Urban form and sustainable development[☆]

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Abstract

In this paper we study how the urban structure affects two environmental outcomes : greenhouse gas emissions from commuting and the consumption of agricultural/natural land ressources. The urban structure is characterized by its degree of polycentricity and by the share of urban and peri-urban dwellers. Polycentricity may lead to opposite effects on these indicators as lower commuting costs in secondary centers lead to lower land rents that allow households to consume more residential land; furthermore commuting lenght may decrease, inducing less GHG emissions. The environmental impact of the urban structure is very dependant on residential lot sizes, inversely related to the availability of local public goods in each zone of the urban structure : primary (secondary) urban or peri-urban area. Then we address the implementation of two types of instruments to comply with an exogenous GHG target, a transport tax/subsidy and a communication tax/subsidy for firms established in the secondary center, as well as a buget-balanced combination of the two.

Keywords: polycentricity, urban costs, communication costs, environmental policy, greenhouse gas emissions, land consumption.

JEL codes : Q54, Q58, R12, R21

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1. Introduction

Cities are home to an increasing share of the world population. It is therefore important to understand how urban development affects their environmental performance. Increasingly, jobs, hence households, are decentralised within cities : polycentricity is becoming a major feature of the urban landscape worldwide [3]. Despite a good understanding of the economic forces favoring the ermergence of polycentric structures, there is no real consensus on their environmental performance. This paper analyses how polycentricity affects two important environmental issues associated with urban development : the emission of greenhouse gases (GHG) by commuters and the consumption of surrounding agricultural/natural land.

The emergence of polycentric urban structures can be explained by the combination of three main factors: the increase in population, the increase in commuting costs and the fall in firms' communication costs between decentralized locations and the central business district (CBD). With increasing city size, urban costs (building and commuting) tend to rise. This has to be compensated for by firms through higher wages. This creates an incentive for firms to locate outside the main center, in secondary centers where urban costs are lower. Indeed, Timothy and Weaton [31] report large variations in wages according to intra-urban location (15% higher in central Boston than in outlying work zones, 18% between central Minneapolis and the fringe counties). As they enjoy living on large plots and/or move along with firms, workers may also want to live in suburbia [16]. The relocation of firms is further facilitated by a fall in communication costs, costs related to the fact that the primary centers retain some specific services, such as high finance, so that firms established in secondary centers incur an access cost to these services. The development of new information and communication technologies in the last decades has greatly reduced these costs, without totally suppressing the need for access to these services. Cavailhès et al. [8] analyze how the interplay between these various costs and the trade costs of the inter-regional shipment of commodities affects both the inter-regional and the intra-urban location of firms in a two-regions model. They show that under some conditions, polycentric agglomerations outperform monocentric cities on economic grounds : "*the emergence of subcenters within cities is a powerful strategy for large cities to maintain their attractiveness*" [8, p.384]. Absent from this analysis, though, are environmental concerns.

Urban development is associated with numerous damage to the environment : the transport of people and goods contributes to local air pollution and GHG emissions [20][17]; the increase in impervious surfaces alters the functioning of water ecosystems [23]; land fragmentation is detrimental to biodiversity [24]; etc. In this paper, we focus on two of the most pressing issues that are directly affected by the urban structure : the hold on surrounding agricultural and natural land and the emission of GHG from the transport of people.

Indeed, urban spread, whether continuous or leagfrogging, implies of high rate of conversion of agro-forested or natural land into developed land. Ahearn et al. [2] note that "*in large part, this new use of previously undeveloped land is for rural residences, often times on the fringe of urban areas, and often times with large lot sizes*". These large peripherical residential lots are explained by the fundamental trade-off of urban economics, between cost of land and cost of commuting to the central business district, or Clark's Law on density gradients [10]. These mechanisms operate in a non homogeneous space, with natural or administrative boundaries and zoning, and positive or negative amenities. Urban growth boundaries that exist in many U.S. metropolises or greenbelts of U.K. cities constitute spatial discontinuities : before and beyong, the lot sizes are different, due to different supplies of urban public goods, zoning, etc. Instead of the negative exponential function [10], we prefer to use a non-smooth lot size gradient between urban and peri-urban areas. In France, for instance, the lot size of single-detached houses increases from 400 m^2 downtown to 600 m^2 in the suburbs and 900-1000 m^2 in the peri-urban belt[1]. The administrative limit of the "pôle urbain"[2] creates a break, which may be due to a discontinuity in local public goods (LPGs) availability: in the pôle urbain, inhabitants enjoy a lot of urban public goods (urban transport system, high-standard schools, etc.) that are not -or less- available in the peri-urban area.

