness to live in the residential area close to the business district and they therefore offer lower bid-rents. This entices firms to move to this part of the city and triggers dispersion of economic activity. Then, the lower

[10] Note that the population size is bounded to ensure that all firms have a positive interaction for any feasible distance in the city ($M < \alpha/(2\tau)$, see footnote 8). As in Fujita and Ogawa (1982), this constraint does not permit to study very large cities with multiple business subcenters. For the study of multiple business subcenters, see Ogawa and Fujita (1980), or Mossay et al. (2020).

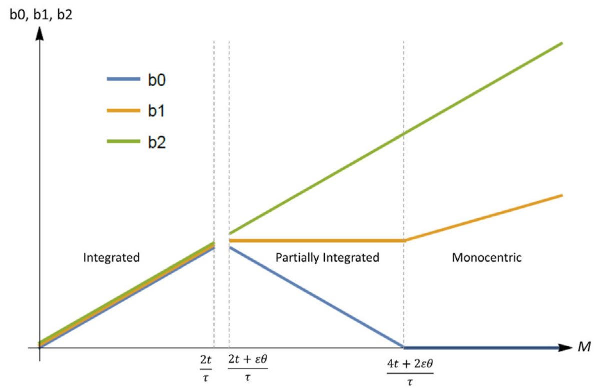

Fig. 4. Equilibrium urban structure as function of city size.

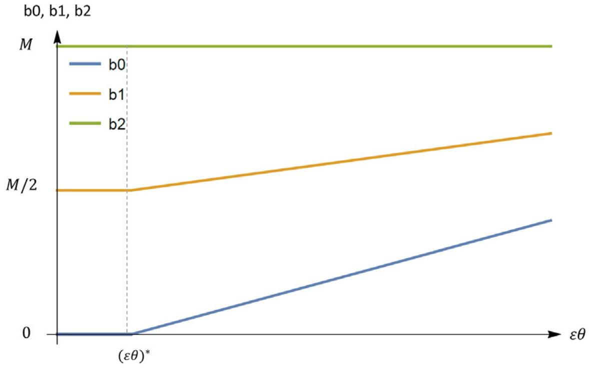

Fig. 5. Equilibrium urban structure as function of traffic-induced pollution parameters.

concentration of economic activity decreases firms' productivity and their corresponding bid-rents at the city center. This allows residents to bid for the land in the employers' location at the city center. An integrated district is then created at the city center.

As discussed in Section 4.2, the introduction of new technologies, such as the use of cleaner, more fuel-efficient, combustion engine vehicles or the wider use of electric or hybrid vehicles decreases ε, which, in turn, affects the monocentric and the partially integrated configurations. More precisely, it is clear from Proposition 3 that lower levels of generated emissions might turn a partially integrated city into a monocentric city. In the former case, though, there is one more effect. That is, cleaner vehicles will change the internal structure of the city, shrinking the central mixed area and creating larger specialized areas. In addition, we can show that the new technologies restrict the set of equilibrium parameters for which the partially integrated configuration is an equilibrium outcome. For $\widehat{\varepsilon} < \varepsilon$, the equilibrium condition is $\left(2t + \widehat{\varepsilon}\theta\right)/\tau < M < \left(4t + 2\widehat{\varepsilon}\theta\right)/\tau$, which corresponds to an interval of $\left(2t + \widehat{\varepsilon}\theta\right)/\tau$ that is clearly smaller than the one in the case of more polluting vehicles, $(2t + \varepsilon\theta)/\tau$.

Proposition 3 shows that none of the above three urban configurations are a spatial equilibrium for population sizes lying in the interval $(2t/\tau, (2t + \varepsilon\theta)/\tau)$. This is depicted in Fig. 4 where the values of district borders (b_0, b_1, b_2) vanish. In the absence of pollution ($\varepsilon\theta = 0$) this range is indeed empty. Then, urban configurations continuously change from fully to partially integrated structures as population size M crosses the value $2t/\tau$. Things, however, differ in the presence of traffic pollution. In Appendix B, we show that when the population size M is smaller than $(2t + \varepsilon\theta)/\tau$ the partially integrated city structure is not robust to the no-commuting condition in the central integrated district. Pollution entices workers to reside in this district with no traffic. This enlarges the size of the district and its agglomeration effects, so that firms' bid-rents fall more steeply when one moves to the outskirts of the district. Workers then have incentives to commute, which breaks the no-commuting condition. In that interval of population size, the spatial equilibrium has none of the structures studied in this paper and may be any other combination of mixed, residential, and business districts.[11]

Proposition 4. *In a closed city with a given population size, a higher per-vehicle pollution ε or stronger pollution aversion θ can turn a monocentric city into a partially integrated city, and the latter to a fully integrated city.*

[11] Our computations show that the duocentric city is also not a spatial equilibrium (Proof available on request). The precise urban structure is therefore hard to characterize and is left for future research.

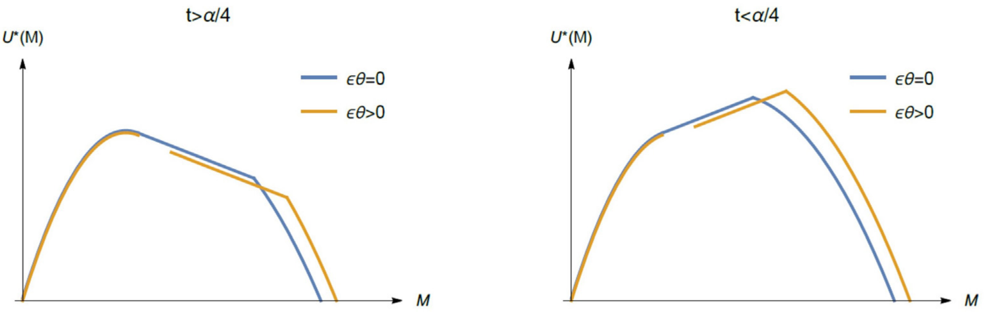

Fig. 6. Equilibrium utility as function of population size.

