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Are compact cities environmentally friendly?[*]

Carl Gaigné[†] Stéphane Riou[‡] and Jacques-François Thisse[§]

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Abstract

There is a large consensus among international institutions and national governments to favor urban-containment policies - the compact city - as a way to improve the ecological performance of the urban system. This approach overlooks a fundamental fact: what matters for the ecological outcome of cities is the mix between the level of population density and the global pattern of activities. As expected, when both the intercity and intraurban distributions of activities are given, a higher population density makes cities more environmentally friendly. However, once we account for the fact that cities may be either monocentric or polycentric as well as for the possible relocation of activities between cities, the relationship between population density and the ecological performance of cities appears to be much more involved. Indeed, because changes in population density affect land rents and wages, firms and workers are incited to relocate, thus leading to new commuting and shipping patterns. We show that policies favoring the decentralization of jobs in big cities may be more desirable because they both reduce pollution and improve welfare.

Keywords: greenhouse gas, commuting costs, transport costs, cities; urban-containment policy

JEL Classification: D61; F12; Q54; Q58; R12.

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1 Introduction

According to Yvo de Boer, Executive Secretary of the United Nations, “given the role that transport plays in causing greenhouse gas emissions, any serious action on climate change will zoom in on the transport sector” (Speech to Ministerial Conference on Global Environment and Energy in Transport, 15 January 2009). The transport of commodities and people is indeed a big and growing emitter of greenhouse gases (hereafter, GHG). This sector accounts for 30% of total GHG emissions in the USA and about 20% of GHG emissions in the EU-15 (OECD, 2008). Within the EU-27, GHG emissions in the transport sector has increased by 28% over the period 1990-2006, while the average reduction of emissions across all sectors is 3%. Road-based transport accounts for approximately 80% of transport sector GHG emissions, of which two-thirds are attributable to private cars. The main contributors to GHG emissions generated by the transport of people are, therefore, the commuters, while the shipping of goods between cities is the main driver in the use of trucks, with an increase in road transport of 58% from 1996 to 2006. Although new technological solutions for some transport modes might allow for substantial reductions in GHG emissions (Kahn and Schwartz, 2008), it is recognized that improvements in energy efficiency are likely to be insufficient to stabilize the pollution level in the transport sector (European Environment Agency, 2007). Thus, other initiatives are needed like mitigation policies based on *the reduction of average distances travelled by commodities and people*.

The analysis of global warming and climate change neglects the spatial organization of the economy and, therefore, its impact on transport demand and the resulting GHG emissions. It is our contention that such a neglect is unwarranted. Indeed, the bulk of road-based transport flows between production and consumption sites take place between cities. Furthermore, there is also a large empirical literature that highlights the effect of city size and structure on GHG emissions through the amount of commuting (Bento et al., 2006; Kahn, 2006; Brownstone and Golob, 2009; Glaeser and Kahn, 2010). The current trend toward increased vehicle use has been reinforced by urban sprawl as suburbanites’ trips between residences and workplaces has increased (Glaeser and Kahn, 2004). Kahn (2006) reports that the predicted gasoline consumption for a representative household is the lowest in relatively compact cities such as New York and San Francisco, and the highest in sprawling Atlanta and Houston. If the environmental costs of urban sprawl is increasingly investigated in North America, it is becoming an important issue in Europe as well. For example, in the region of Barcelona, from 1986 to 1996, the level of per capita emissions has doubled, the average trip distance has increased by 45%, and the proportion of trips made by car has increased by 62% (Muniz and Galindo, 2005).

Recognizing the environmental cost of urban sprawl, there seems to be a remarkable consensus among international institutions as well as local and national governments to implement urban-containment policies as a way of reducing the ecological impact of cities, and hence of contributing to the achievement of sustainable urban development. More precisely, scholars and city planners advocate city compactness as an ideal.[1]. The objective is to restrict urban sprawl by implementing smart growth policies that increase population density and limit the supply of new lots. When assessing the impact of urban-containment policies on the emissions of GHG, the existing literature has failed to address two major issues. First, the locations of firms and households are assumed to be given. Instead, the effects of a higher population density should be analyzed within a framework in which firms' and workers' locations are endogenously chosen in response to prices, wages and land rents determined by market mechanisms. Second, most empirical studies focus on individual cities. Yet, because of the intercity relocation of firms and households, ecological gains within a city arising from land use control may induce ecological losses in other cities. For example, by controlling its population growth, California has become the least emissions intensive area in the United States. This has, however, an undesirable consequence that was unnoticed by many environmentalists: a large number of households have to set up in other states, thus making these places less environmentally friendly (Glaeser and Kahn, 2010). Therefore, a sound environmental policy should be based upon the ecological assessment of the entire urban system. As will be seen, accounting for these various effects impact on the emissions of GHG in unsuspected ways.

The objective of this paper is to assess the ecological effect of higher population density when both firms and households are free to relocate *between* and *within* cities. In particular, we determine whether it is ecologically desirable for the public authorities to implement land use policies that reduce transport-related GHG emissions. In doing so, we do not adopt an approach based on a social welfare function. As argued by Stern (2008), the emissions of GHG are likely to be the biggest market failure that the public authorities have to manage, thus suggesting that deadweight losses associated with market imperfections are of second order. Although policy-makers often assign a high weight to consumers' welfare when they design policies related to climate change, it is widely accepted among environmentalists that global warming is so important for the future of

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[1] See Dantzig and Saaty (1973) for an old but sound discussion of the advantages of compact cities, whereas Gordon and Richardson (1997) provide a critical appraisal of this idea.

our societies that land use should be evaluated through its ecological footprint only. Even for those who like us find this position somewhat extreme, it should be clear that the ecological impact of land use policies is of interest for its own sake, regardless of the way the ecological goal is accounted for in social welfare. Nevertheless, we find it important to determine whether this goal is detrimental to households living standards. This is why our analysis also addresses the social deadweight losses of having a higher population density.

Our analysis relies on the following major trade-off: on the one hand, the agglomeration of activities decreases the polluting emissions stemming from commodity shipping between cities; on the other hand, agglomerating activities increases GHG emissions by making worktrips longer. When both the intercity and intraurban distributions of activities are given, high density levels render cities more environmentally friendly. However, a policy that aims to make cities more compact also impacts on the interregional pattern by fostering the progressive agglomeration of activities, hence the level of GHG within bigger and bigger cities. This is because changes in population density affect land rents and wages, which incite firms to change place. As a consequence, the *size* of cities becomes another critical variable in assessing the ecological performance of the urban system. Further, besides the endogenous relocation of economic activities between cities, we must also account for the fact that cities may be monocentric or polycentric. It should be clear, therefore, that *what matters for our purpose are both the level of population density and the spatial pattern of activities*. This leads us to suggest a possible alternative to the promotion of compact cities, that is, the creation of secondary business centers within large cities.

The following two results are worth mentioning. First, because an increasing-density policy favors the agglomeration of activities, we show that this policy may generate an upward jump in the level of global pollution. Furthermore, because markets do not provide the right signals about the desirability of agglomeration, a higher population density may also be detrimental to welfare. Thus, contrary to general beliefs, *pursuing the objective of compact cities may both raise global pollution and reduce welfare*. Second, once it is recognized that the internal structure of cities may also change with the population density level, the ecological effect of an increasing-density policy turns out to be even more ambiguous. Longer commuting flows are now caused by the development of the central business district that takes place at the expense of secondary business centers. We will see how policies favoring the decentralization of jobs in big cities may reduce the amount of commuting and improve global welfare. In a nutshell, *an increasing-density* *policy should be supplemented with instruments that induce the decentralization of jobs within polycentric cities.*

The remaining of the paper is organized as follows. In the next section, we present a model with two monocentric cities and discuss the main factors affecting the ecological outcome. Section 3 presents the ecological assessment of the resulting market outcome. In section 4, we extend our analysis to the case of polycentric cities and highlight the positive impact that the decentralization of jobs within cities may have on the emission of carbon dioxides. In section 5, we deal with the more general case in which both the internal structure of cities and the intercity distribution of activities are determined endogenously by the market. The last section offers our conclusions.

2 The model

2.1 The economy

Consider an economy with two cities, labelled $r = 1, 2$, $L > 0$ mobile workers, one manufacturing sector, and three primary goods: labor, land, and the numéraire, which is traded costlessly between the two cities. Each city, which is formally described by a one-dimensional space, can accommodate firms and workers. Whenever a city is formed, it has a central business district (CBD) located at $x = 0$ where city r-firms are set up.[2] Without loss of generality, we focus on the right-hand side of the city, the left-hand side being perfectly symmetrical. Distances and locations are expressed by the same variable x measured from the CBD. Our purpose being to highlight the interactions between the transport sector and the location of activities, we assume that the supply of natural amenities is the same in both cities.

