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Are compact cities environmentally friendly?[*]

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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 may be more environmentally desirable.

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, former 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, whereas 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. In other words, the main contributors to GHG emissions generated by the transport of people are 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, which goes together with an increase in the average kilometers per shipment.[1] 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.* To a large extent, this explains why there is a remarkable consensus among international institutions as well as local and national governments to implement large and compact cities as a way of reducing the ecological impact of cities, and hence of contributing to the achievement of sustainable development. Nevertheless, the analysis of global warming and climate change neglects the spatial organization of the economy as a whole and, therefore, its impact on transport demand and the resulting GHG emissions. It is our contention that such a neglect is unwarranted.

There is 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

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[1] In France, from 1975 à 1995, the average kilometers per shipment has increased by 38% for all transportation modes, and by 71% for road transport only (Savin, 2000). Similar evolutions have been observed in the richer EU countries and in the USA.

between residences and workplaces has increased (Brueckner, 2000; 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 metropolitan area 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, scholars and city planners advocate city compactness as an ideal.[2] Specifically, 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. Our main point is that the environmental footprint of cities depends on how the economic activity is organized across space. Although seemingly intuitive, this global approach has never

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[2] 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.

really been part of the debate surrounding the desirability of compact cities.

In what follows, 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 our societies that land use should be evaluated through its ecological footprint only. Another reason for our approach is that it is hard to assess the impact of the lot size and GHG emissions on welfare. In this respect, it is worth stressing that it is not clear how policy-makers value reduced GHG in social welfare (to a large extent, the stagnating debates on climate change reflect this difficulty).

Our analysis relies on the following major trade-off: on the one hand, the agglomeration of firms and households decreases the polluting emissions stemming from commodity shipping between cities; on the other hand, agglomerating activities increases GHG emissions both by making work-trips longer and intensifying intra-urban trade flows. When both the intercity and intra-urban distributions of activities are given, high density levels render cities more environmentally friendly. However, a policy that aims at making 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 and households 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.

Our main results are as follows. First, because an increasing-density policy favors a greater agglomeration of activities, this policy may generate an upward jump in the level of global pollution. Second, for given lot size and intercity distribution of activities, the global GHG emissions are lower when cities are polycentric rather than monocentric. Note that making cities more compact reduces the ecological gains of polycentricity. Third, once it is recognized that the internal structure of cities may also change with lot size, the ecological effect of an increasing-density policy turns out to be even more ambiguous.

For instance, the resulting changes in the size and structure of cities may generate higher emissions from commuting and intra-urban trade flows. Therefore, our analysis shows that, contrary to general beliefs, *pursuing the objective of compact cities may raise global pollution.* This suggests that an increasing-density policy should be supplemented with instruments influencing the intra- and interurban distributions of households and firms. For instance, our analysis highlights the positive effects of job decentralization within 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 (or urban regions), 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.[3] 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 compete on a land market and consume a residential plot of fixed size $1/\delta > 0$, so that δ measures the *city compactness.*[4] Although technically convenient, the assumption of a common and fixed lot size does not agree with empirical evidence when consumers

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

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

compete on 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 the lot size parametrically. Denoting by L_r the population residing in city r (with $L_1 + L_2 = L$), the right endpoint of this city is then given by

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

Although new economic geography typically focuses on trade in differentiated products, it is convenient from the algebraic standpoint to assume that manufacturing firms produce a homogeneous good. Even in the presence of trade costs, trade arises because markets are imperfectly competitive (Brander and Krugman, 1983). Furthermore, the economic geography effects uncovered under monopolistic competition and differentiated products are qualitatively the same under oligopolistic competition with a homogeneous product (Gaigné and Wooton, 2011; Haufler and Wooton, 2010; Thisse, 2010). When the good is homogeneous, the quadratic utility proposed by Ottaviano et al. (2002) becomes

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

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. Each individual works at the CBD and bears a unit commuting cost given by $t > 0$, which implies that the commuting cost of a worker located at $x > 0$ is equal to tx. The budget constraint of a worker residing at x in city r is thus 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, $R_r(x)$ 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, 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 individual inverse demand for the manufactured good

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

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

Firms do not use land. Producing q units of the manufactured good requires $\phi > 0$ units of labor.[5] Labor market clearing 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 $n = L$, and thus $L_r = n_r$ and $L_s = n_s$. The manufactured good is 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 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 $s \neq r$ where p_r is given by (4) and $Q_r = n_r q_{rr} + n_s q_{sr}$, n_r being the number of firms located in city r (with $n_1 + n_2 = n$).