Fig. 6 depicts the urban utility as a function of the city size as a set of pieces of concave and linear functions. For small population sizes the city is integrated and utility is a concave function that increases at zero population size. For large enough population sizes, the city adopts a monocentric structure and the utility is a concave function of population. Utility falls for large enough population sizes. At intermediated population sizes, the city adopts a partially integrated structure. The utility is a linearly decreasing function of population size with the slope $U^{*\prime}(M) = \alpha - 4t$. It is decreasing for $t > \alpha/4$ and increasing otherwise, as shown in the left and right panels of Fig. 6. The utility curve is continuous in the absence of pollution ($\varepsilon\theta = 0$). Agglomeration forces dominate for small population sizes so that the utility increases. By contrast, congestion forces dominate for large city sizes so that utility decreases.

Importantly for our study, the impact of higher per-vehicle pollution ε or stronger pollution aversion θ is to lower the utility for partially integrated cities and raise it for monocentric cities (see Fig. 6). As mentioned in the last paragraph, it also implies a piece where none of the monocentric, partially integrated, and fully integrated structures are spatial equilibria.

5. Optimal urban structure

In the presence of externalities, the spatial equilibrium urban configuration is not optimal. On the one hand, when firms choose their location, they ignore the positive production externality they cause to other firms. On the other hand, when residents choose their location, they ignore the negative pollution externality they impose on the other residents. What do those externalities imply for the optimal city structure? In this section, we first consider the optimal allocation of goods and land plots to firms and residents by a utilitarian urban planner, and then study its decentralization through a system of taxes or subsidies.

5.1. Social optimal allocation

We start by considering the first-best configuration where a benevolent, utilitarian planner chooses the location of firms and residents. Her objective can be written in the following way:

$$W = \int_{-M}^{M} A(y(x), 1-n)(1-n(y(x)))\mathrm{d}x - \int_{-M}^{M} t|x-y(x)|n(x)\mathrm{d}x - \int_{-M}^{M} \varepsilon\theta N(x)n(x)\mathrm{d}x - 2MR_A \tag{27}$$

where the first term represents the benefits from business interaction, the second term the total commuting cost, the third the disutility of local traffic pollution, and the last term the opportunity cost of land.[12] In this expression, $y(x)$ is a commuting assignment function that returns the work location y of a resident located at x, while the function $A(y, m)$ makes apparent the dependence of the agglomeration function on the firms' density profile m (where $m = 1 - n$). The difficulty is to find this commuting assignment function. One can get around this difficulty by using the aggregate costs of commuting and traffic pollution. Let $G(x) = \int_x^M (n(z) - m(z))\mathrm{d}z$ measure the mass of commuters from the city border $b_2 = M$ to location x. Then, the total distance travelled can be rewritten as

$$\int_{-M}^{M} |x-y(x)|n(x)\mathrm{d}x = \int_{-M}^{M} |G(x)|\mathrm{d}x \tag{28}$$

Similarly, the total mass of vehicles crossing all residential locations can be written as

$$\int_{-M}^{M} N(x)n(x)\mathrm{d}x = \frac{1}{2}\int_{-M}^{M} |G(x)|\mathrm{d}x \tag{29}$$

[12] The opportunity cost of land is $2MR_A$ because (i) workers and firms jointly occupy 2 M units of land which are withdrawn from the agricultural sector and (ii) the agricultural land rent is R_A. See Fujita (1985).

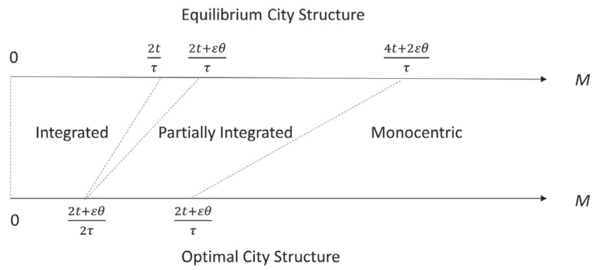

Fig. 7. Equilibrium & optimal city structures.

This naturally is half of the travelled distance as, on average, commuters pass by as many residential houses as firm sites. The planner's objective is then given by

$$W = \int_{-M}^{M} \left\{ A(x, 1-n)(1-n(x)) - \left(t + \frac{\varepsilon\theta}{2}\right) |G(x)| \right\} dx - 2MR_A \tag{30}$$

It is clear that the model is invariant to the bundle of terms $(t + \varepsilon\theta/2)$. We can then use the first-best allocation found by Fujita (1985) with t and extend it to $(t + \varepsilon\theta/2)$.[13] The planner then trades off between fostering production externalities and diminishing commuting cost and pollution exposure. Pollution exposure is congruent to commuting cost.

Proposition 5. *The optimal city structure is (i) fully integrated if* $M < (2t + \varepsilon\theta) / (2\tau)$; *(ii) monocentric if* $M > (2t + \varepsilon\theta) / \tau$; *(iii) partially integrated if* $(2t + \varepsilon\theta) / (2\tau) < M < (2t + \varepsilon\theta) / \tau$; *in this case,* $b_1^{\mathrm{FB}} = (2t + \varepsilon\theta) / (2\tau)$ *and* $b_0^{\mathrm{FB}} = (2t + \varepsilon\theta) / \tau - M$.