Workers consume a residential plot of fixed size $1/\delta > 0$, regardless of their locations, so that δ is the *population density.* Although technically convenient, the assumption of a common and fixed lot size does not agree with empirical evidence with free land markets: individual plots tend to be smaller in big cities than in small cities. However, since the average commuting is typically longer in large than in small cities, we find it natural to believe that the plot size effect is dominated by the population size effect. In addition, our analysis focuses on the effect of a policy controlling lot size. It is, therefore, not unreasonable to assume that households treat parametrically the lot size.

Denoting by L_r the population residing in city r (with $L_1+L_2 = L$), the right endpoint

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[2] See Duranton and Puga (2004) for a survey of the reasons explaining the emergence of a CBD.

of this city is then given by

$$y_r = \frac{L_r}{2\delta}.$$

Workers have the same utility function

$$U_r = \left(a - \frac{q_r}{2}\right) q_r + q_0 \tag{1}$$

where q_r is the consumption of the manufactured good and q_0 the consumption of the numéraire. The unit of the manufactured good is chosen for $a = 1$ to hold. Each worker is endowed with one unit of labor and $\bar{q}_0 > 0$ units of the numéraire. The initial endowment $\bar{q}_0$ is supposed to be large enough for the individual consumption of the numéraire to be strictly positive at the equilibrium outcome.[3] Each worker commutes to the CBD and pays a unit commuting cost given by $t > 0$, so that a worker located at $x > 0$ bears a commuting cost equal to tx. The budget constraint of a worker residing at x in city r is given by

$$q_r p_r + q_0 + R_r(x)/\delta + tx = w_r + \bar{q}_0 \tag{2}$$

where p_r is the price of the manufactured good, $R_r(x)$ is the land rent at x, and w_r the wage paid by firms in city r's CBD. Within each city, a worker chooses her location so as to maximize her utility (1) under the budget constraint (2).

Because of the fixed lot size assumption, it is well known that the equilibrium value of urban costs, defined as the sum of commuting costs and land rent, is the same across workers' locations. The opportunity cost of land being normalized to zero, the equilibrium land rent is then given by

$$R_r^*(x) = t\left(\frac{L_r}{2} - \delta x\right) \qquad \text{for } x < y_r. \tag{3}$$

Utility maximization leads to the inverse demand for the manufactured good, $p_r = 1 - q_r$, so that city r's inverse demand for this good is given by

$$p_r = \min\{1 - Q_r/L_r, 0\} \tag{4}$$

where Q_r is the total quantity of the manufactured good sold in this city.

Firms do not use land. Producing q units of the manufactured good requires $\phi > 0$ units of labor. Free entry implies that there are $n = L/\phi$ (up to the integer problem) oligopolistic firms competing in quantity. Without loss of generality, the unit of labor is chosen for ϕ to be equal to 1, thus implying $n = L$. The manufactured good can

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[3] For simplicity, we assume that land is owned by absentee landlords.

be shipped at the cost of $\tau > 0$ units of the numéraire. Because they are spatially separated, the two regional markets are supposed to be segmented. This means that each firm chooses a specific quantity to be sold on each market; let q_{rs} be the quantity of the manufactured good that a city r-firm sells in city $s = 1, 2$. The market clearing condition for the manufactured good is such that $Q_r = n_r Q_{rr} + n_s Q_{sr}$, where n_r is the number of firms located in city r (with $n_1 + n_2 = n$). The operating profits of a city r-firm are then given by

$$\pi_r = q_{rr} p_r + q_{rs} \left(p_s - \tau \right)$$

with $s \neq r$. The equilibrium quantities sold by a city r-firm are such that $q^*_{rr} = L_r p^*_r$ and $q^*_{rs} = L_s \left(p^*_s - \tau \right)$, while the equilibrium price in city r is

$$p^*_r = \frac{1 + \tau n_s}{n + 1}. \tag{5}$$

Trade between cities arises at the equilibrium prices regardless of the intercity distribution of firms if and only if

$$\tau < \tau_{trade} \equiv \frac{1}{n + 1} \tag{6}$$

a condition which is supposed to hold throughout the paper.

The profits of a city r-firm are then given by $\Pi_r = \pi_r - w_r$. Urban labor markets are local and the equilibrium wage is determined by a bidding process in which firms compete for workers by offering them higher wages until no firm can profitably enter the market. In other words, operating profits are completely absorbed by the wage bill. Hence, the equilibrium wage rate in city r must satisfy the condition $\Pi_r = 0$, which yields

$$w^*_r = \pi^*_r = p^{*2}_r L_r + (p^*_s - \tau)^2 L_s. \tag{7}$$

2.2 The ecological trade-off in a space-economy

In our setting, workers' commuting and trade flows are the two sources of GHG emissions. Therefore, the ecological outcome E_m is obtained from the total distance travelled by commuters within cities (C_m) and from the total quantity of the manufactured good shipped between cities (T):

$$E_m = e_C C_m + e_T T$$

where e_C is the amount of carbon dioxides generated by one unit of distance travelled by a worker, while shipping one unit of the manufactured good generates e_T units of carbon dioxides. The value of e_C depends on the technology used (fuel less intensive and non-fuel vehicles, eco-driving and cycling) and on the commuting mode (public transportation versus individual cars), while the value of e_T is determined by the transport mode (road freight versus rail freight), technology (e.g. truck size), and the transport organization (empty running, deliveries made at night, ...).

The value of C_m depends on the intercity distribution of workers:

$$C_m(\lambda) = \frac{L^2}{4\delta^2}[\lambda^2 + (1-\lambda)^2] \tag{8}$$

where $\lambda \in [1/2, 1]$ is the share of workers residing in city 1 (with $L_1 = \lambda L$ ...). Clearly, the emission of GHG stemming from commuting increases with λ for all $\lambda > 1/2$ and is minimized when workers are evenly dispersed between two cities ($\lambda = 1/2$). In addition, for any given intercity distribution of activities, the total amount of emission decreases with the population density because the distance travelled by each worker shrinks.

Regarding the value of T, it is given by the sum of trade flows:

$$T(\lambda) = n_1 q_{12}^* + n_2 q_{21}^* = \frac{[2 - \tau(L+2)]L^2}{L+1}\lambda(1-\lambda) \tag{9}$$

where $T > 0$ since (6) holds. As expected, T is minimized when workers and firms are agglomerated within a single city ($\lambda = 0$ or 1). Note also that T increases when shipping goods becomes cheaper because there is more intercity trade. Hence, transport policies that foster lower shipping costs give rise to a larger emission of GHG.

The ecological trade-off we want to study may then be stated as follows: *a more agglomerated pattern of activity reduces pollution arising from commodity shipping, but increases the GHG emissions stemming from a longer average commuting, and vice versa.*

3 City size and the environment

In this section, we provide the ecological evaluation of the market outcome by studying the impact of increasing population density on workers' and firms' locations.

3.1 The market outcome

The indirect utility of a city r-worker is given by

$$V_r(\lambda_r) = S_r^* + w_r^* - UC_r + \overline{q}_0 \tag{10}$$

where S_r^* is the consumer surplus evaluated at the equilibrium prices (5):

$$S_r^* = \frac{n^2(1-\tau\lambda_s)^2}{2(n+1)^2} \tag{11}$$

and UC_r the urban costs borne by this worker. Using (3), it is readily verified that

$$UC_r \equiv \frac{R_r^*}{\delta} + tx = \frac{tL_r}{2\delta}. \tag{12}$$

An equilibrium arises at $0 < \lambda^* < 1$ when the utility differential $\Delta V(\lambda^*) \equiv V_1(\lambda^*) - V_2(\lambda^*) = 0$, or at $\lambda^* = 1$ when $\Delta V(1) \geq 0$. An interior equilibrium is stable if and only if the slope of the indirect utility differential ΔV is strictly negative in a neighborhood of the equilibrium, i.e., $d\Delta V(\lambda)/d\lambda < 0$ at λ^*; an agglomerated equilibrium is stable whenever it exists.

It is readily verified that the utility differential is given by (up to a positive and constant factor):

$$\Delta V(\lambda) \equiv \frac{L(\varepsilon_2 - \varepsilon_1\tau)\tau}{\delta}(\delta - \delta_m)\left(\lambda - \frac{1}{2}\right) \tag{13}$$

with

$$\delta_m \equiv \frac{t}{(\varepsilon_2 - \varepsilon_1\tau)\tau} > 0$$

where $\varepsilon_1 \equiv (L+2)(2L+1)/\left(1+L\right)^2 > 0$ and $\varepsilon_2 \equiv 2\left(2+3L\right)/\left(1+L\right)^2 > 0$. Clearly, $(\varepsilon_2 - \varepsilon_1\tau)\tau$ is positive and increasing with respect to τ when (6) holds because $\tau_{trade} < \varepsilon_2/\varepsilon_1$. Hence, the agglomeration of firms and workers within one monocentric city is the only stable equilibrium when $\delta > \delta_m$. In contrast, if $\delta < \delta_m$, dispersion with two identical monocentric cities is the unique stable equilibrium.