The pressing importance of the second environmental variable we study is illustrated by the following quote from the former Executive Secretaire of the United Nation Framework Convention on Climate Change : "*given the role that transport plays in causing greenhouse gas emissions, any serious action on climate change will zoom in on the transport sector*"[3]. Commuters are the main contributors to GHG emissions by the transport of people [13], and even if substantial reductions in polluting emissions might be warranted by technological innovation [20], these reductions will not suffice to stabilize the contribution of the transport sector to GHG emissions [12]. A large empirical literature is devoted to analyzing the impact of city size and structure on GHG emissions, via commuting [4, 20, 5, 17]. Among the theoretical contributions, Gaigné et al. [13] investigate the relevance of city compactness - understood as high-density urban area - as a way to mitigate GHG emissions from the inter-regional shipping of commodities and the intra-regional commuting of workers. On the one hand, agglomeration in one region reduces the level of pollution from commodity shipping between regions; on the other hand, it increases the amount of commuting within the only metropolis, hence the associated polluting emissions. The authors advocate the combination of a density-increasing policy and of a policy encouraging polycentricity in order to achieve the best environmental outcome. Given our focus on a single metropolis, we analyse the GHG emissions from commuting only.

In this paper, we build on [8] and [13] to propose an investigation of the environmental performance of a monocentric configuration made of a primary compact city surrounded by a residential peri-urban belt (where density is lower) compared to a polycentric structure with a secondary city and its peri-urban belt. We focus on this urban structure, leaving inter-regional trade issues aside, and consider two environmental impacts of urban development. We consider different lot sizes in the primary and secondary cities and in the peri-urban belts, to capture the stylized fact that lot sizes vary according to the location. In a second step, we study the efficient management of GHG emissions and undeveloped land preservation at the agglomeration level, by introducing environmental policies in this urban economics framework.

We describe our modeling strategy in Section 2 and derive the decentralized equilibrium in Section 3. Section 4 analyses the environmental outcomes of the equilibrium urban structure. In section 5 we discuss various policy instruments to ensure compliance with a GHG target. Section 6 concludes.

2. The Model

(i) The spatial structure. We consider a one-dimensional metropolis with mobile workers, one sector and two primary goods, labor and land. This metropolis is made of three *urban areas.* Its centre is a punctiform *central business district* (CBD); two punctiform *secondary business districts* (SBDs) - if any - are located

[1] Authors' calculation from the Housing surveys by the INSEE.

[2] In the 1999 statistical zoning of aires urbaines, a French urban area is a densely built-up "pôle urbain" (city-center +suburbs) offering more than 5,000 jobs, and a peri-urban belt made up of communes where the built-up area is not adjacent to the pôle urbain (separated by agriculture, forests, etc.), and from which 40% or more of the working population commutes daily to another commune, generally to the "pôle urbain".

[3] Yvo de Boer, Speech to the Ministerial Conference on global Environment and Energy in Transport, 15 January 2009.