The comparison between equilibrium and optimum is displayed in Fig. 7. From this figure, it can be seen that *all equilibrium monocentric cities remain monocentric at the optimum, all equilibrium partially integrated cities become monocentric while equilibrium integrated cities with high population sizes become partially integrated*. With and without pollution externalities, the planner compactifies the business area by gathering firms closer to the city center. In fact, the consideration of production externalities calls for smaller integrated areas and larger specialized areas while the consideration of per-vehicle pollution and pollution disutility calls for larger mixed areas and smaller specialized areas. The first agglomeration force nevertheless dominates.

5.2. Decentralization through taxes and subsidies

We now look at different types of taxes and subsidies that correct the above externalities and permit to decentralize the optimal urban structure. To this aim, it is shown in Appendix D that, to correct for the pollution externality, the planner can impose a site-specific tax on a worker living at x given by:

$$T(x) = \begin{cases} 0 & \text{if } x \in [0, b_1] \\ \int_{b_1}^{x} \varepsilon\theta n(z)\, dz & \text{if } x \in (b_1, b_2] \end{cases} \tag{31}$$

This tax integrates the negative effect of her commute on all residents along her commuting route. In other words, the commuter fully internalizes the effect of her negative externality on other residents. Long-distance commuters harm a larger mass of residents and therefore pay higher taxes. Commuters residing close to the business district drive a shorter distance, impose a lower negative externality on residents and therefore pay lower taxes.

To correct for the production externalities, the planner can also propose a subsidy on each firm that internalizes the production gains of other firms. The production gain that a firm at y brings to another firm at z is equal to $(\alpha - \tau|y - z|)$. Therefore, the gains to all firms are given by $\int_{-b_2}^{b_2} (\alpha - \tau|y - z|)m(z)dz$. So, the optimal subsidy is then given by

$$S(y) = \int_{-b_2}^{b_2} (\alpha - \tau|y - z|)m(z)\, dz, \quad x \in [0, b_2] \tag{32}$$

Note that because firms have homogeneous production technologies, the optimal subsidy is equal to the firm's productivity $A(y)$. The optimal policy consists of a site-specific subsidy that makes firms internalize the positive effect of a specific firm on other firms. This subsidy is higher when firms are located in areas with a high density of firms around them. In monocentric cities, the subsidy is higher in the center of the business city. It is also higher in the city center of integrated cities. As for the partially integrated cities, it is higher in the business sub-center where the density of firms is higher. It is shown in Appendix D that when those two instruments are jointly implemented, the condition of the existence of a spatial equilibrium with a monocentric city

[13] The Proof uses optimal control and is long. It can be obtained upon request to the authors.

matches the first-best condition for monocentric configuration. Also, equilibrium values of the internal borders of the partially integrated city match those of the optimal configuration.

Finally, we briefly discuss the distributional effects of these policies. On the one hand, the site-specific tax creates changes in the land market, with the areas closer to the border between the residential and business districts becoming more attractive. Thus, the tax increases unevenly the residential land rent in the whole residential area by $T(M) - T(x)$ and proportionally decreases the composite good (see Appendix D). By continuity, the business land rent is increased by $T(M)$. On the other hand, the site-specific subsidy increases the business land rent by $S(y) - S(b_1)$ in the business center of the monocentric city and by $S(y) - S(b_0)$ in that of the partially integrated city, while it also increases the wages. The mechanism is the same as the one described in Sections 4.2 and 4.3 when studying the effect of the per-vehicle pollution parameter on the utility function. Equilibrium utility decreases by two times the amount of taxation paid by the commuter located at the border of the city (due to decreased consumption of the good and increased land rents), while it increases by the amount of the subsidy (calculated at b_1 in monocentric cities and at b_0 in partially integrated cities). Thus, the aggregate effect on equilibrium utility by the joint implementation of the two site-specific instruments is unclear. On the contrary, the effect on the land market is clear. Both instruments work in the same direction: they increase land rents in the whole city and benefit the landlords.

Subsidy to the pollution victim. The tax on polluters, given by (31) has the same effect on the urban structure as the compensation to pollution victims. This is a particularity of our model with linear commuting cost, linear utility, and unit residential land use. Each resident faces a negative externality given by $\theta P(x) = \varepsilon\theta N(x)$. It can be shown that the site-subsidy (negative tax) of $\varepsilon\theta N(x)$ to the resident located at x also yields the optimal city configuration.[14]

Subsidy on commuting cost. The urban planner can also subsidize or tax the commuting cost per unit of distance with the aim to match the optimal city structure. It can be shown that a subsidy equal to $\frac{1}{2}\left(t + \frac{\varepsilon\theta}{2}\right)$ on commuting cost reproduces the optimal urban structure as an equilibrium outcome. After subsidy, the commuting cost becomes $\widehat{t} = t - \frac{1}{2}\left(t + \frac{\varepsilon\theta}{2}\right) = \frac{1}{2}\left(t - \frac{\varepsilon\theta}{2}\right) < t$, which gives $b_0^{FB} = b_0^*$ and $b_1^{FB} = b_1^*$. The first part of the subsidy, $t/2$, incentivizes workers to commute from the suburb and facilitates the agglomeration of firms around the geographical city center. The rest of the subsidy, $\varepsilon\theta/4$, relates to the local pollution externality. When the planner offers no subsidy and the per-vehicle pollution parameter ε rises, workers quit the residential area and the business district shifts toward the city border. This spreads the business activities too much from a welfare viewpoint. The planner then has incentives to subsidize the commuting cost to entice workers to stay in the residential area.

6. Discussion

In the previous sections, we studied the case of local traffic pollution that affects only the place where it is produced. We now discuss how diffusion of pollution modifies the above results. This is important because the literature often uses the assumption of diffused pollution (e.g., Regnier and Legras, 2018; Denant-Boemont et al., 2018).