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 market clearing condition for the manufactured good implies that the equilibrium price in city r is

$$p_r^* = \frac{1 + \tau L_s}{L + 1}. \tag{5}$$

Trade flows from city r to city s are given by

$$q_{rs}^* = L_s\left(\frac{1 - \tau - \tau L_r}{L + 1}\right)$$

which decrease with the trade cost level. Therefore, trade between cities arises regardless of the intercity distribution of firms if and only if

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

a condition which we assume to hold throughout the paper.

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[5] Because inverse demand functions are linear, without loss of generality the common marginal cost may be normalized to zero.

The profits of a city r-firm are then given by $\Pi_r = \pi_r - w_r$. Urban labor markets are local. The equilibrium wage is determined by a bidding process in which firms compete for workers until 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

$$w_r^* = \pi_r^* = p_r^{*2} L_r + (p_s^* - \tau)^2 L_s. \tag{7}$$

2.2 The ecological trade-off in a space-economy

As mentioned in the introduction, goods' shipping and work-trips are the two main sources of GHG emissions generated in the transport sector. The shipping of goods arise at both the intra- and interurban scales. For example, the US commodity flows survey reports that more than 50% of commodities (in volume) are shipped over a distance less than 50 miles (US Census Bureau, 2007). Even though the share due to intra-urban shipping remains unknown, it seems reasonable to assume that its environmental cost is sufficiently significant to enter into the picture as a specific source of emissions.

To convey our message in a simple way, the ecological footprint E of a monocentric city is obtained from the total distance travelled by commuters within cities (C), the total quantity of the manufactured good shipped between cities (T), and the distribution of goods within cities (D) which depends on both the size of and consumption level in each city:

$$E = e_C C + e_T T + e_D D$$

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 between cities generates e_T units of carbon dioxides. The parameter e_D is the amount of carbon dioxides produced by shipping one unit of the good over a unit distance within a city. 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). In the same vein, the value of e_T and e_D 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, ...).

For simplicity, we assume that e_C, e_T and e_D are given parameters which are independent from city size and compactness. Admittedly, these are strong assumptions. First, because collective forms of transport are more viable in larger and/or more compact cities, one would expect e_C to be a decreasing function of city size and/or compactness. Under these circumstances, migrations from city r to city s reduce the value of e_C in the origin city but leads to a higher e_C in the destination city. As a result, the global impact of migration would depend on the behavior of the second derivative of e_C, an effect that is hard to assess. In what follows, we treat e_C as a parameter and will discuss what our results become when e_C varies. Second, treating e_T as a parameter is a priori restrictive because the ecological impact of the last miles covered in shipping goods increases with city size. However, we account for a large share of this impact through our definition of D.

The value of C depends on the intercity distribution of the manufacturing sector and is given by

$$C(\lambda) = 2\int_0^{y_1} x dx + 2\int_0^{y_2} x dx = \frac{L^2}{4\delta^2}[\lambda^2 + (1-\lambda)^2] \tag{8}$$

where $\lambda \in [0, 1]$ 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, $n_1 q_{12}^* + n_2 q_{21}^*$, that is

$$T(\lambda) = \frac{[2 - \tau(L+2)]L^2}{L+1}\lambda(1-\lambda) \tag{9}$$

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.

It remains to define D. The intra-urban distribution of goods increases with the local consumption of the manufactured good as well as with the spatial extension of cities. Specifically, we have

$$D(\lambda) = \frac{L_r}{\delta}Q_r + \frac{L_s}{\delta}Q_s = \frac{L^3}{\delta(L+1)}[\lambda^2 + (1-\lambda)^2 - \tau(1-\lambda)\lambda] \tag{10}$$

which decreases with both δ and τ. Note how these three terms change with our structural parameters: C (T) depends on δ (τ) only, while D varies with both.

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 inter-city shipping, but increases the GHG emissions stemming from a longer average commuting and higher intra-urban shipping; and vice versa.* It is worth stressing that both C and D similarly vary with λ and δ.

The model could be augmented by introducing emissions stemming from the production of the manufactured good. Since the total output

$$Q_r^*(\lambda) + Q_s^*(\lambda) = \frac{L^2}{L+1}[1 - 2\tau\lambda(1-\lambda)]$$

behaves like functions $C(\lambda)$ and $D(\lambda)$, we may disregard this source without affecting the nature of our results.[6] Note, however, that pollution generated by production is minimized (maximized) when $\lambda = 1/2$ ($\lambda = 1$), which means that accounting for production in the ecological footprint of cities fosters the dispersion of activities.

3 City size and the environment

In this section, we provide the ecological evaluation of the market outcome by studying the impact of a decreasing lot size on workers' and firms' locations.