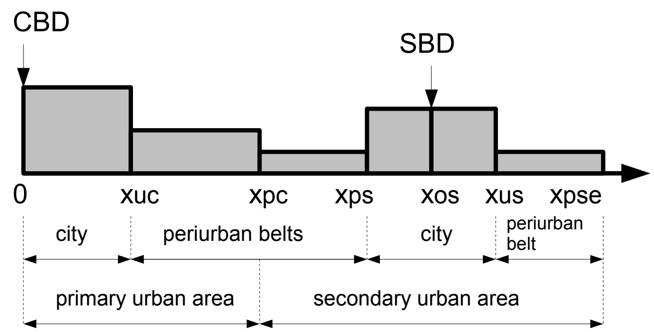

Figure 1: The metropolis

towards the right and the left of the CBD. Jobs are located in the CBD and the SBDs. Workers are housed in *cities* that spread around the CBD and SBDs, and in *peri-urban belts* - if any - beyond. The settlement is dense in cities, and scattered in the peri-urban belts. Without loss of generality, we focus on the right-hand side (RHS) of the metropolis (see Figure 1). Hereafter, subscript c refers to the CBD and subscript s to the SBD, while u and p denote, respectively, city and peri-urban belts. $x = 0$ is the center of the metropolis, x_{uc} the eastern limit of the city of the primary urban area and x_{pc} the eastern limit of the peri-urban belt of this primary urban area. Around the SBD (x_{os}) lies a city between x_{ps} and x_{us} surrounded by a peri-urban belt. The eastern limit of the metropolis is x_{pse}. We denote $X_{uc} = [0, x_{uc}]$, $X_{pc} = [x_{uc}, x_{pc}]$, $X^L_{ps} = [x_{pc}, x_{ps}]$, $X_{us} = [x_{ps}, x_{us}]$ and $X^R_{ps} = [x_{us}, x_{pse}]$ the various segments of the metropolis.

(ii) Firms. Let M be the total number of workers and N the total number of identical firms. Technology in manufacturing is such that producing $Q(k)$ units of the composite good requires a given number ϕ of labor units. Firms do not consume land and are free to locate either in the CBD or the SBD. They pay a wage w_j, $j \in \{c, s\}$ depending on which business district they are settled in. To simplify notations, without loss of generality we assume $M = 1$. The profit of the CBD firms is Π_c, and Π_s the profit of the SBD firms. The latters incur a fixed communication cost $K > 0$ reflecting the fact that some high standard services or facilities (such as banking, airports, etc.) are only available in the CBD : firms located in the SBD have to visit those services periodically, at a cost. Profit functions for a firm k are set as follows, assuming that, within the metropolis, the output price does not vary and the cost of shipping the good is nul :

$$\Pi_c(k) = PQ(k) - \phi w_c, \tag{1}$$

$$\Pi_s(k) = PQ(k) - \phi w_s - K, \tag{2}$$

where P denotes the output price and $Q(k)$ the quantity of output. Since both types of firms face the same demand function, setting the profits to zero, we obtain the following equilibrium condition :

$$w_c - w_s = \frac{K}{\phi} \tag{3}$$

Hence, the equilibrium wage wedge increases with the communication costs faced by firms in the SBD.

(iii) Households. A proportion α ($\frac{1}{3} \leq \alpha \leq 1$) of households live in the primary urban area, among which $\alpha\beta_1$ live in the city and $\alpha(1-\beta_1)$ live in the peri-urban belt, with $0 < \beta_1 \leq 1$. The secondary urban area also comprises a city, where $(1-\alpha)\beta_2$ households live, and a peri-urban belt, where $(1-\alpha)(1-\beta_2)$ households reside, with $0 < \beta_2 \leq 1$.

Households are assumed to comprise a single worker. They enjoy a utility $U(q_{ij}, h_{ij}, g_{ij}) = v_1 \ln(q_{ij}) + v_2 \ln(h_{ij}) + v_3 \ln(g_{ij})$, $i \in \{u, p\}$ and $j \in \{c, s\}$, through the consumption of three goods :

- a residential good, with lot size $h_{ij}(x)$ and rent $R_j(x)$;
- a quantity $q_{ij} > 0$ of an aspatial composite good at unitary price P;
- a local public good (LPG) $g_{ij} > 0$ that is perfectly immobile, i.e. only available where citizens live (e.g. public tranportation, schools, etc.). There, this good is free and does not entail any cost in addition to the commuting cost; in other areas it is not available so that free-riding is impossible. The regional authority of the metropolis decides the availability and the quantity of the local public good in the four zones ij. Inside each of these zones it is uniformly allocated.

Households incur a transport cost of commuting between their residential location and the closest business district where they work, either CBD or SBD. Hence we assume no cross-commuting. However, we consider that transport costs differ between urban and peri-urban areas because of network congestion in the former. Hence, distances travelled in a city have a unitary cost $t = 1$ while those travelled in a peri-urban area have a cost of $0 < \theta < 1$.