For simplicity, suppose that the pollutant diffuses uniformly over a segment with length 2κ that includes the whole city ($\kappa > b_2$). Then, aggregate emissions of traffic pollution are given by $TP = \varepsilon \int_{-b_2}^{b_2} N(x)\mathrm{d}x$. Under pollution diffusion, every resident is exposed to the same (per-capita) pollutant concentration $P_G \equiv \left[\varepsilon \int_{-b_2}^{b_2} N(x)\mathrm{d}x\right]/(2\kappa)$, which depends on the city size but not on the resident's location in the interior of the city. We define $\varepsilon' = \varepsilon/(2\kappa)$ so that

$$P_G = \varepsilon' \int_{-b_2}^{b_2} N(x)\mathrm{d}x \tag{33}$$

which includes pollution that diffuses in all districts. This is illustrated in Fig. 8.

The city structure can readily be established by replacing $P(x)$ by P_G in the previous analysis. We can show that, first, there is no change in the integrated city structure since there is no (local or global) pollution. Second, the spatial equilibrium with a monocentric city differs in the following way. The residential land rent and utility can readily be obtained from (8) and (9) as

$$\Psi^{**}(x) = R_A + t\,(M - x) \tag{34}$$

$$U^{**}(M) = A_m(M/2) - tM - 2R_A - \theta P_G \tag{35}$$

where we use the double asterisk ** to denote the equilibrium with pollution diffusion. From the first expression it can be deduced that *diffused pollution does not affect the residential land rent.* This is because diffused pollution does not generate any spatial differences that landlords can exploit. From the second expression, we observe that *equilibrium utility falls with diffused*

[14] The site-subsidy $\varepsilon\theta N(x)$ is equivalent to the (negative) tax $-\varepsilon\theta N(x)$, which is equal to $T(x) + T_0$, where T_0 is a lump-sum tax equal to $-\varepsilon\theta(b_2 - b_1)\,(< 0)$. As mentioned above, appropriate incentives to residential decisions require to induce appropriate land gradients and therefore implement appropriate tax gradient: here, $T'(x) = -\varepsilon\theta N'(x)$.

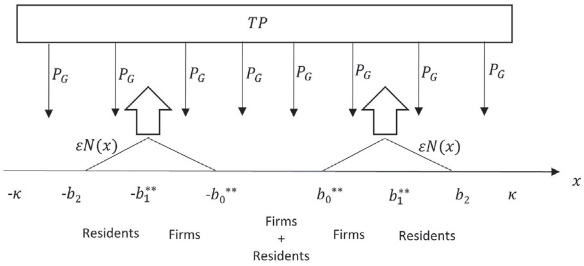

Fig. 8. Local vs. diffused pollution.

pollution, which contrasts with the case of local traffic pollution. Diffused pollution is given by

$$P_G = 2\varepsilon' \int_{b_0^{**}}^{b_2} N(x)\mathrm{d}x = \frac{1}{2}\varepsilon' M^2 \tag{36}$$

which increases with urban population size. The equilibrium utility is therefore a concave function of population size M. Finally, the condition supporting a monocentric city equilibrium (20) simplifies to $M \geq 4t/\tau$, which is independent of pollution parameters ε' and θ. Thus, under diffused pollution *the emergence of a monocentric city is independent of pollution parameters*.

What about partially integrated cities? It can be shown that the existence conditions and the internal city borders of this urban structure are the same as in Proposition 2 where $\varepsilon\theta$ is set to 0. So, *the emergence and the internal borders of partially integrated cities are independent of pollution parameters.* This is again because diffused pollution does not generate any spatial differences that landlords can exploit. The utility level is, however, given by

$$U^{**}(M) = A_p(b_0^{**}) - 2t\left(M - b_0^{**}\right) - 2R_A - \theta P_G \tag{37}$$

This is the same utility as in (24), except for the value of the district border b_0^{**} and the last term expressing the utility loss from diffused pollution. The diffused pollution level is given by

$$P_G = 2\varepsilon' \int_{b_0^{**}}^{b_2} N(x)\mathrm{d}x = 2\varepsilon'(M - 2t/\tau)^2 \tag{38}$$

which also increases with a larger population size.

This analysis reveals that the structure of the city boundaries under diffused pollution are those established with zero local pollution effects. As population size grows, the spatial equilibrium is a fully integrated city if $M \leq 2t/\tau$, a partially integrated city if $2t/\tau < M < 4t/\tau$ and a monocentric city if $M \geq 4t/\tau$. As there is no discontinuity in those conditions, every population size M yields exactly one of the three studied configurations. Furthermore, the internal district borders b_0^{**} and b_1^{**} are not affected by diffused pollution. Again, the reason is that individuals are affected in the same way by diffused pollution so that land rents within the city are not altered by pollution. *Thus, the diffusion of pollution shrinks the integrated district* as $b_0^{**} < b_0^*$ *and enlarges the business and the residential districts* as $b_1^{**} - b_0^{**} > b_1^* - b_0^*$ *and* $b_2^{**} - b_1^{**} > b_2^* - b_1^*$. Finally, it can easily be shown that equilibrium utility is smaller under diffused pollution in all urban configurations (see Appendix E).

7. Conclusion

The purpose of this paper is to study the implications of local traffic pollution on the land markets and on the location decisions of firms and workers in the interior of a city. Our contribution lies in the use of an urban framework where firms and workers compete for land in the presence of two market failures: local traffic pollution from workers and production externalities between firms. Workers offer their labor to firms and can choose either to reside close to their workplaces or to dwell far from them and incur commuting costs. They are also harmed by local traffic pollution. The location of firms results from their balance between land rents and access to other firms and workers. The location of residents results from their balance between land rents, access to their employers, and local traffic pollution. We study three types of urban structures with districts either specializing or mixing the residential and business functions.