To sum up, we have:

Proposition 1 *Workers and firms are agglomerated into a monocentric city when the population density is high, commuting costs are low, and transport costs are high. Otherwise, they are evenly dispersed between cities.*

3.2 The ecological assessment of the market outcome

At the market equilibrium, the total emission of GHG is given by

$$E_m(\lambda) = \left\{\frac{e_T[2 - \tau(L+2)]}{L+1} - \frac{e_C}{2\delta^2}\right\}\lambda\left(1-\lambda\right)L^2 + \frac{e_C}{4\delta^2}L^2.$$

This expression being described by a concave or convex parabola, the emission of GHG is minimized either at $\lambda = 1$ or at $\lambda = 1/2$. In particular, agglomeration minimizes GHG emissions if and only if $\delta > \delta_m^e$ where

$$\delta_m^e \equiv \sqrt{\frac{e_C(L+1)}{2e_T[2 - \tau(L+2)]}}$$

with $\mathrm{d}\delta_m^e/\mathrm{d}\tau > 0$ and $\mathrm{d}\delta_m^e/\mathrm{d}L > 0$. Otherwise, dispersion is ecologically desirable. Hence, we have:

Proposition 2 *Assume that cities are monocentric. The pollution arising from transport is minimized under agglomeration (resp., dispersion) when population density is high (resp., low), transport costs are low (resp., high), or both.*

Hence, agglomeration or dispersion is not by itself the most preferable pattern from the ecological point of view. Contrary to general beliefs, big compact cities need not imply low levels of pollution. For agglomeration to be ecologically desirable, the population density must be sufficiently high for the average commuting distance to be short enough.

But what do "high" and "low" mean? The answer depends on the structural parameters of the economy that determine the value of the threshold δ_m^e. For instance, the adoption of commuting modes with high environmental performance (low e_C) decreases the density threshold value above which agglomeration is ecologically desirable. Conversely, high transport costs of commodities induce low emissions of GHG from commodity shipping. In this case, the agglomeration of firms and workers induces weak environmental benefits except for very high densities. Hence, the evaluation of the carbon tax effect levied on road transport activities should not focus only upon price signals. The impact on the spatial pattern of activities should also be considered. Finally, observe that δ_m^e is independent from the commuting cost level because the demand for commuting is perfectly inelastic. Nevertheless, as shown by Proposition 1, the value of t impacts on the intercity market pattern, thus on the ecological outcome.

3.3 Are more compact cities desirable?

(i) Ecological outcome. We now determine the conditions under which the market yields a good or a bad outcome from the ecological viewpoint. Figure 1 depicts the four possible cases. In panel A, the market outcome yields agglomeration and minimizes the pollution emission. In panel C, the market outcome yields dispersion and minimizes pollution. In contrast, in panels B and D, the market delivers a configuration that maximizes the emissions of GHG. Consequently, *the market yields either the best or the worst ecological outcome.*

Insert Figure 1 about here

What precedes will allow us to show how difficult it is in practice to find the optimal mix of instruments. To this end, we compare δ_m and δ_m^e. We have

$$\delta_m \gtreqless \delta_m^e \qquad \text{iff} \qquad t \gtreqless \bar{t}$$

where

$$\bar{t} \equiv (\varepsilon_2 - \varepsilon_1 \tau)\tau \sqrt{\frac{e_C(L+1)}{2e_T[2-\tau(L+2)]}}.$$

Consider first the case where t exceeds $\bar{t}$ (see Figure 2a). If $\delta < \delta_m$, the market outcome involves two cities. Keeping this configuration unchanged, an increase in population density always reduces the emissions of pollutants. Once δ exceeds δ_m, the economy gets agglomerated, thus leading to an downward jump in the GHG emissions. Further increases in population density allow for lower emissions of GHG. Hence, when commuting costs are high enough, increasing the population density fosters lower emissions of GHG. Nevertheless, under agglomeration, lower levels of GHG emissions could also have been reached under lower densities, i.e. for $\delta \in [\delta_m^e, \delta_m]$.

Assume now that $t < \bar{t}$ (see Figure 2b). As in the foregoing, provided that $\delta < \delta_m$, the market outcome involves dispersion while the pollution decreases when the population density increases. When δ crosses δ_m from below, the pollution now displays an upward jump. Under dispersion, however, lower levels of GHG emissions would have been sustainable over $[\delta_m, \delta_m^e]$. In other words, more compact cities need not be ecologically desirable because this recommendation neglects the fact that it may trigger the intercity relocation of activities. Consequently, once it is recognized that workers and firms are mobile, what matters for the total emission of GHG is the mix between population density (δ) and city size (λ), thus pointing to *the need of coordinating environmental policies at the local and global levels*. This has the following major implication: environmental policies should focus on the urban system as a whole and not on individual cities. Though developed within a very simple setting, this shows how difficult it is to identify the pattern of activities that is desirable from the environmental viewpoint.

Insert Figure 2 about here

Our model also allows us to derive some unsuspected results regarding the ability of instruments other than population density (carbon tax, low emission transport technology, ...) to reduce the pollution. For example, when $t < \bar{t}$ the development of more ecological technologies in shipping goods (low e_T) combined with the implementation of a carbon tax on carriers, which causes higher transport costs (high τ), lead to a higher value of

δ_m^e and a lower value of δ_m. This makes the interval $[\delta_m, \delta_m^e]$ wider, while the value of $\bar{t}$ increases. Hence, the above policy mix, which seems a priori desirable, may exacerbate the discrepancy between the market outcome and the ecological optimum. Therefore, when combining different environmental policies, one must account for their impacts on the location of economic activities. Otherwise, they may result in a higher level of GHG emissions.

The conventional wisdom is that population growth is a key driver in damaging the environmental quality of cities. Restraining population growth is, therefore, often seen as a key instrument for reducing pollution. And indeed, for a given intercity pattern and a given density level, we have $dE_m/dL > 0$. Nevertheless, since firms and workers are mobile, an increase in population size may change the intercity pattern of the economy. For that, we must study how the corresponding increase in population size affects the greenness of the economy. In our setting, increasing L has the following two consequences. First, it raises the density threshold level $(\mathrm{d}\delta_m^e/\mathrm{d}L > 0)$ above which agglomeration is the ecological optimum. Second, dispersion becomes the market equilibrium for a larger range of density levels $(\mathrm{d}\delta_m/\mathrm{d}L > 0)$. What matters for our purpose is how the four domains in Figure 1 are affected by a population increase. Note, first, that $\bar{t}$ increases with L. Since $\delta_m - \delta_m^e$ decreases with L when $t > \bar{t}$, the occurrence of a conflict between the market and the ecological objective is reduced (see Figure 2a). On the other hand, when $t < \bar{t}$, $\delta_m^e - \delta_m$ increases with L, thus making bigger the domain over which the market outcome is ecologically bad (see Figure 2b). Hence, as observed by Kahn (2006), *there is no univocal relationship between urban population growth and the level of pollution*. The above analysis provides a rationale for the non-monotonicity of this relationship. It also suggests that urban population control should be added to the policy mix.

(ii) Welfare. We now aim to evaluate the impact of denser cities at the light of a standard public economics approach. Since we have studied the environmental gains or losses generated by the market outcome, we find it natural to adopt a second best approach in which social welfare is also evaluated at the equilibrium wages and prices (see (A.1) in Appendix A). Although we recognize that smaller lots negatively affect consumers' well-being, we do not account for this effect in our welfare analysis. This is because it would be arbitrary to assign a specific weight to land consumption against the deadweight losses generated by market imperfections, thus making the comparison meaningless.

For any given intercity distribution of activities, a higher population density is welfare-enhancing because the average commuting costs are lower. However, when the population density becomes sufficiently high, firms and workers are agglomerated, which in turn affects the welfare level. This implies that we must determine the intercity allocation of firms and workers (λ^o) that maximizes social welfare. It is shown in Appendix A that $\lambda^o = 1$ (resp., $\lambda^o = 1/2$) is welfare-maximizing when $\delta > \delta_m^o$ (resp., $\delta < \delta_m^o$) with $\delta_m^o > \delta_m$ where δ_m^o is given by (26). In other words, the market yields agglomeration when $\delta_m^o > \delta > \delta_m$ whereas dispersion is socially desirable. Otherwise, the market outcome is identical to the second best optimum. This does not imply that a higher density is always welfare-enhancing: when δ crosses δ_m from below, the welfare level displays a downward jump (see Figure 3).

Insert Figure 3 about here

When commuting costs are low ($t < \bar{t}$), our results imply that an increasing population density should be accompanied by a growth control of the larger city because the polluting emissions in the global economy also increases when δ crosses δ_m from below (see Figure 2b). In this case, by preventing the agglomeration of activities, the public authorities reduce the GHG emissions and improve global welfare. On the other hand, the desirability of a growth control policy is more controversial when commuting costs are high ($t > \bar{t}$). When δ crosses δ_m from below and takes a value in $[\delta_m, \delta_m^o]$, a policy preventing agglomeration yields higher welfare but washes out the environmental gains generated by the market (see Figure 2a). This is not the end of the story, however. This conflict vanishes when $\delta > \delta_m^o$ because the market outcome both minimizes GHG emissions and maximizes social welfare.