Absentee landowners allocate land to the highest bidder. Noting $\Psi_j(x)$ the bid rent of urban households and $\Phi_j(x)$ the bid rent of peri-urban households, $j \in \{c, s\}$, the rent function is :

$$R_j(x) = \max\{\Psi_j(x), \Phi_j(x), R_A\} \tag{4}$$

The opportunity rent, which is the agricultural land rent, R_A is set equal to 0 for simplicity.

Consequently, households' budget constraint depend on the location of their residence :

$$x \in X_{uc}\ ,\ w_c - x = Pq_{uc}(x) + h_{uc}(x)R_c(x) \tag{5.uc}$$

$$x \in X_{pc}\ ,\ w_c - \theta(x - x_{uc}) - x_{uc} = Pq_{pc}(x) + h_{pc}(x)R_c(x) \tag{5.pc}$$

$$x \in X_{us}\ ,\ w_s - |x_{0s} - x| = Pq_{us}(x) + h_{us}(x)R_s(x) \tag{5.us}$$

$$x \in X_{ps}^L\ ,\ w_s - \theta(x_{ps} - x) - (x_{0s} - x_{ps}) = Pq_{us}(x) + h_{ps}(x)R_s(x) \tag{5.psL}$$

$$x \in X_{ps}^R\ ,\ w_s - \theta(x - x_{ps}) - (x_{ps} - x_{0s}) = Pq_{ps} + h_{ps}(x)R_s(x) \tag{5.psR}$$

In the following section, we derive the spatial equilibrium urban structure. After establishing the relationship between public good availability and lot size in section 3.1, we derive the optimal repartition of population between the primary and the secondary urban areas when the urban/peri-urban shares are assumed fixed in section 3.2

3. Equilibrium urban structure

3.1. The equilibrium lot sizes

The objective of each household is to maximise its utility $U(q_{ij}, h_{ij}, g_{ij}) = v_1 \ln(q_{ij}) + v_2 \ln(h_{ij}) + v_3 \ln(g_{ij})$ subject to its budget constraint $(5.ij)$ by choosing a residential location x, a consumption level of both the composite good q_{ij} and a lot size h_{ij}. The first-order conditions of this program lead to the following, where λ is the Lagrangian multiplier associated to the budget constraint :

$$\lambda = \frac{v_2}{h_{ij} R_{ij}} \quad \text{and} \quad \lambda = \frac{v_1}{P q_{ij}} \tag{5}$$

which can be rewritten as $h_{ij} R_{ij} = P \frac{v_2}{v_1} q_{ij}$. Plugging this into the budget constraint, we obtain the q^*_{ij}, that we plug into the utility function to obtain the following for each segment of the metropolis :

$$UI_{uc} = v_1 \ln\left(\frac{1}{P}\frac{v_1 + v_2}{v_1}[w_c - x]\right) + v_2 \ln h_{uc} + v_3 \ln g_{uc} \tag{6}$$

$$UI_{pc} = v_1 \ln\left(\frac{1}{P}\frac{v_1 + v_2}{v_1}[w_c - \theta x + x_{uc}(1-\theta)]\right) + v_2 \ln h_{pc} + v_3 \ln g_{pc} \tag{7}$$

$$UI_{us} = v_1 \ln\left(\frac{1}{P}\frac{v_1 + v_2}{v_1}[w_s - x_{os} + x]\right) + v_2 \ln h_{us} + v_3 \ln g_{us} \tag{8}$$

$$UI_{ps} = v_1 \ln\left(\frac{1}{P}\frac{v_1 + v_2}{v_1}[w_s - \theta(x - x_{ps}) + x_{ps} - x_{os}]\right) + v_2 \ln h_{ps} + v_3 \ln g_{ps} \tag{9}$$

Equating UI_{uc} and UI_{pc} to an exogenous utility level $\bar{U}$, we get the following relation between equilibrium lot size and public good availability (established at $x = x_{uc}$) in the primary city :

$$\frac{h_{pc}}{h_{uc}} = \left(\frac{g_{uc}}{g_{pc}}\right)^{\frac{v_3}{v_2}} \tag{10}$$