The analysis explains that the emergence of monocentric cities is hindered by the presence of local traffic pollution. Surprisingly, because of the interaction between land and labor markets, technologies and policies that decrease the per-vehicle emissions in monocentric cities benefit the landlords at the expense of the residents. This is because those technologies and policies enhance landlords' spatial discrimination power. The analysis also explains how a city's internal borders are influenced by local traffic pollution. We discuss the case of a partially integrated city with a central integrated district mixing both firms and workers, business (sub-)centers, and residential districts at the periphery. In that urban configuration, technologies and policies that lower per-vehicle emissions enlarge the residential areas at the periphery and compactify the business districts near the city center, enhancing city productivity. We show that those effects are specific to the local property of traffic pollution.

That is, they do not exist if pollution diffuses in the city as is generally assumed in the literature. Finally, we study the first-best urban configuration and the policy instruments that implement it. Compared to the equilibrium, the planner wants to compactify business activities and thereby entice workers to reside further out near the periphery. Technologies and policies that lower per-vehicle emissions give her further incentives to compactify businesses and favor monocentric urban structures. This point suggests that urban policies attempting to curb local vehicle pollution may not be compatible with the recent policies aiming at densifying city centers with residences.

Appendix A. Cross-commuting

Consider two residents at x and x' ($x < x'$) commuting respectively to firms at y and y'. There exists cross-commuting if $y' < y$, so that the commuting paths of the two workers will cross in the interval $[y', y]$. We show that this cannot be an equilibrium.

In equilibrium, a resident located at x strictly prefers to commute to y rather than y' iff $U(x,y) > U(x,y')$, or equivalently if, $w(y) - t|y-x| - R(x) - \theta P(x) > w(y') - t|y'-x| - R(x) - \theta P(x)$. This is equivalent to $w(y) - t|y-x| > w(y') - t|y'-x|$. The opposite equilibrium condition applies for the resident at x' who strictly prefers to commute to y' rather than y iff $U(x',y') > U(x',y)$. So, $w(y') - t|y'-x'| > w(y) - t|y-x'|$. The last two conditions imply that

$$|y-x| + |y'-x'| < |y'-x| + |y-x'| \tag{A1}$$

The equilibrium yields the shortest total commuting distance (and cost). Note that the pollution term cancels out in those inequalities, which are similar to the conditions without pollution that are discussed in Ogawa and Fujita's (1980). We continue their argument for the sake of completeness.

Assume w.l.o.g. that $x < x'$. Cross-commuting implies that the commuter paths cross, which happens if $y' < y$, and leads to cross-commuting in the interval $[y', y]$. There can be five cases of cross-commuting, which are all impossible. Formally:

1. If $x < x' < y' < y$, then (A1) becomes $(y-x) + \left(y'-x'\right) < \left(y'-x\right) + \left(y-x'\right) \iff 0 < 0$, which is false.
2. If $x < y' < x' < y$, then (A1) becomes $(y-x) - \left(y'-x'\right) < \left(y'-x\right) + \left(y-x'\right) \iff 0 < y'-x'$, which is false.
3. If $x < y' < y < x'$, then (A1) becomes $(y-x) - \left(y'-x'\right) < \left(y'-x\right) - \left(y-x'\right) \iff 0 < y'-x'$, which is false.
4. If $y' < x < y < x'$, then (A1) becomes $(y-x) - \left(y'-x'\right) < -\left(y'-x\right) - \left(y-x'\right) \iff y-x < 0$, which is false.
5. If $y' < y < x < x'$, then (A1) becomes $-(y-x) - (y'-x') < -(y'-x) - (y-x') \iff 0 < 0$, which is false.

Appendix B. Partially integrated city

In what follows, we characterize the partially integrated city structure at a given city size.

Necessary conditions at district borders. The first relationship relates to labor and commuting arbitrage in the employment basin $[b_0, b_2]$. In equilibrium, workers have the same utility U^* for any workplace $y, y' < x$ so that

$$U^* = w(y) - t\,(x-y) - R_H(x) - \theta P(x) = w(y') - t\left(x-y'\right) - R_H(x) - \theta P(x) \tag{B1}$$

This yields the labor-commuting arbitrage relationship

$$w(y) + ty = w(y') + ty', \quad y, y' \in [b_0, b_1] \tag{B2}$$

To be attractive, firms in the business area must compensate for commuting cost from the residential area.

The second relationship relates to land arbitrage at the city border. There, bid-rents must equalize the cost of farming land so that $\Psi(b_2) = R_A$. Because $P(b_2) = 0$ and using (B2) at $y' = b_0$, we get

$$w(b_0) - t\left(b_2 - b_0\right) - U^* = R_A \tag{B3}$$

By (B2), this gives the wage function in the business area as

$$w(y) = R_A + t\left(b_2 - y\right) + U^*, \quad y \in [b_0, b_1] \tag{B4}$$

The third relationship relates to the wage setting in the integrated area. Workers in $[0, b_0]$ do not commute and, in equilibrium, they must offer the same bid-rents as firms, i.e. $\Psi(x, U^*) = \Phi(y)$. Taking $x = y$ and $P(x) = 0$, this gives $w(x) - U^* = A(x) - w(x)$, which yields the wage function:

$$w(x) = \frac{1}{2}\left[A(x) + U^*\right], \quad x \in [0, b_0] \tag{B5}$$

Applying this at $x = b_0$, we have the condition $\Psi(b_0, U^*) = \Phi(b_0)$, which gives

$$w(b_0) = \frac{1}{2}\left[A(b_0) + U^*\right] \tag{B6}$$

Combining (B3) and (B6) allows us to solve for the utility in the city as

$$U^* = A(b_0) - 2t\left(M - b_0\right) - 2R_A \tag{B7}$$

From this we get the wage values at b_0 and b_1:

$$w(b_0) = A(b_0) - t\left(M - b_0\right) - R_A \tag{B8}$$

$$w(b_1) = w(b_0) - t\left(b_1 - b_0\right) \tag{B9}$$

The fourth relationship uses the land arbitrage between business and residential areas at $x = b_1$. In equilibrium, it should be that $\Psi(b_1, U^*) = \Phi(b_1)$. This gives the equality $w(b_1) - t|b_1 - y| - U^* - \theta P(b_1) = A(b_1) - w(b_1)$ and, after simplification,

$$A(b_0) - A(b_1) + 2t\left(b_0 - b_1\right) = \varepsilon\theta N(b_1) \tag{B10}$$