3.1 The market outcome

As in the core-periphery model, firms and workers move hand-in-hand, which means that workers' migration drives firms' mobility. A *spatial equilibrium* is reached when no worker, hence firm, has an incentive to move. For that, we need to evaluate the indirect utility of a city r-worker:

$$V_r(\lambda_r) = S_r^* + w_r^* - UC_r + \overline{q}_0 \tag{11}$$

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

$$S_r^* = \frac{L^2 (1 - \tau\lambda_s)^2}{2(L+1)^2} \tag{12}$$

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

$$UC_r \equiv \frac{R_r^*}{\delta} + tx = \frac{tL_r}{2\delta}. \tag{13}$$

A spatial equilibrium arises at $0 < \lambda^* < 1$ when the utility differential between the two cities $\Delta V(\lambda^*) \equiv V_1(\lambda^*) - V_2(\lambda^*) = 0$, 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.

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[6] The impact of trade liberalization on emissions from production is well documented in the literature (see. Copeland and Taylor, 2003)

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

$$\Delta V(\lambda) \equiv \frac{L(\varepsilon_2 - \varepsilon_1\tau)\tau}{\delta}(\delta - \delta_m)\left(\lambda - \frac{1}{2}\right) \tag{14}$$

with

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

where $\varepsilon_1 \equiv (L+2)(2L+1)/(1+L)^2 > 0$ and $\varepsilon_2 \equiv 2(2+3L)/(1+L)^2 > 0$. Clearly, $(\varepsilon_2 - \varepsilon_1\tau)\tau$ is positive and increasing with respect to τ when (6) holds because $\tau_{trade} < \varepsilon_2/2\varepsilon_1$. 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 lot size is small, 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

Since E is described by a concave or convex parabola in λ, the emission of GHG is minimized either at $\lambda = 1$ or at $\lambda = 1/2$. Thus, it is sufficient to evaluate the sign of

$$E(1;\delta) - E(1/2;\delta) \propto e_C\frac{L+1}{\delta^2} - e_T\frac{2-\tau(L+2)}{2} + e_D\left(1+\frac{\tau}{2}\right)\frac{L}{\delta}.$$

Since this function decreases with δ from ∞ to a negative value over $(0,\infty)$, there exists a single solution $\delta_m^e > 0$ to the equation $E(\delta;1) - E(\delta;1/2) = 0$. Clearly, the agglomeration of activities within a single city is ecologically desirable if and only if $\delta > \delta_m^e$. Otherwise, dispersion is ecologically desirable. It is readily verified that $\mathrm{d}\delta_m^e/\mathrm{d}\tau > 0$ and $\mathrm{d}\delta_m^e/\mathrm{d}L > 0$. Hence, we have:

Proposition 2 *Assume that cities are monocentric. The pollution arising from transport is minimized under agglomeration (dispersion) when the lot size is small (big), transport costs are low (high), or the total population is low (high).*

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 lot size must be sufficiently small for the average commuting distance and/or the intra-urban shipping to be small enough. But what do “small” and “low” mean? The answer depends on the structural parameters of the economy that determine the value of the threshold δ_m^e. Indeed, δ_m^e increases with e_C and e_D but decreases with e_T, thus implying that e_C and e_D play a similar role in the determination of the ecologically desirable outcome. In addition, the adoption of commuting modes with high environmental performance (low e_C) decreases the density threshold value above which agglomeration is ecologically desirable, while transport modes for commodities with high environmental performance (low e_T) increases this threshold value.

Our framework also sheds light on the effects of a carbon tax levied on the transport of commodities. The implementation of such a tax is formally equivalent to an increase in trade costs (τ). For any intercity distribution of firms, increasing trade costs reduce pollution (see (9) and (10)). However, a rise in trade costs fosters agglomeration (because δ_m decreases), while this spatial configuration tends to become ecologically less desirable (because δ_m^e increases). Therefore, the evaluation of a carbon tax should not focus only upon price signals. It should also account for its impact on the spatial pattern of activities. 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 interregional market pattern, thus on the ecological outcome.

3.3 Are more compact cities desirable?

We now determine the conditions under which the market yields a good or a bad outcome from the ecological viewpoint. Since $\delta_m = 0$ at $t = 0$ and increases with t, while δ_m^e is independent from t, there are four possible cases, as depicted in Figure 1. 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 may yield as well as 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. Figure shows that there exist a unique $\bar{t}$ such that

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

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, a more compact city, i.e. a higher δ, always reduces the emissions of pollutants. Note, however, that lower levels of GHG emissions could be reached under agglomeration for $\delta \in [\delta_m^e, \delta_m]$. Once δ exceeds δ_m, the economy gets agglomerated, thus leading to a downward jump in the GHG emissions. Further increases in δ allow for lower emissions of GHG. Hence, when commuting costs are high enough, a denser city yields lower emissions of GHG.