Equating UI_{us} and UI_{ps} to an exogenous utility level $\bar{U}$, we get the following relation between lot size and public good availability (established at $x = x_{ps}$) in the secondary city :

$$\frac{h_{ps}}{h_{us}} = \left(\frac{g_{us}}{g_{ps}}\right)^{\frac{v_3}{v_2}} \tag{11}$$

Equating UI_{ps} and UI_{pc} to an exogenous utility level $\bar{U}$ (established at $x = x_{pc}$), we get the following relation between lot size and public good availability in the periurban areas :

$$\frac{h_{ps}}{h_{pc}} = \left(\frac{g_{pc}}{g_{ps}}\right)^{\frac{v_3}{v_2}} \left(\frac{w_c - \theta(x_{pc} - x_{uc}) - x_{uc}}{w_s - \theta(x_{pc} - x_{ps}) + x_{ps} - x_{os}}\right)^{\frac{v_1}{v_2}} \tag{12}$$

Equations (10)-(12) establish the lot sizes as decreasing functions of the LPG availability in their respective segments of the city : households compensate a lower availability of LPG by benefiting from a higher residential lot size. In the remainder of the paper, we will assume that the public good levels in each area of the metropolis are decided by the regional authority, so that the lot sizes will be considered exogenously fixed for each segment. Following on our approach of peri-urban areas as less attractive zones with respect to LPG than city centers, we will assume that $h_{pc} = h_{ps} > h_{uc}, h_{us}$. Furthermore, we authorize a difference in LPG availability between the primary and the secondary cities, with the idea that primary centers are historically more attractive than secondary ones - so that in general $h_{uc} \leq h_{us}$[4]. Finally, without loss of generality, we set $h_{uc} = 1$.

With three different lot sizes, we only imperfectly account for the increase in lot size with distance and the decrease with population observed in the real world. However, this formalisation provides a richer depiction of this reality than the assumption of a fixed lot size over the entire urban system.

Inside a zone ij the local public good g_{ij} and the lot size h_{ij} are constant. Consequently, the equilibrium consumption of aspatial goods is the same within each zone. The bid rents are derived by equating the urban costs (housing plus commuting) within each area where the lot size is of equal value. Refer to Appendix 1 for the expressions of the bid rents and to Figure 2 for an illustration.

3.2. The equilibrium degree of polycentricity

The worker located in x_{pc} is indifferent about her workplace. She pays a land rent $R_c(x_{pc}) = R_s(x_{pc}) = R_A = 0$ and she consumes a residential lot of size $h_{pc} = h_{ps}$. Consequently, she consumes the same level of composite good $q(x_{pc})$ whatever her workplace. Equating the budget equations (5.pc) and (5.psL) evaluated at $x = x_{pc}$, we obtain a condition on the wage difference between the CBD and the SBD :

$$w_c - w_s = \theta\left(2x_{pc} - x_{uc} - x_{ps}\right) + x_{uc} - x_{0s} + x_{ps} \tag{13}$$

The wage differential compensates for the gap in commuting costs. Combining Equations (13) and (3), we obtain a condition on the various segment limits for given θ, K and ϕ :

$$\frac{K}{\phi} = \theta\left(2x_{pc} - x_{uc} - x_{ps}\right) + x_{uc} - x_{0s} + x_{ps} \tag{14}$$

Solving for α in the above equation and replacing the zonal limits by their values (see Appendix 2) we obtain the equilibrium level of polycentricity :

$$\alpha^* = \frac{4\frac{K}{\phi} + \theta h_{pc}(1-\beta_2) + \beta_2 h_{us}}{2\beta_1 + 2h_{pc}\theta(1-\beta_1) + \theta h_{pc}(1-\beta_2) + \beta_2 h_{us}} \tag{15}$$

[4] We will see from French data that this is not always true.