Substituting for the number of commuters at b_1, $N(b_1) = b_1 - b_0$, this simplifies to:

$$A(b_1) - A(b_0) + (\varepsilon\theta + 2t)\left(b_1 - b_0\right) = 0 \tag{B11}$$

As a result, using the fact that $b_2 = M$, the urban equilibrium is given by the pair of scalars (b_0, b_1) that solve conditions (B7) and (B11) and the feasibility constraints $0 < b_0 < b_1 < b_2 = M$. Note that given the definition of b_1 those constraints are satisfied if $0 < b_0 < M$.

Conditions (B7) and (B11) simplify when we consider the value of agglomeration benefits. This gives the following identity:

$$\left(M - b_0\right)\left(4t + 2\varepsilon\theta - \tau\left(M + b_0\right)\right) = 0 \tag{B12}$$

which solves for $b_0 \in (0, M)$. The solution gives the border between integrated and business areas $b_0 = (4t + 2\varepsilon\theta)/\tau - M$, which yields the border between business and residential areas $b_1 = (2t + \varepsilon\theta)/\tau$. Those borders respect the constraints $0 < b_0 < M$ if and only if $M \in ((2t + \varepsilon\theta)/\tau, (4t + 2\varepsilon\theta)/\tau)$. If M lies in this interval then the city has three types of areas: from center to border, integrated, business and residential. If M lies below this interval, the city is fully integrated ($b_0 > M = b_2$). Proposition 2 summarizes the results.

Before proceeding, we compute the wages and bid-rents. Using the value of U^*, equilibrium wages are given by

$$w(y) = \begin{cases} \frac{1}{2}\left[A(y) + A(b_0)\right] - t\left(M - b_0\right) - R_A, & x \in [0, b_0] \\ A(b_0) - t\left(y - b_0\right) - t\left(M - b_0\right) - R_A, & y \in [b_0, b_1] \end{cases} \tag{B13}$$

Firms' bid-rents are given by $\Phi(y) = A(y) - w(y)$, which leads to

$$\Phi(y) = \begin{cases} \frac{1}{2}\left[A(y) - A(b_0)\right] + t\left(M - b_0\right) + R_A, & x \in [0, b_0] \\ A(y) - A(b_0) + t\left(y - b_0\right) + t\left(M - b_0\right) + R_A, & y \in [b_0, b_1] \end{cases} \tag{B14}$$

The resident's bid-rent is

$$\Psi(x, U^*) = \begin{cases} \frac{1}{2}\left[A(y) - A(b_0)\right] + t\left(M - b_0\right) + R_A, & x \in [0, b_0] \\ (t - \varepsilon\theta)(M - x) + R_A & x \in [b_1, b_2] \end{cases} \tag{B15}$$

It is clear that the business land rents are not affected by the level of pollution. On the contrary, the residential land rents are affected by local traffic pollution. More specifically, the higher the local traffic pollution in the pure residential area, the lower the amount of money that people are willing to pay in order to locate in $[b_1, b_2]$.

The above characterization fulfills necessary conditions between district borders. The spatial equilibrium nevertheless imposes two additional sufficient conditions about the ranking of bid rents in business and residential districts and the commuting in the integrated district.

Ranking of bid rents in business and residential districts. In equilibrium, residential bid rents must be higher in the residential district and lower in the business district. That is, $\Phi(y) \geq \Psi(y)$ for $y \in (b_0, b_1)$ and $\Phi(x) < \Psi(x)$ for $x \in (b_1, b_2]$. To show this, we first express the bid-rents (B14) and (B15) on the full city support and show that $\Phi(y)$ is weakly concave and $\Psi(x)$ is a convex function of x on the interval $[b_0, b_2]$.

First, the business bid-rent $\Phi(y)$ can be extended on $[b_1, b_2]$ as follows. One can notice that $A(y)$ is a linear expression with slope $-\tau b_0$ on $[b_1, b_2]$. Since bid-rents are continuous at $y = b_1$ we have that $\Phi(y)$ is given by

$$\Phi(y) = \Phi(b_1) - \tau b_0\left(b_1 - y\right) \tag{B16}$$

which is linear in y on $[b_1, b_2]$. One can show that the $\Phi(y)$ is also continuous at $y = b_1$ (see Fujita and Thisse, 2002). Since $\Phi(y)$ is a concave function on $[b_0, b_1]$, $\Phi(y)$ is weakly concave on $[b_0, b_2]$.

Second, take a worker employed at $y \in (b_0, b_1)$ with $y < x$. The resident bid-rent for $x > b_1$ is given by

$$\Psi(x) = w(y) - t(x-y) - \varepsilon\theta(b_2 - x) - U^* \tag{B17}$$

with slope $\Psi'(x) = -t + \varepsilon\theta$. If she locates at $x \in [y, b_1]$, she bids

$$\Psi(x) = w(y) - t(x-y) - \varepsilon\theta(x - b_0) - U^* \tag{B18}$$

with slope $\Psi'(x) = -t - \varepsilon\theta$. By condition (B2), this argument holds for any y so that bid rents are equal to

$$\Psi(x) = \begin{cases} w(b_0) - t(x-b_0) - \varepsilon\theta(b_2 - x) - U^* & \text{if} \quad x \in [b_1, b_2] \\ w(b_0) - t(x-b_0) - \varepsilon\theta(x - b_0) - U^* & \text{if} \quad x \in [b_0, b_1) \end{cases}$$

Hence, $\Psi(x)$ is a convex function of x on $[b_0, b_2]$.