To summarize,

Proposition 3 *Assume that cities are monocentric. A higher population density reduces the pollution and raises welfare when commuting costs are high. Furthermore, when commuting costs are low, a higher density may be harmful to both the environment and social welfare.*

Hence, in the case of monocentric cities, urban compactness yields fairly similar welfare and environmental effects.

4 Polycentric cities and the environment

In the foregoing section, we have studied the ecological effects of urban population density and size in the case of monocentric cities. In what follows, we propose another strategy to reduce the pollution emissions in the global economy: public authorities may control the intraurban distribution of firms to decrease the average distance traveled by workers. To reach our goal, we build on Cavailhès *et al.* (2007) and extend our basic model to the case of polycentric cities.

4.1 The distribution of activities in a polycentric city

(i) Secondary business centers. Firms are now free to locate in the CBD or to form a *secondary business district* (SBD). Both the CBD and the SBD are surrounded by residential areas occupied by workers. Although firms consume services supplied in the SBD, the higher-order functions (specific local public goods and non-tradeable business-to-business services) are still provided by the CBD. Hence, for using such services, firms set up in a SBD must incur a communication cost $K > 0$. Communicating requires the acquisition of specific facilities, which explains why communication costs have a fixed component. In addition, relationships between the CBD and a SBD also involves face-to-face communication. We capture this by assuming that the CBD and SBD residential areas must be adjacent. Furthermore, as the distance between the CBD and SBDs is small compared to the intercity distance, shipping the manufactured good between the CBD and SBDs is assumed to be costless, which implies that the price of this good is the same everywhere within a city. Finally, without significant loss of generality, we restrict ourselves to the case of two SBDs. Hence, apart from the assumed existence of the CBD, the internal structure of each city is endogenous. Note that the equilibrium distribution of workers within cities depends on the distribution of workers between cities. In what follows, the superscript C is used to describe variables related to the CBD, whereas S describes the variables associated with a SBD.

(ii) The market outcome. At a *city equilibrium*, each individual maximizes her utility subject to her budget constraint, each firm maximizes its profits, and markets clear. Individuals choose their workplace (CBD or SBD) and their residential location with respect to given wages and land rents. Given equilibrium wages and the location of workers, firms choose to locate either in the CBD or in the SBD. Or, to put it differently, no firm has an incentive to change place within the city, and no worker wants to change her working place and/or residence. In particular, at the city equilibrium, the distribution of workers is such that $V_r^C(\lambda) = V_r^S(\lambda) \equiv V_r(\lambda)$. Likewise, firms are distributed at the city equilibrium such that $\Pi_r^C(\lambda) = \Pi_r^S(\lambda)$.

Denote by y_r the right endpoint of the area formed by residents working in the CBD and by z_r the right endpoint of the residential area on the right-hand side of the SBD, which is also the outer limit of city r. Let x_r^S be the center of the SBD in city r. Therefore, the critical points for city r are as follows:

$$y_r = \frac{\theta_r L_r}{2\delta} \qquad x_r^S = \frac{(1+\theta_r) L_r}{4\delta} \qquad z_r = \frac{L_r}{2\delta} \tag{14}$$

where $\theta_r < 1$ is the share of city r-firms located in the CBD. Observe that the bid rents at y_r and z_r are equal to zero because the lot size is fixed and the opportunity cost of land is zero.

At the city equilibrium, the budget constraint implies that $w_r^C - R_r^C(x) - tx = w_r^S - R_r^S(x) - t\left|x - x_r^s\right|$, where R_r^C and R_r^S denote the land rent around the CBD and the SBD, respectively. Moreover, the worker living at y_r is indifferent between working in the CBD or in the SBD, which implies $w_r^C - R_r^C(y_r) - ty_r = w_r^S - R_r^S(y_r) - t(x_r^S - y_r)$. It then follows from $R_r^C(y_r) = R_r^S(y_r) = 0$ that

$$w_r^C - w_r^S = t(2y_r - x_r^S) = t\frac{3\theta_r - 1}{4\delta}L_r \tag{15}$$

where we have used the expressions of y_r and x_r^S given in (14).

In each workplace (CBD or SBD), the equilibrium wages are determined by a bidding process in which firms compete for workers by offering them higher wages until no firm can profitably enter the market. Hence, the equilibrium wage rates in the CBD and in the SBD must satisfy the conditions $\Pi_r^C = \Pi_r^S = 0$, respectively. Solving these expressions for w_r^C and w_r^S, we get:

$$w_r^{C*} = \pi_r^* \qquad w_r^{S*} = \pi_r^* - K \tag{16}$$

which shows that the wage wedge $w_r^{C*} - w_r^{S*}$ is positive. Finally, the equilibrium land rents are given by

$$R_r(x) = R_r^C(x) = t\left(\frac{\theta_r L_r}{2} - \delta x\right) \qquad \text{for } x < y_r \tag{17}$$

where we have used the expression of y_r and the condition $R^C(y_r) = 0$ and by

$$R_r(x) = R_r^S(x) = t\left[\frac{(1-\theta_r) L_r}{4} + \delta\left(x_r^S - x\right)\right] \qquad \text{for } x_r^S < x < z_r. \tag{18}$$

Substituting (7) and (16) into (15) and solving with respect to θ yields:

$$\theta_r^* = \frac{1}{3} + \frac{4\delta K}{3tL_r} \tag{19}$$

which always exceeds 1/3. Observe first that, when $\theta_r^* < 1$, a larger population leads to a decrease in the relative size of the CBD, though its absolute size rises, whereas both the relative and absolute sizes of the SBD rise. Indeed, increasing $\lambda_r L$ leads to a more than proportionate increase in the wage rate prevailing in the CBD because of the rise in the average commuting cost. Moreover, since $\theta_r^* < 1$, the higher the population density, the larger the CBD; the lower the commuting cost, the larger the CBD.

It is readily verified that city r is polycentric ($\theta_r < 1$) if and only if

$$\delta < \frac{tL_r}{2K}. \tag{20}$$

Hence, a polycentric city is likely to occur when the density is low, the population density is low, the city size is large, and commuting costs are high. In particular, *when the population density steadily rises, both SBDs shrink smoothly and, eventually, the city becomes monocentric.*

(iii) The ecological impact of commuting in a polycentric city. Since the total distance travelled by commuters in the polycentric city r is equal to

$$\frac{L_r^2}{4\delta^2}\left[\theta_r^2 + \frac{1}{2}(1-\theta_r)^2\right] \tag{21}$$

the decentralization of jobs away from the CBD leads to less GHG emissions through a shorter average commuting. Regarding the impact of a higher density, it is a priori ambiguous. Indeed, for a given degree of decentralization of jobs, it induces shorter commuting distances and, therefore, lower emissions. However, (19) shows that a rising population density also leads to a higher number of jobs in the CBD at the expense of the SBDs, which in turn increases the emission of GHG. By plugging (19) into (21), it is readily verified that the latter effect overcomes the former. Hence, *regardless of the city structure, a higher population density generates lower GHG emissions.*

4.2 The ecological outcome in a system of polycentric cities

Since shipping the manufactured good within a city is costless, the value of T is still given by (9). On the other hand, the total distance travelled by commuters, denoted C_p, now depends on the internal structure of each city (θ_1 and θ_2) as well as on the distribution of workers/firms between cities:

$$C_p \equiv \frac{\lambda^2 L^2}{4\delta^2}\left[\theta_1^2 + \frac{1}{2}(1-\theta_1)^2\right] + \frac{(1-\lambda)^2 L^2}{4\delta^2}\left[\theta_2^2 + \frac{1}{2}(1-\theta_2)^2\right] \tag{22}$$

which reduces to (8) when the two cities are monocentric ($\theta_1 = \theta_2 = 1$). It is straightforward to check that the GHG emissions increase when the CBDs grow. However, the strength of this effect decreases with the population density.

Substituting the equilibrium values of θ_1 and θ_2 given by (22) into (19), we obtain

$$C_p(\lambda) = \frac{16K^2\delta^2 + L^2t^2}{12t^2\delta^2} - \frac{\lambda(1-\lambda)L^2}{6\delta^2}$$

which, unlike C_m, depends on the level of commuting costs t. Note that C_p reaches its minimum when workers are evenly dispersed between cities ($\lambda = 1/2$).