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 level decreases when the city gets more compact. 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 interurban migrations. Consequently, once it is recognized that workers and firms are mobile, what matters for the total emission of GHG is the mix between city compactness (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 framework, the above results are already sufficient to figure out why implementing the ecological optimum is likely to be problematic.

Insert Figure 2 about here

Our model also allows us to derive some unsuspected results regarding the ability of instruments other than regulating the lot size (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 between cities (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. 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.

When $\bar{t}$ increases with L, then $\delta_m - \delta_m^e$ decreases with L provided that $t > \bar{t}$, whereas $\delta_m^e - \delta_m$ increases when $t < \bar{t}$. In this event, urban population growth decreases the occurrence of a conflict between the market and the ecological objective when commuting costs are high enough (see Figure 2a) but makes bigger the domain over which the market outcome is ecologically bad (see Figure 2b). When $\bar{t}$ decreases with L, the opposite holds. In both cases, as already noted by Kahn (2006) in a different context, *there is no univocal relationship between urban population growth and the level of pollution.* Our analysis provides a rationale for the non-monotonicity of the relationship observed between these two magnitudes.

To sum up,

Proposition 3 *Assume that cities are monocentric. If commuting costs are high, making cities more compact reduces pollution when the economy switches from dispersion to agglomeration. Furthermore, when commuting costs are low, a more compact city may be ecologically harmful.*

4 Polycentric cities and the environment

In this section, we consider the case of polycentric cities and show that the main results obtained when cities are monocentric still hold. This will allow us to propose an alternative strategy to reduce the pollution emissions in the global economy: public authorities may control the intra-urban distribution of firms and workers to decrease the average distance traveled by workers. To reach our goal, we extend our basic model by building on Cavailhès *et al.* (2007). In what follows, the subscript p refers to 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) on each side of the CBD, thus implying that a polycentric city has one CBD and two SBDs. Both the CBD and the SBDs 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 established 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 worker 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:

$$y_r = \frac{\theta_r L_r}{2\delta} \qquad x_r^S = \frac{(1+\theta_r)\,L_r}{4\delta} \qquad z_r = \frac{L_r}{2\delta} \tag{15}$$

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 $w_r^C - R_r^C(x) - tx = w_r^S - R_r^S(x) - t\,|x - x_r^s|$, 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

$$w_r^C - w_r^S = t(2y_r - x_r^S) = t\frac{3\theta_r - 1}{4\delta}L_r \tag{16}$$

where we have used the expressions of y_r and x_r^S given in (15).

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:

$$w_r^{C*} = \pi_r^* \qquad w_r^{S*} = \pi_r^* - K \tag{17}$$

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

$$R_r(x) = R_r^C(x) = t\left(\frac{\theta_r L_r}{2} - \delta x\right) \qquad \text{for } x < y_r \tag{18}$$

where we have used the expression of y_r and the condition $R^C(y_r) = 0$ and by[7]

$$R_r(x) = R_r^S(x) = t\left[\frac{(1-\theta_r)\,L_r}{4} + \delta\left(x_r^S - x\right)\right] \qquad \text{for } x_r^S < x < z_r. \tag{19}$$

Substituting (7) and (17) into (16) and solving with respect to θ yields:

$$\theta_r^* = \frac{1}{3} + \frac{4\delta K}{3tL_r} \tag{20}$$

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[7] In this expression, we do not account for the fact that transport modes may not be the same in these different areas of the metropolis. Our results remain valid as long as individual worktrips to a SBD do not generate much higher pollutants than those to the CBD.

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 city compactness, 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

$$\delta < \delta_r \equiv \frac{tL_r}{2K}. \tag{21}$$

Hence, a polycentric city is likely to occur when city compactness is low, the city size is large, and commuting costs are high. In particular, *when city compactness 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

$$\frac{L_r^2}{4\delta^2}\left[\theta_r^2 + \frac{1}{2}(1-\theta_r)^2\right] \tag{22}$$

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, (20) shows that a rising δ 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 (20) into (22), it is readily verified that the latter effect overcomes the former. Hence, *regardless of the city structure, a more compact city generates lower GHG emissions.*

4.2 The ecological outcome in a system of polycentric cities

Note first that the values of T and D are still given by (9) and (10) because they do not depend on city structure. 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:

$$C_p \equiv \frac{\lambda^2 L^2}{4\delta^2}\left[\theta_1^2 + \frac{1}{2}(1-\theta_1)^2\right] + \frac{(1-\lambda)^2 L^2}{4\delta^2}\left[\theta_2^2 + \frac{1}{2}(1-\theta_2)^2\right] \tag{23}$$

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 when cities become more compact.