Finally, remind that the configuration that satisfies the district border conditions $\Phi(b_0) = \Psi(b_0)$ and $\Phi(b_1) = \Psi(b_1)$. Therefore, because Φ and Ψ are respectively weakly concave and convex functions on $[b_0, b_2]$, it must be that $\Phi(y) > \Psi(y)$ for $y \in (b_0, b_1)$ and $\Phi(y) < \Psi(y)$ for $y \in (b_1, b_2]$. Also, consider the interval $[b_1, b_2]$. Since $\Psi(b_2) = R_A$ and $\Psi'(x) = -t + \varepsilon\theta$, we have $\Psi(x) \geq R_A$ only if $\varepsilon\theta < t$.

We have thus shown that residents overbid firms in the residential district while firms overbid residents in the business district. Residents overbid farmers if $\varepsilon\theta < t$.

No commuting in the integrated district. In equilibrium, workers should have no incentives to relocate and start commuting in the integrated area. That is, there is not possible deviation in the no-commuting constraint in the interval $[0, b_0]$.

Consider the interval $[0, b_0]$. Suppose an initial location z where that worker resides and works. She gets utility

$$U = w(z) - R(z) \tag{B19}$$

Consider a deviation in the residence location x so that her utility is

$$U' = w(z) - R(x) - t|x - z| \tag{B20}$$

The deviation is not beneficial if $U > U'$ or equivalently if

$$R(z) - R(x) < t|x - z| \tag{B21}$$

At the limits where $x \to z$ by the left and right-hand side this gives $|R'(z)| < t$. In the integrated areas, $R(z) = \Phi(z)$ where $\Phi'(z) = \frac{1}{2}A'(z)$ while $A'(z) = -\tau z$. So, the above condition becomes $\frac{1}{2}\tau z < t$. The left-hand side has the largest value for $z = b_0$. So, it must be that $\frac{1}{2}\tau b_0 < t$. The central mixed area should not be too big and the commuting costs should not be too small. In the case of a partially integrated city we have $b_0 = \frac{(4t+2\varepsilon\theta)}{\tau} - M$. Then, the condition becomes

$$\frac{(4t+2\varepsilon\theta)}{\tau} - M < \frac{2t}{\tau} \iff \frac{2\,(t+\varepsilon\theta)}{\tau} < M \tag{B22}$$

The central integrated district should not be too large. For this to happen, the city should be large enough to entice the emergence of large enough business and residential districts.

Appendix C. Fully Integrated City

In the fully integrated city, the density of firms and workers is then equal to $m(z) = n(z) = 1/2$ and the city border is set to $b_0 = M$. No commuting implies no pollution so that $P(z) = 0$. In this city structure, we must have an equalization of bid-rents everywhere, $\Psi(z, U^*) = \Phi(z), z \in [0, M]$, while at the city border the land rent is equal to the agricultural land rent, i.e., $\Phi(M) = R_A$. In addition, the no-commuting condition implies that $|\Phi'(z)| < t,\ z \in [0, M]$. The latter imposes that land rents do not change fast enough to prevent workers from residing in spatial locations that are far away from their job places. The business production function computes as

$$A_i(y) = \int_{-M}^{M} (\alpha - \tau|z-y|)\frac{1}{2}dz = M\alpha - \frac{\tau}{2}(M^2 + y^2) \tag{C1}$$

The above bid-rent equalization conditions solve for the wage as $w(z) = \frac{1}{2}\left[A_i(z) + U^*\right]$ and the city utility which is expressed as a function of the city population is

$$U^*(M) = A_i(M) - 2R_A \tag{C2}$$

The equilibrium utility is equal to the value of firm production (with agglomeration effects) minus the opportunity cost of the land used by each residence and plant associated with a worker. The no-commuting condition successively gives

$$|\Phi'(z)| = |A_i'(z) - w'(z)| = \frac{1}{2}|A_i'(z)| = \frac{\tau}{2}|-x| \leq t,\ z \in [0, M] \tag{C3}$$

or equivalently $M \leq 2t/\tau$.

Intuitively, an integrated city structure cannot be an equilibrium when the mass of firms – and therefore the mass of workers – is large. In this case, agglomeration forces are so intense that the firm profits fall more and more rapidly when one moves away from the city center. In equilibrium, the land rents follow the same pattern and become very steep close to the city border. As a result, workers residing and employed there have incentives to initiate a short commuting trip and reside slightly further away from their firms because the gain from land rent differences outweigh their commuting costs.

Appendix D. Equilibrium with site-specific taxes and subsidies

We show that by simultaneously introducing the optimal tax and the optimal subsidy (given by (31) and (32), respectively), we obtain the optimal configuration as an equilibrium outcome. In what follows, we solve (i) the utility-maximization problem when households located at x have to pay a site-specific tax $T(x)$ (31) for the environmental externality, and (ii) the profit-maximization problem when firms located at y receive the optimal site-specific subsidy $S(y)$ (32).