The total emissions of GHG arising when cities are polycentric is given by

$$E_p(\lambda) = e_C C_p + e_T T = \left\{ \frac{e_T[2 - \tau(L+2)]}{L+1} - \frac{e_C}{6\delta^2} \right\} \lambda\,(1-\lambda)\,L^2 + \frac{e_C\left(L^2t^2 + 16K^2\delta^2\right)}{12t^2\delta^2}.$$

In order to evaluate the ecological performance of a system of polycentric cities, we first compare E_p and E_m at the same λ and the same δ. It is readily verified that $E_m(\lambda) - E_p(\lambda) > 0$, meaning that for any given population density and intercity distribution of the manufacturing sector, *the global GHG emissions are lower in a system of polycentric cities than in a system of monocentric cities.* Nevertheless, from the ecological viewpoint, higher population densities reduce the desirability of polycentricity: $\mathrm{d}(E_m - E_p)/\mathrm{d}\delta < 0$. On the other hand, higher commuting costs strengthen the advantage of polycentric cities: $\mathrm{d}(E_m - E_p)/\mathrm{d}t > 0$. Indeed, higher commuting costs leads to an increase in the relative size of the SBDs when cities are polycentric, which in turn leads to lower GHG emissions. Finally, since $\mathrm{d}(E_m - E_p)/\mathrm{d}L > 0$, the ecological gain due to a move from monocentric cities to polycentric cities increases when the total population grows.

To sum up

Proposition 4 *Assume that the intercity distribution of the manufacturing sector and the population density are exogenous. Then, polycentricity generates ecological gains that decrease with the population density but increase with the population size.*

Finally, observe that agglomeration ($\lambda = 1$) minimizes the emission of GHG if and only if:

$$\delta > \delta_p^e \equiv \sqrt{\frac{e_C\,(L+1)}{6e_T[2-(L+2)\tau]}}.$$

As in the monocentric case, pollution is minimized under agglomeration when the population density is sufficiently high. Since $\delta_p^e < \delta_m^e$, we also have:

Proposition 5 *Agglomeration minimizes the pollution for a wider range of population density levels when cities are polycentric rather than monocentric.*

5 The ecological impact of urban development

So far, we have treated the urban morphology (monocentric or polycentric cities) as given. In this section, we provide an ecological evaluation of the market outcome when the size and spatial structure of each city are endogenously determined. To evaluate the environmental performance of the market outcome, we must determine first the equilibrium size and structure of cities.

5.1 The distribution of activities between cities

With polycentric cities, the utility differential between cities depends on the degree of decentralization within each city. The indirect utility of an individual working in the CBD is still given by (10) in which the urban costs she bears are now given by[4]

$$UC_r^C \equiv \theta_r^* \frac{tL_r}{2\delta} < UC_r.$$

From the polycentricity condition (20), it follows that

$$\delta_1 \equiv \frac{\lambda Lt}{2K} \qquad \delta_2 \equiv \frac{(1-\lambda)Lt}{2K}. \tag{23}$$

where $\delta_1 \geq \delta_2$ since $\lambda \geq 1/2$. Using (20), it is easy to show that the following three patterns may emerge: (i) when $\delta > \delta_1$, both cities are monocentric, (ii) when $\delta_1 > \delta > \delta_2$, city 1 is polycentric and city 2 is monocentric, and (iii) when $\delta_2 > \delta$, both cities are polycentric. Under dispersion ($\lambda = 1/2$), we have $\delta_1 = \delta_2 = \delta_p$ where

$$\delta_p \equiv Lt/4K$$

so that the two cities are monocentric if $\delta > \delta_p$ and polycentric if $\delta < \delta_p$. Similarly, under agglomeration ($\lambda = 1$), $\delta_1 = 2\delta_p$ while $\delta_2 = 0$. Thus, agglomeration arises within a monocentric city when $\delta > 2\delta_p$ or within a polycentric city when $\delta < 2\delta_p$. Last, $\delta_1 > \delta > \delta_2$ holds if and only if $1/2 < \lambda < 1$.

In order to determine the equilibrium outcome, we must consider the utility differential corresponding to each of these three patterns. In Appendix B, we show the existence and stability of five equilibrium configurations: (i) dispersion with two monocentric cities having the same size (m, m); (ii) agglomeration within a single monocentric city $(\mathrm{m}, 0)$;(iii) partial agglomeration with one large polycentric city and a small monocentric city (p, m);

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[4] We may disregard the case of SBD-workers because, at the city equilibrium, they reach the same utility level as the CBD-workers.

(iv) agglomeration within a single polycentric city $(\mathrm{p}, 0)$ and (v) dispersion with two polycentric cities having the same size (p, p). In Figure 4, the domains of the positive quadrant (K, δ) in which each of these configurations is a market outcome are depicted.

It is worth stressing that the spatial implications of an increased population density depend on the level of communication costs. In particular, when communication costs are large, i.e. $K > 3\bar{K}$ with

$$\bar{K} \equiv \frac{L(\varepsilon_2 - \varepsilon_1 \tau)\tau}{4}$$

the economy traces out the following path when the population density steadily increases from very small to very large values: (p, p) when $\delta < \delta_p$, then (m, m) when $\delta_p < \delta < \delta_m$, and $(\mathrm{m}, 0)$ when $\delta_m < \delta$. This may be explained as follows. By inducing high urban costs, a low population density leads to both the dispersion and decentralization of jobs, that is, the emergence of two polycentric cities. When the density gets higher, urban costs decrease sufficiently for the centralization of jobs within cities to become the equilibrium outcome; however, they remain high enough for the equilibrium to involve two monocentric cities. Last, for very high density levels, urban costs become almost negligible, thus allowing one to save the cost of shipping the manufactured good through the emergence of a single monocentric city.

Insert Figure 4 about here

At the other extreme, when communication costs are low, i.e. $K < \bar{K}$, we have (p, p) or (p, m) when $\delta < \delta_m/3$, then (p, m) when $\delta_m/3 < \delta < \delta_{pm}$, further $(\mathrm{p}, 0)$ when $\delta_{pm} < \delta < 2\delta_p$, and $(\mathrm{m}, 0)$ when $2\delta_p < \delta$, with

$$\delta_{pm} \equiv \frac{t}{3(\varepsilon_2 - \varepsilon_1 \tau)\tau - 4K/L}$$

which is positive since $K < \bar{K}$. The intuition is similar to that presented above. Note, however, that two stable equilibria, (p, p) and (p, m), exist for low densities $(\delta < \delta_p)$.

5.2 The ecological effects of compact cities

In the above subsection, we have seen how the equilibrium outcome depends on both the population density and the level of communication costs. We are now equipped to determine whether more compact cities leads to lower GHG emissions when firms and workers are free to locate between and within cities. Recall that the total level of emissions of GHG corresponding to the spatial structure $(\lambda^*, \theta_1^*, \theta_2^*)$ is given by

$$E(\lambda^*, \theta_1^*, \theta_2^*) = e_C C(\lambda^*, \theta_1^*, \theta_2^*) + e_T T(\lambda^*).$$

In order to disentangle the different effects at work, we begin by focusing on pollution arising from commuting. For any given location pattern, a higher density leads to a lower level of pollution stemming from workers' commuting. However, the impact of an increasing population density on the total distance travelled by commuters becomes ambiguous when firms and workers may change their locations. For example, under the equilibrium pattern (p, m), the global emissions of GHG generated by commuting is given by C_{pm}:[5]

$$C_{\mathrm{pm}} \equiv \frac{L^2(4\lambda_{pm}^{*2} - 6\lambda_{pm}^{*} + 3)}{12\delta^2} + \frac{2K^2}{3t^2}$$

where λ_{pm}^{*} is the share of firms and workers located in the polycentric city.[6] When K takes on low values, λ_{pm}^{*} increases with δ, whereas λ_{pm}^{*} decreases with δ when K is large. The impact of a density increase on C_{pm} is, therefore, a priori undetermined.

In addition, one may wonder what happens when the economy shifts from one pattern to another. To illustrate, consider the special, but today relevant, case of low communication costs ($K < \bar{K}$) and assume that the initial market outcome is given by (p, p). The corresponding emissions of GHG generated by commuting is then given by C_{pp}, where

$$C_{\mathrm{pp}} \equiv \frac{L^2}{24\delta^2} + \frac{4K^2}{3t^2}.$$

As long as this configuration prevails, densification reduces commuting pollution. However, once δ crosses $\delta_m/3$ from below, the economy shifts to the configuration (p, m) (see Figure 4). At $\delta = \delta_m/3$, the level of pollution exhibits an upward jump.[7] This is because city 1, which remains polycentric, becomes larger while city 2, which now accommodates fewer workers, becomes monocentric.

At the configuration (p, m), λ_{pm}^{*} increases with δ whenever $K < \bar{K}$. Thus, the level of pollution C_{pm} unambiguously decreases with density. Furthermore, at $\delta = \delta_{pm}$, the economy moves from (p, m) to $(\mathrm{p}, 0)$, which implies that the level of GHG emissions due to commuting is given by

$$C_{\mathrm{po}} = \frac{L^2}{12\delta^2} + \frac{2K^2}{3t^2}.$$

Once more, a change in the intercity structure generates an upward jump in commuting pollution.[8]

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[5] Note that $4\lambda_{pm}^{*2} - 6\lambda_{pm}^{*} + 3 < 1$ because $\lambda_{pm}^{*} \in (1/2, 1)$.

[6] Note that λ_{pm}^{*} can be directly derived from case (iii) in the Appendix B by solving $\Delta_{pm}V(\lambda) = 0$.

[7] Indeed, we have $C_{\mathrm{pp}} < C_{\mathrm{pm}}$ for $\delta \leq \delta_m/3$.