Substituting the equilibrium values of θ_1 and θ_2 given by (23) into (20), 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 (8), 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

$$E_p(\lambda) = e_C C_p + e_T T + e_D D.$$

In order to evaluate the ecological performance of a system of polycentric cities, we first compare E_p and E at the same λ and the same δ. It is readily verified that $C_p < C$, which implies that $E(\lambda) - E_p(\lambda) > 0$. Hence, for any given lot size 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, a higher δ reduces the desirability of polycentricity because $\mathrm{d}(E - E_p)/\mathrm{d}\delta < 0$. On the other hand, higher commuting costs strengthen the advantage of polycentric cities since $\mathrm{d}(E - E_p)/\mathrm{d}t > 0$. Indeed, higher commuting costs lead to an increase in the relative size of the SBDs when cities are polycentric, which in turn leads to lower GHG emissions. Finally, since $\mathrm{d}(E - E_p)/\mathrm{d}L > 0$, 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 lot size but increase with the population size.*

As in Section 3.2, there exists a unique value δ_p^e for which agglomeration ($\lambda = 1$) minimizes the emission of GHG if and only if $\delta > \delta_p^e$. Provided that $\theta_r^* < 1$, as in the monocentric case, pollution is minimized under agglomeration when the lot size is sufficiently small. Furthermore, since $\delta_p^e < \delta_m^e$, we also have:

Proposition 5 *Agglomeration minimizes the pollution for a wider range of lot size 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 structure of each city are endogenously determined. To this end, we must determine the equilibrium size and structure of cities. Having done this, we show the possible perverse effects of city compactness and highlight the positive effects of job decentralization.

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 (11) in which the urban costs she bears are now given by[8]

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

Let

$$\delta_1 \equiv \frac{\lambda Lt}{2K} \qquad \delta_2 \equiv \frac{(1-\lambda)Lt}{2K}. \tag{24}$$

where $\delta_1 \geq \delta_2$ since we focus on the domain $\lambda \geq 1/2$. It follows from (21) 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, 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 (m, 0);(iii) partial agglomeration with one large polycentric city and a small monocentric city (p, m); (iv) agglomeration within a single polycentric city (p, 0) and (v) dispersion with two

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

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 implications of a higher degree of compactness 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 δ 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 (m, 0) when $\delta_m < \delta$. This may be explained as follows. By inducing high urban costs, a low δ-value leads to both the dispersion and decentralization of jobs, that is, the emergence of two polycentric cities. When cities' compactness 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 δ-values, 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 (p, 0) when $\delta_{pm} < \delta < 2\delta_p$, and (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 $\delta < \delta_p$.

5.2 The ecological effects of compact cities

In the above subsection, we have seen how the equilibrium outcome depends on both the lot size and the level of communication costs. We now determine whether more compact cities lead 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

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

1. 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 δ leads to a lower level of pollution stemming from workers' commuting. However, the impact of such a change in lot size on the total distance travelled by commuters becomes ambiguous when firms and workers are able to change places. For example, under the equilibrium pattern (p, m), the global emissions of GHG generated by commuting is given by C_{pm}:[9]

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

where λ_{pm}^{*} is the share of firms and workers located in the polycentric city.[10] 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, we 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 GHG emissions generated by commuting are then given by

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

As long as this urban configuration prevails, compactness 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.[11] 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 δ. 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.[12]

Finally, when the δ 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.

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

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

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

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

At $\delta = 2\delta_p$, we have $C_{\text{po}} = C_{\text{mo}}$ where

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

In this case, decreasing further the lot size leads to lower pollution.

The entire equilibrium path is described in Figure 5. It reveals an interesting and new result: although decreasing the lot size reduces GHG emissions when the urban system remains the same, *the resulting change in urban structure raises GHG emissions stemming from commuting.* 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 $(\text{p}, 0)$ through (p, m) leads to higher levels of commuting pollution. In other words, higher δ that affect the urban system may have undesirable effects from the environmental viewpoint.

Insert Figure 5 about here

2. Consider now GHG emissions generated by the transport of goods. Regarding the intra-urban shipping of goods, it is readily verified that the impact of δ on the GHG emissions is similar to what we have shown for commuting. Again, for a given intercity distribution, increasing δ leads to lower emissions, whereas a rise in δ triggers an upward jump in D when λ^* rises.

As for the interregional 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 and internal shipping (C and D) and interregional 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 and intra-urban shipping jumps upward, while the pollution stemming from the interregional transport of goods vanishes. In this event, 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 intra-urban shipping in the global emission of carbon dioxides, we believe that the conclusions derived above for the former case are empirically more relevant.