Households maximize utility $U = c - \theta P$ subject to their budget constraints $c + R + T(x) + t|x-y| \leq w(y)$. The bid-rent is given by

$$\Psi(x, U^*) = w(y) - t|x-y| - T(x) - U^* - \theta P(x) \tag{D1}$$

Firms maximize their profits $\pi(y) = A(y) + S(y) - R(y) - w(y)$. The zero-profit condition implies that:

$$\Phi(y) = A(y) + S(y) - w(y) \tag{D2}$$

For the monocentric city to be an equilibrium outcome, the following condition should be satisfied:

$$\Phi(0) \geq \Psi(0) \text{ and } \Phi\left(\frac{M}{2}\right) = \Psi\left(\frac{M}{2}\right) \tag{D3}$$

Using the second identity, the first inequality can be written as $\Phi(0) - \Phi(\frac{M}{2}) \geq \Psi(0) - \Psi(\frac{M}{2})$. Those conditions simplify to

$$\tau\frac{M^2}{4} + S(0) - S\left(\frac{M}{2}\right) \geq tM + \varepsilon\theta\frac{M}{2} \tag{D4a}$$

$$w\left(\frac{M}{2}\right) - t\frac{M}{2} - T\left(\frac{M}{2}\right) - U^* - \theta P\left(\frac{M}{2}\right) = A\left(\frac{M}{2}\right) + S\left(\frac{M}{2}\right) - w\left(\frac{M}{2}\right) \tag{D4b}$$

Substituting the values of the subsidy (32) and the tax (31), we get $M \geq \frac{2t+\varepsilon\theta}{\tau}$, which is the same as the optimal condition for the monocentric city.

For the partially integrated city, we solve the model as in Appendix B. After simplification, the land arbitrage conditions between business, residential and farming areas at $x = b_0, b_1$ and b_2 reduce to the condition

$$A(b_0) - A(b_1) + S(b_0) - S(b_1) + 2t\left(b_0 - b_1\right) = \varepsilon\theta N(b_1) + T(b_1) \tag{D5}$$

which replicates (B10). Substituting for the number of commuters at b_1, $N(b_1) = b_1 - b_0$, this simplifies to

$$A(b_1) - A(b_0) + S(b_0) - S(b_1) + (\varepsilon\theta + 2t)\left(b_1 - b_0\right) - T(b_1) = 0 \tag{D6}$$

Substituting the values of the productions externalities, the subsidy (32) and the tax (31), we obtain the value of $b_0 = (2t + \varepsilon\theta)/\tau - M$, which yields the optimal border value. The border between business and residential areas is then given by $b_1 = (2t + \varepsilon\theta)/2\tau$, which corresponds to the optimal value.

In the monocentric city, we obtain the equilibrium utility and wage

$$U^* = A_m(M/2) - tM - 2R_A + \varepsilon\theta M/2 + S(M/2) - 2T(M) \tag{D7}$$

$$w(y) = A_m(M/2) - ty + \varepsilon\theta M/2 - R_A + S(M/2) - T(M) \tag{D8}$$

The residential bid-rent becomes

$$\Psi(x, U^*) = R_A + t(M - x) - \varepsilon\theta(M - x) + T(M) - T(x) \tag{D9}$$

while the business bid-rent is given by

$$\Phi(y) = A_m(y) - A_m(M/2) + ty + R_A - \varepsilon\theta M/2 + S(y) - S(M/2) + T(M) \tag{D10}$$

In the partially integrated city, the equilibrium utility given by

$$U^* = A(b_0) + S(b_0) - 2t\left(M - b_0\right) - 2R_A - 2T(M) \tag{D11}$$

The wage is given by

$$w(y) = \begin{cases} \frac{1}{2}\left[A(y) + A(b_0) + S(y) + S(b_0)\right] - t\left(M - b_0\right) - R_A - T(M), & y \in [0, b_0] \\ A(b_0) + S(b_0) - t\left(y - b_0\right) - t\left(M - b_0\right) - R_A - T(M), & y \in [b_0, b_1] \end{cases} \tag{D12}$$

while the bid-rents are equal to

$$\Psi(x, U^*) = (t - \varepsilon\theta)(M - x) + R_A + T(M) - T(x), \quad x \in [b_1, b_2] \tag{D13}$$

and

$$\Phi(y) = \Psi(y, U^*) = \frac{1}{2}\left[A(y) - A(b_0)\right] + t\left(M - b_0\right) + R_A + \frac{1}{2}\left[S(y) - S(b_0)\right] + T(M), \quad y \in [0, b_0] \tag{D14}$$

and

$$\Phi(y) = \left[A(y) - A(b_0)\right] + t\left(y - b_0\right) + t\left(M - b_0\right) + R_A + \left[S(y) - S(b_0)\right] + T(M), \quad y \in [b_0, b_1] \tag{D15}$$

Appendix E. Pollution diffusion

Equilibrium utility is altered by the diffusion of traffic pollution. For monocentric cities, the utility is smaller under diffused pollution because local pollution raises utility while diffused pollution does the opposite. Formally, one successively computes

$$U^{**}(M) - U^*(M) = -\theta P_G - \theta P(M/2) = -\frac{1}{2}\theta\left(\varepsilon' M + \varepsilon\right) M < 0 \tag{E1}$$

For partially integrated cities, the utility is also smaller under diffused pollution. Indeed, we compute

$$U^{**}(M) - U^*(M) = \left[A_p(b_0^{**}) - A_p(b_0^*)\right] + 2t\left(b_0^{**} - b_0^*\right) - \theta P_G \tag{E2}$$

The expression shows three effects as the diffusion of pollution compactifies the integrated district and expands the business and the residential areas. First, the more compact integrated district increases the agglomeration effects, which increases productivity, wages, and utility (first term). Second, larger residential districts increase commuting and decrease utility (second term). Finally, diffused pollution decreases the utility in the same way for all residents (last term). Substituting the equilibrium values, we observe that the negative effects dominate the positive one:

$$U^{**}(M) - U^*(M) = -\varepsilon\theta\frac{8t + \varepsilon\theta}{\tau} - 2\theta\varepsilon'(M - 2t/\tau)^2 < 0 \tag{E3}$$

Thus, the diffusion of pollution unambiguously decreases utility.

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