[8] This is because $C_{\mathrm{pm}} < C_{\mathrm{po}}$ over the interval $\delta_m/3 \leq \delta \leq \delta_{pm}$.

Finally, when the density keeps rising, the CBD grows at the expense of the SBDs. When δ reaches the threshold $2\delta_p$, the SBDs vanish, meaning that city 1 becomes monocentric. At $\delta = 2\delta_p$, we have $C_{\mathrm{po}} = C_{\mathrm{mo}}$ where

$$C_{\mathrm{mo}} = \frac{L^2}{4\delta^2}.$$

In this case, increasing further the population density leads to lower pollution.

The entire equilibrium path is described in Figure 5. It reveals an interesting and new result: although increasing population density reduces GHG emissions when the urban system remains the same, a density increase that changes the structure of the urban system does not reduce the GHG emissions. In particular, since the minimum value of C_{pm} over $(\delta_m/3, \delta_{pm})$ exceeds the maximum value of C_{pp} over $(\delta_p, \delta_m/3)$, moving from (p, p) to $(\mathrm{p}, 0)$ through (p, m) leads to higher levels of commuting pollution. This shows that higher density levels that affect the urban system may have undesirable effects from the environmental point of view.

Insert Figure 5 about here

Regarding the GHG emissions generated by the transport of goods, dispersion ($\lambda = 1/2$) is the worst and agglomeration ($\lambda = 1$) the best configuration: $T(1/2) > T(\lambda^*_{pm}) > T(1)$. Consequently, for the case where $K < \bar{K}$, the recommendations based on commuting (C) and shipping (T) do not point to the same direction. Specifically, when the city structure shifts from (p,m) to (p,0), the pollution generated by workers' commuting jumps upward while the pollution generated by goods' shipping vanishes. In this case, it is a priori impossible to compare the various market outcomes, hence to determine the best ecological configuration. Yet, given the relative importance of commuting and shipping in the global emission of carbon dioxides, we believe that the conclusions derived above for the commuting case are empirically more relevant.

As a final point, observe that, provided that the population density sustains polycentric cities, we always have $C_{\mathrm{pp}} + T(1/2) < C_{\mathrm{mm}} + T(1/2)$ and $C_{\mathrm{po}} < C_{\mathrm{mo}}$. In other words, when cities become polycentric, the environmental performance of the urban system is improved. Or, to put it differently, a policy that turns monocentric cities into polycentric cities leads to lower GHG emissions.

5.3 Welfare and the environment

Our results suggest that the decentralization of jobs within cities could be a better instrument than a higher population density from the ecological standpoint. One may wonder what this recommendation becomes when it is evaluated at the light of a second best approach in which the planner chooses the number and structure of cities $(\lambda^o, \theta_1^o, \theta_2^o)$.

At any given intercity distribution of firms (λ), the intraurban allocation of firms maximizing global welfare is given by:

$$\theta_r^o = \frac{1}{3} + \frac{2\delta K}{3tL_r} < \theta_r^*. \tag{24}$$

Hence, starting from the market equilibrium, a coordinated decrease in the size of the CBD both raises welfare and decreases GHG emissions. It is readily verified that the second best outcome implies that city r is polycentric if

$$\delta < \delta_r^o \equiv \frac{tL_r}{K}. \tag{25}$$

Let us now turn to the intercity distribution of activities. Since the number of cases to consider is very large, we follow the same strategy as in the foregoing and restrict ourselves to the case of low communication costs $(K < \bar{K})$. It is shown in Appendix A.2 that the second best optimum is given by (i) two identical polycentric cities when $\delta_m^o/3 > \delta$, (ii) two asymmetric cities when $\delta_{pm}^o > \delta > \delta_m^o/3$, (iii) one single polycentric city when $4\delta_p > \delta > \delta_{pm}^o$, and (iv) one single monocentric when $\delta > 4\delta_p$ (the expressions for δ_{pm}^o and δ_m^o are given in Appendix A). Since $\delta_m^o > \delta_m$ and $\delta_{pm}^o > \delta_{pm}$, the market does not deliver the second best optimum. For example, the market sustains two asymmetric cities when $\delta_m^o/3 > \delta > \delta_m/3$ while two identical polycentric cities corresponds to the second best optimum. In addition, when $\delta_{pm}^o > \delta > \delta_m^o/3$, a single polycentric city is the equilibrium spatial configuration while the second best optimum corresponds to a large polycentric city with a small monocentric city.

To conclude, a marginal increase in δ is both ecologically and socially desirable. However, when the population density increase generates a new pattern of activities (when δ crosses $\delta_m^o/3$ or δ_{pm}^o from below), the move is detrimental to both objectives. This means that what we have seen above about the ecological impact of city compactness also applies to the social welfare. Therefore, though incomplete, *our analysis does not suggest the existence of a major conflict between welfare and environmental objectives*. It should kept in mind, however, that our social welfare function does account for the fact that consumers typically have a preference for large plots against small ones.

6 Conclusion

This paper has focused on a single facet of compact cities: the transport demand. In doing so, we have left aside the role of density in the emissions of carbon dioxides generated by home heating and air conditioning. Therefore, a housing sector should be grafted onto our setting to capture this additional facet of the problem. In the same vein, one should also account for the residential density preferences. Thus, our work is far too preliminary to make strong and specific policy recommendations. Instead, it must be viewed as a first step toward the still missing theory of what an ecologically and socially desirable urban system might be. However, we believe that our results are sufficiently convincing to invite city planners and policy-makers to pay more attention to the various implications of urban compactness. Since local land-use restriction policies may have a global negative environmental impact through the relocation of activities, our results also casts doubts on the idea that more compact cities is always ecologically desirable. Compact and monocentric cities may generate more pollution than polycentric and dispersed cities, unless modal changes lead workers to use mass transport systems. On the other hand, by lowering urban costs without reducing the benefits generated by large urban agglomerations, the creation of secondary business centers may allow large cities to reduce GHG emissions while maintaining their productivity. Last, we have seen that combining technological and urban instruments is probably the best strategy. Therefore, seeking the best policy mix should rank high on city planners' and policy-makers' agenda.

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Appendix A

1. When cities are monocentric, the second best intercity allocation is the solution of the following program:

$$\text{Max } W(\lambda) = L_1 S_1^* + L_2 S_2^* + L_1(w_1 - UC_1) + L_2(w_2 - UC_2). \tag{A.1}$$

Plugging S_r^*, w_r^* and UC_r into (A.1) for a given intercity distribution of firms and workers, we obtain:

$$W_m(\lambda) = \frac{L(\varepsilon_2^o - \varepsilon_1^o \tau)\tau}{\delta} \lambda (\lambda - 1)(\delta - \delta_m^o) + \frac{(L+2)L}{2(L+1)^2} - \frac{tL}{2\delta}$$

with

$$\delta_m^o \equiv \frac{t}{(\varepsilon_2^o - \varepsilon_1^o \tau)\tau} > \delta_m \tag{26}$$

where $\varepsilon_1^o \equiv (2L^2 + 5L + 4)/2(L+1)^2$ and $\varepsilon_2^o \equiv 2(L+2)/(L+1)^2$. In this case, agglomeration (resp., dispersion) is welfare-maximizing when $\delta > \delta_m^o$ (resp., $\delta < \delta_m^o$).

2. When cities can be monocentric or polycentric the second best allocation is the solution of the following program:

$$\begin{aligned} \text{Max } W(\theta_1, \theta_2, \lambda) \;\; &= \;\; L_1 S_1^* + L_2 S_2^* + \theta_1 L_1 (w_1^c - UC_1^c) + \theta_2 L_2 (w_2^c - UC_2^c) \\ &\quad + (1 - \theta_1) L_1 (w_1^s - UC_1^s) + (1 - \theta_2) L_2 (w_2^s - UC_2^s). \end{aligned}$$

Plugging (24) into this expression, we get:

(i) if $\delta > \delta_1^o$ where δ_1^o is given by (25), both cities must be monocentric and the second best outcome is given by the solution to (A.1);

(ii) if $\delta_1^o > \delta > \delta_2^o$, city 1 must be polycentric and city 2 must be monocentric, which implies that W is given by

$$W_{pm}(\lambda) \equiv \left[(\varepsilon_2^o - \varepsilon_1^o \tau)\tau - \frac{2t}{3\delta}\right] \lambda^2 L - \left[(\varepsilon_2^o - \varepsilon_1^o \tau)\tau - \frac{t}{\delta} + \frac{2K}{3L}\right] \lambda L + \frac{(L+2)L}{2(L+1)^2} - \frac{tL}{2\delta} + \frac{\delta K^2}{3tL}.$$

The second best outcome now involves an interior configuration (λ_{pm}^o) when $\delta < 2\delta_m^o/3$ and $\delta < \delta_{pm}^o$ with

$$\delta_{pm}^o \equiv \frac{t}{3(\varepsilon_2^o - \varepsilon_1^0 \tau)\tau - 2K/L}.$$

Note that $W_m(1/2) = W_{pm}(\lambda_{pm}^o)$ at $\delta = 2\delta_m^o/3$, whereas $W_{pm}(\lambda_{pm}^o) < W_m(1/2)$ when $\delta < 2\delta_m^o/3$.