As a end note, observe that, as long as the lot size sustains polycentric cities, the following inequalities always hold: $C_{\text{pp}} + T(1/2) + D(1/2) < C_{\text{mm}} + T(1/2) + D(1/2)$ and $C_{\text{po}} < C_{\text{mo}}$. 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.*

It seems natural to wonder what are the welfare-counterparts of the above results. We have checked that welfare and the ecological footprint do not conflict significantly. The reason is probably that GHG emissions are driven by either more shipping or more commuting. Both are by themselves usually welfare-reducing, and thus there seems to be a tight connection between the two objectives.

6 Conclusion

This paper has focused on a single facet of compact cities: the transport demand. Observe, however, that trips related to activities such as recreation, school and shopping may have less direct relations to the city structure than commuting, thus blurring the connection between compactness and GHG emissions. Hence, our model should be extended to account for the location of such facilities. Furthermore, 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. In particular, it should be recognized that high population densities generate negative externalities that are likely to clash with the social norms prevailing in many developed countries. Another limit of our approach is the implicit assumption of "liquid housing" in that the population density may be increased at no cost. Accounting for adjustment costs in housing size would make the case for compact cities weaker. In addition, although analytically convenient to capture the idea of densification in a simple way, the assumption of a uniform population density is restrictive because it runs against the well-established fact the this density decreases as the distance to the employment center increases. A possible extension would be to assume a negative exponential $e^{-\lambda x}$ where $\lambda > 0$ measures the sensitivity of the lot size with respect to distance. Under this assumption, the lot size is still exogenous to the workers but it increases with the distance to the center. To sum up, 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. Our results also casts doubts on the idea that compact cities are ecologically desirable since local land-use restriction policies may have a global negative environmental impact through the relocation of activities within and between cities (see Figure 5). 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 thanks to agglomeration economies. 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

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 spatial 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 $\delta < \min\{\delta_p, \delta_{pm}\}$.