(iii) if $\delta_2^o > \delta$, both cities must be polycentric, so that W is now given by

$$W_p = \frac{3L(\varepsilon_2^o - \varepsilon_1^o \tau)\tau}{\delta} \lambda \left(\lambda - 1\right) \left(\delta - \delta_m^o/3\right) - \frac{2KL + L^2 t\delta}{6}$$

Accordingly, dispersion maximizes global welfare when $\delta < \delta_m^o/3$. Note that $W_p(1/2) = W_{pm}(\lambda_{pm}^o)$ at $\delta = \delta_m^o$ and $W_p(1/2) > W_{pm}(\lambda_{pm}^o)$ when $\delta < \delta_m^o$.

If dispersion ($\lambda = 1/2$) is socially desirable from the welfare viewpoint, we have $\delta_1^o = \delta_2^o = 2\delta_p$ so that the two cities must be monocentric if $\delta > 2\delta_p$ and polycentric if $\delta < 2\delta_p$. Similarly, under agglomeration ($\lambda = 1$), $\delta_1^o = 4\delta_p$ while $\delta_2^o = 0$. Thus, agglomeration must arise within a monocentric city when $\delta > 4\delta_p$ or within a polycentric city when $\delta < 4\delta_p$. Last, $\delta_1^o > \delta > \delta_2^o$ holds if and only if $1/2 < \lambda^o < 1$. Consequently, welfare is maximized when the economy is characterized by (i) a single monocentric city when $\delta > \max\{\delta_m^o, 4\delta_p\}$; (ii) a single polycentric city when $\delta_{pm}^o < \delta < 4\delta_p$; (iii) two identical monocentric cities when $2\delta_p < \delta < \delta_m^0$; (iv) two identical polycentric cities when $\delta < \min\{\delta_m^o/3, 2\delta_p\}$; (v) one large polycentric city and one small monocentric city when $\delta_m^o/3 < \delta < \min\{2\delta_p, \delta_{pm}^o\}$.

Appendix B

Case (i). Dispersion with two monocentric cities.

When $\delta < \delta_m$, Proposition 1 implies that $\lambda = 1/2$ is an equilibrium outcome once we restrict ourselves to monocentric cities. Note further that the condition $\delta > \delta_p$ also prevents a marginal deviation to a polycentric city to occur because, in the neighborhood of $\lambda = 1/2$, city r remains monocentric. Hence, the market equilibrium involves two monocentric cities having the same size if and only if $\delta_p < \delta < \delta_m$. For such a configuration to arise, it must be that $\delta_p < \delta_m$, i.e. $K > \bar{K}$.

Case (ii). Agglomeration within a single monocentric city.

Consider now the case of agglomeration in a monocentric city ($\lambda = 1$). For this to arise, it must be that $\delta > 2\delta_p$. In this case, when some workers leave city 2 to city 1, the latter must be monocentric. Because $\Delta V(1) > 0$ when $\delta > \delta_m$, $\lambda^* = 1$ is a stable equilibrium if and only if $\delta > \delta_m$ and $\delta > 2\delta_p$.

Case (iii). Dispersion with one polycentric city and one monocentric city.

When $\delta_1 > \delta > \delta_2$, the utility differential with $\theta_1^* < 1$ and $\theta_2^* = 1$ is given by

$$\Delta_{pm} V(\lambda) \equiv 2\left[(\varepsilon_2 - \varepsilon_1\tau)\tau - \frac{2t}{3\delta}\right]\lambda + \left[-(\varepsilon_2 - \varepsilon_1\tau)\tau + \frac{t}{\delta} - \frac{4K}{3L}\right].$$

Note that $1/2 < \lambda_{pm} < 1$ is a stable equilibrium if and only if $\Delta_{pm}V(1/2) > 0$ and $\Delta_{pm}V(1) < 0$ hold. The first condition is equivalent to $\delta < \delta_p$ whereas the second condition amounts to $\delta < \delta_{pm}$.

Case (iv). Agglomeration within a single polycentric city.

Agglomeration ($\lambda = 1$) in the polycentric city occurs if and only if $\delta_{pm} < \delta < 2\delta_p$. Note that $\delta_{pm} < 2\delta_p$ if and only if $K < 2\bar{K}$, which holds when communication costs are low, transport costs are high, or both. Otherwise, even though agglomeration in a monocentric city remains a possible outcome, agglomeration in a polycentric city is not a global equilibrium.

Case (v). Dispersion with two polycentric cities.

When $\delta < \delta_2$, the corresponding utility differential, which requires $\theta_1^* < 1$ and $\theta_2^* < 1$, is given by

$$\Delta_{pp}V(\lambda) \equiv \frac{L(\varepsilon_2 - \varepsilon_1\tau)\tau}{\delta}\left(\delta - \frac{\delta_m}{3}\right)\left(\lambda - \frac{1}{2}\right). \tag{B.1}$$

Dispersion with two polycentric cities is an equilibrium if $\delta < \delta_2$, which becomes $\delta < \delta_p$ when $\lambda = 1/2$. It remains to show that this configuration is stable. First, it must that the coefficient of λ is negative in (B.1), which amounts to $\delta < \delta_m/3$. Second, this configuration is stable against a marginal deviation to a monocentric city in, say, city 2 because, in the neighborhood of $\lambda = 1/2$, city 2 is polycentric since $\delta < \delta_p$. Therefore, the dispersed configuration with two polycentric cities is a stable equilibrium if and only if $\delta < \delta_m/3$ and $\delta < \delta_p$.

These results are summarized as follows. There exist five stable spatial configurations: (i) a single monocentric city when $\delta > \max\{\delta_m, 2\delta_p\}$; (ii) a single polycentric city when $\delta_{pm} < \delta < 2\delta_p$; (iii) two identical monocentric cities when $\delta_p < \delta < \delta_m$; (iv) two identical polycentric cities when $\delta < \min\{\delta_m/3, \delta_p\}$; (v) one large polycentric city and one small monocentric city when $\delta < \min\{\delta_p, \delta_{pm}\}$.

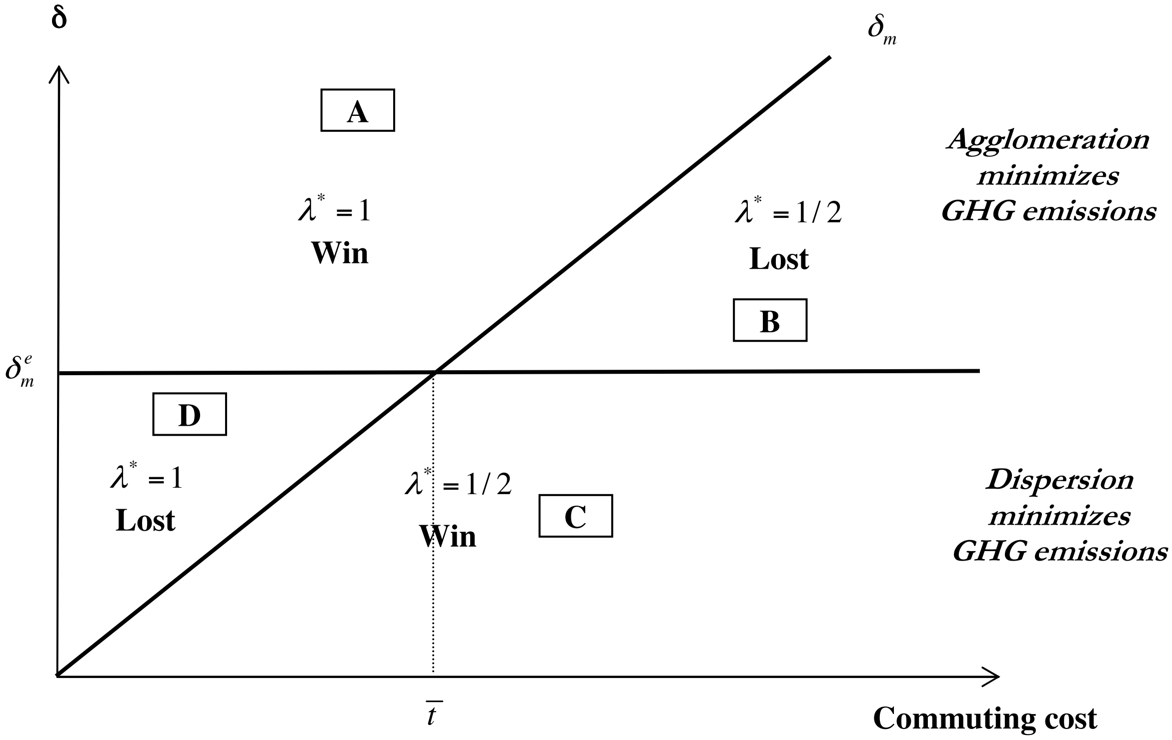

Figure 1. Inter-city distribution and ecological outcome with monocentric cities

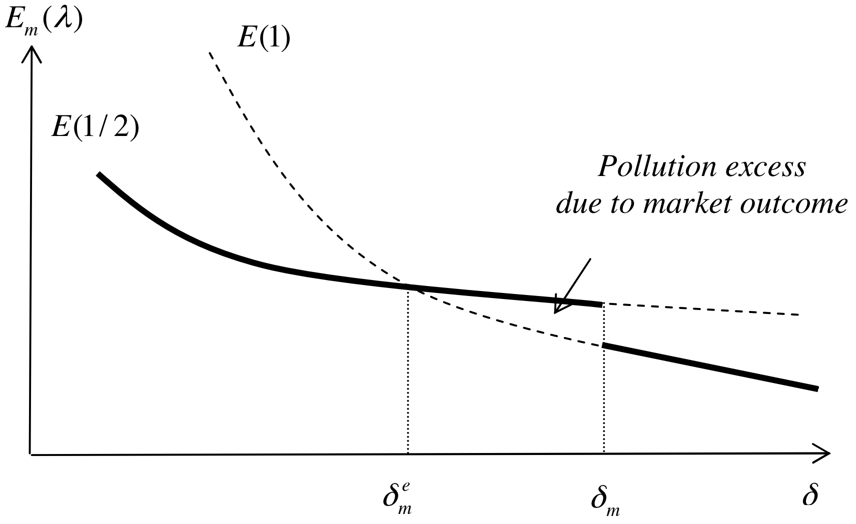

Figure 2a. Ecological and market outcomes when $t > \overline{t}$

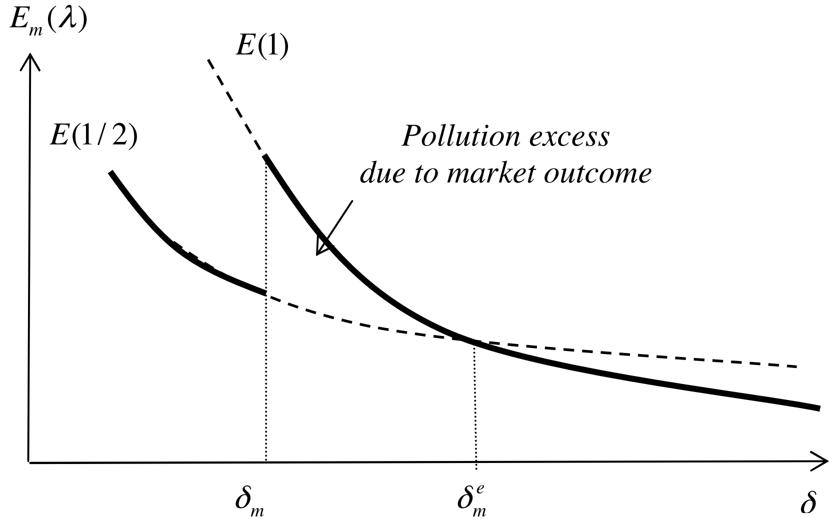

Figure 2b. Ecological and market outcomes when $t < \overline{t}$

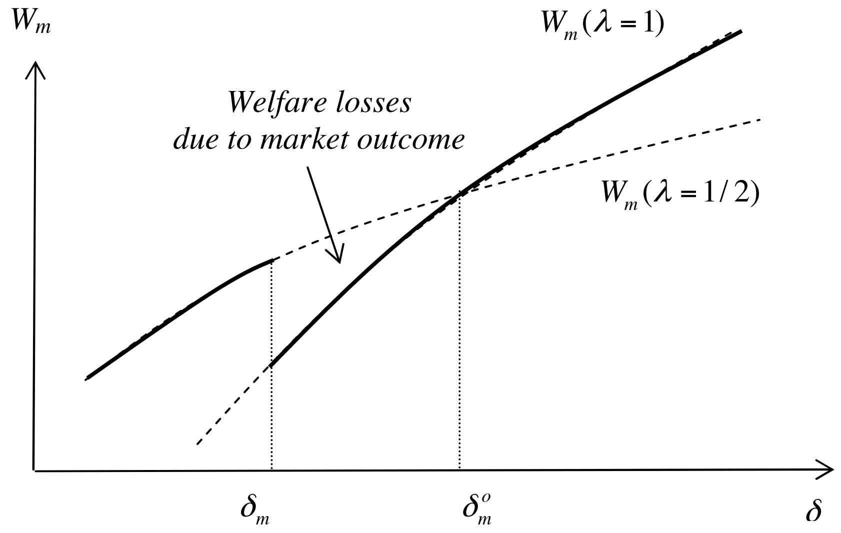

Figure 3. Market outcome and welfare

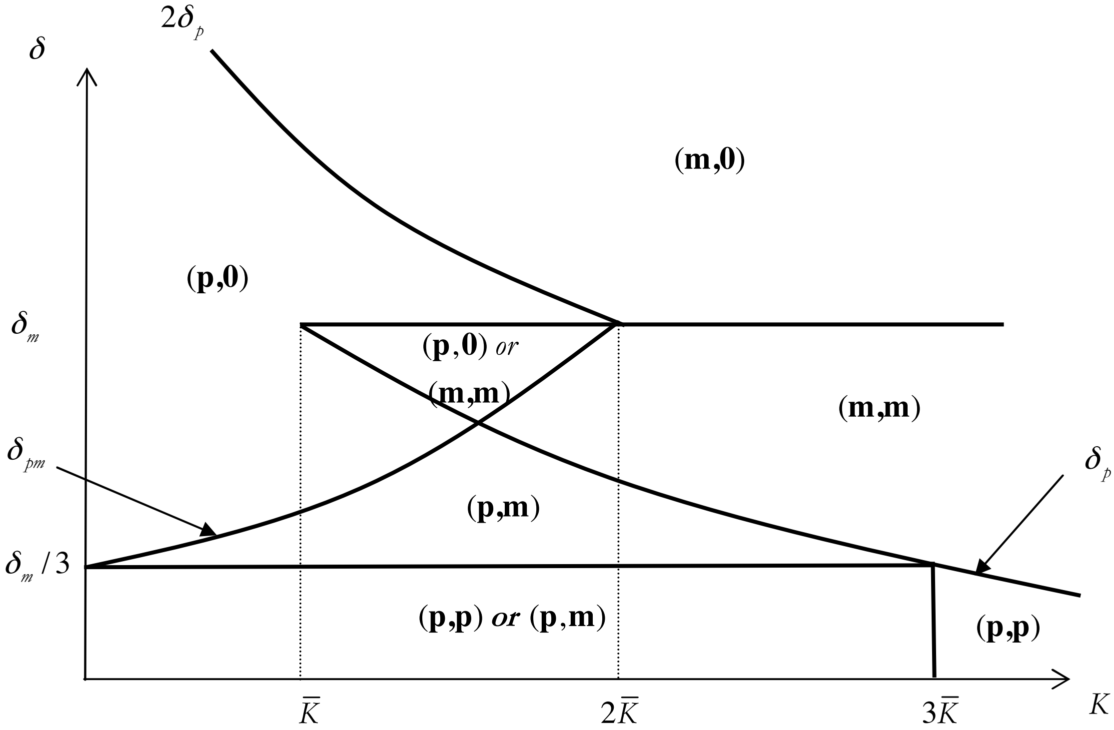

Figure 4. The set of equilibria

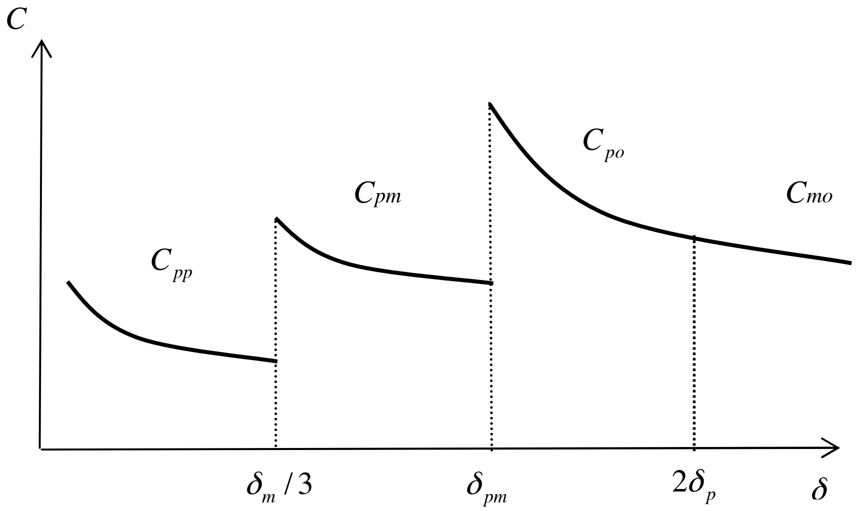

Figure 5. Commuting pollution when $K < \overline{K}$