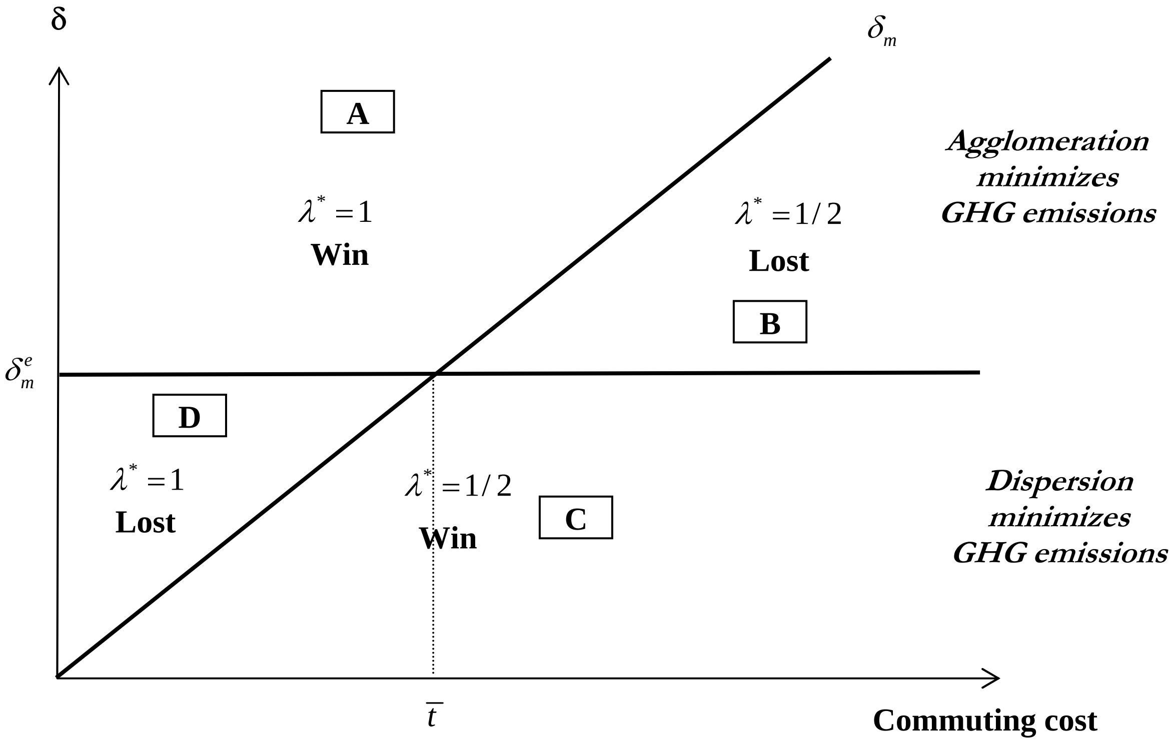

Figure 1. Inter-city distribution and ecological outcome with monocentric cities

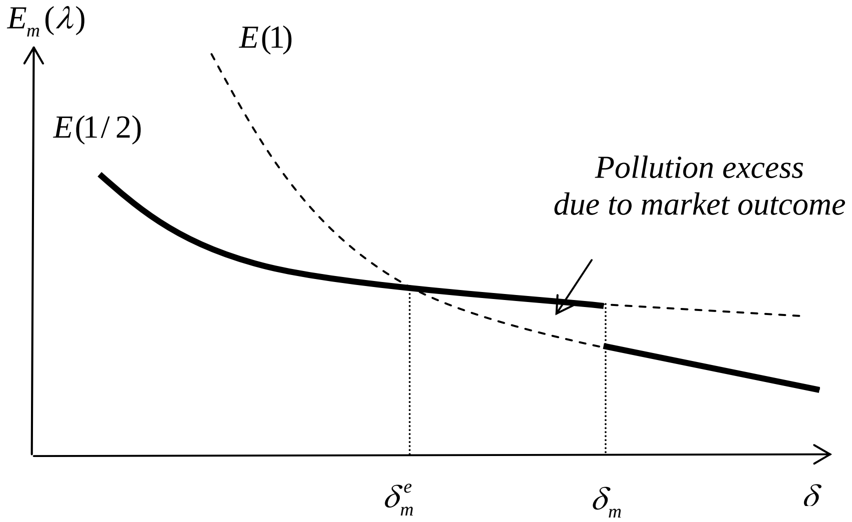

Figure 2a. Ecological and market outcomes when $t > \overline{t}$

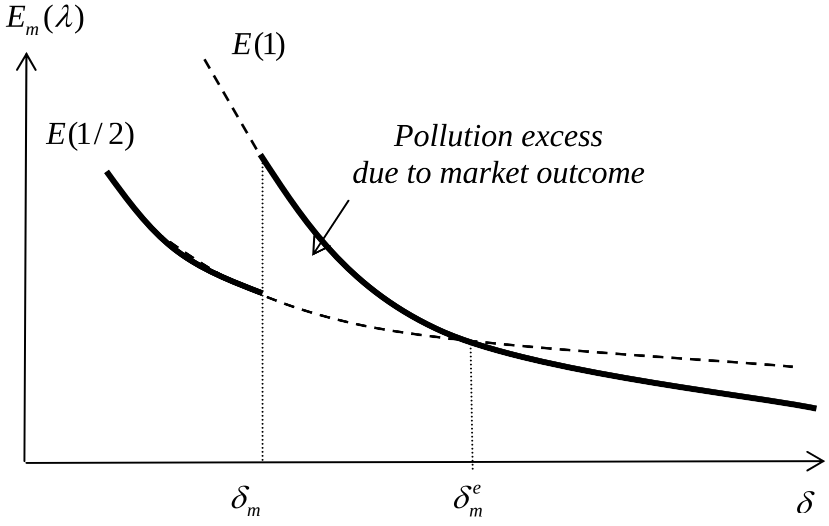

Figure 2b. Ecological and market outcomes when $t < \overline{t}$

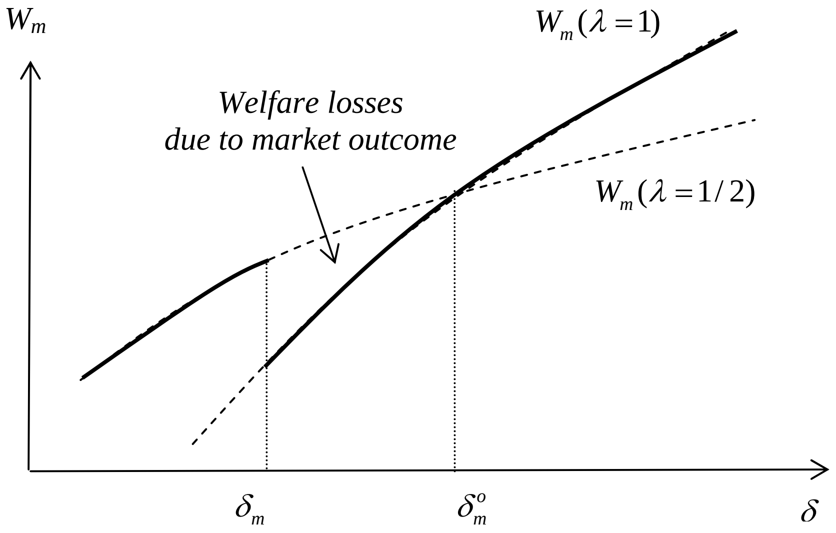

Figure 3. Market outcome and welfare

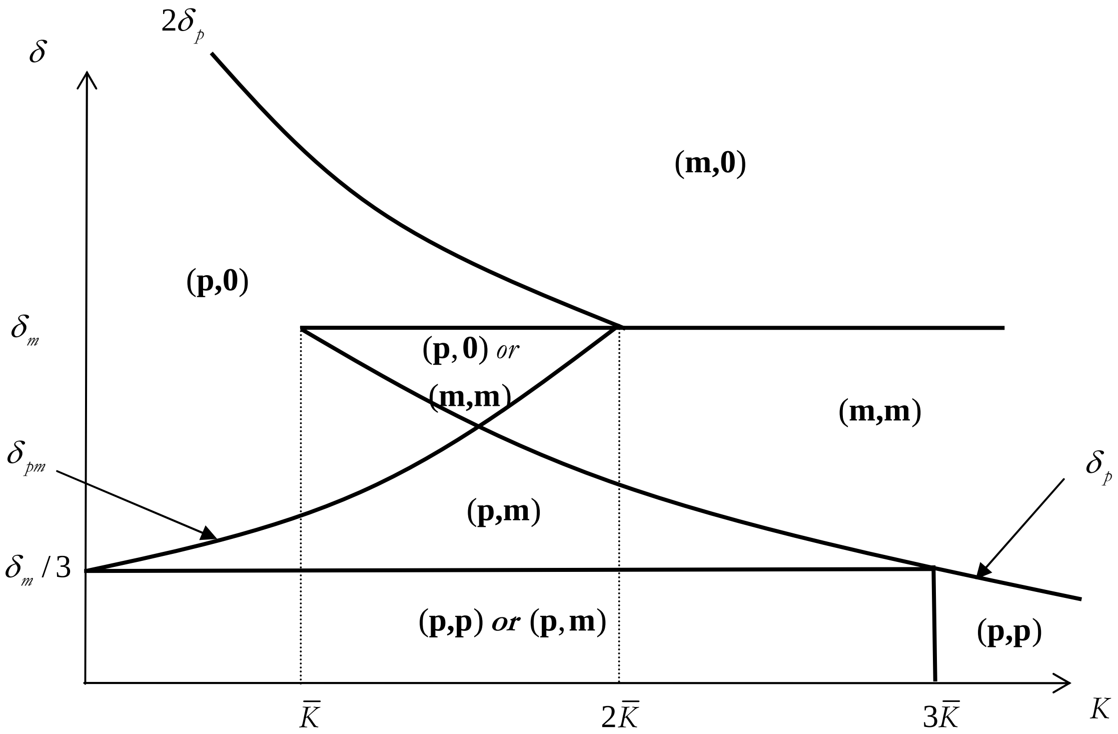

Figure 4. The set of equilibria

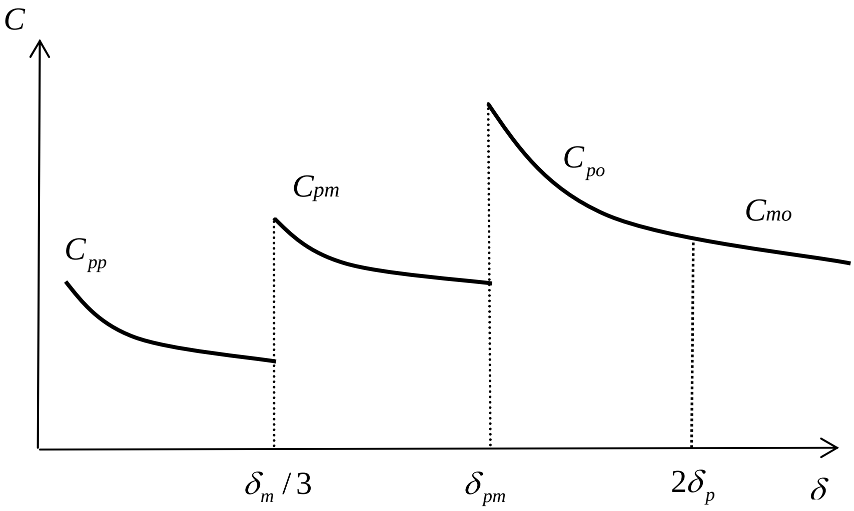

Figure 5. Commuting pollution when $K < \overline{K}$