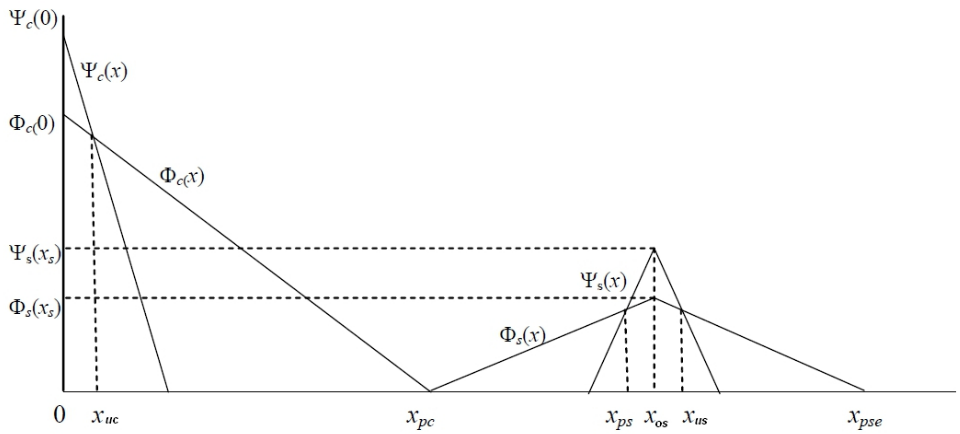

Figure 2: Urban and peri-urban bid rents

Since $\beta_1, \beta_2 \leq 1$, α^* is positive. Setting $\theta = h_{pc} = h_{us} = 1$ we obtain $\alpha^* = \frac{1}{3} + \frac{4}{3}\frac{K}{\phi}$. Consistent with previous studies [8][13], under the assumption of a constant lot size and of a constant transport rate, the primary city is home to at least a third of the total population, since two subcenters are considered. Furthermore, the higher the communication costs incurred by the secondary center firms, the larger the primary city. Under the assumption of different lot sizes and commuting costs, the following condition must apply to ensure that $\alpha^* < 1$:

$$\frac{K}{\phi} < \frac{1}{2}\theta h_{pc}(1 - \beta_1) + \frac{1}{2}\beta_1 \tag{C1}$$

The RHS of the above inequality is always positive since $0 < \beta_1 < 1$ and the impact of increasing β_1 has the sign of $1 - \theta h_{pc}$. All parameters have a positive impact on the RHS, inducing easier compliance with (C1).

The following condition ensures that the primary center attracts at least one third of the population :

$$\frac{K}{\phi} > \frac{1}{6}\left[\beta_1(1 - \theta h_{pc}) - \beta_2(h_{us} - \theta h_{pc})\right] \tag{C2}$$

Refer to Appendix 3 for an analysis of this condition.

Proposition 1. *The impact of firm-related parameters on the urban form is non ambiguous : the system is more polycentric when the communication costs between the CBD and the SBD are low. The impact of household-related parameters are not so clear-cut : an increase in peri-urban tranport costs or in the lot sizes may induce either a higher or a lower polycentricity degree depending on the relative sizes of the peri-urban belts.*

Proof. Let's denote N et D, respectively, the numerator and denominator of α^*, both positive. Then it follows that :

$$\frac{\partial \alpha^*}{\partial K} = \frac{4/\phi}{D^2} > 0 \tag{16}$$

A high wage difference, that is a high communication cost, between the primary and secondary centers, tends to be in defavour of polycentricity (remember that a high α denotes a low level of polycentricity).

Transport cost and peri-urban lot size have an impact of the same direction :

$$\frac{\partial \alpha^*}{\partial \theta} = T \frac{2h_{pc}}{D^2} \text{ and } \frac{\partial \alpha^*}{\partial h_{pc}} = T \frac{2\theta}{D^2} \text{ with } T = (1-\beta_2)(\beta_1 - 2\frac{K}{\phi}) - (1-\beta_1)(4\frac{K}{\phi} + h_{us}\beta_2). \tag{17}$$

It is straightforward to note that T is negative when $\frac{K}{\phi} > 1/2$, since $\beta_1 < 1$: sufficiently high communication costs ensure that commuting costs and a high peri-urban lot size always favor polycentricity. However, $\frac{K}{\phi}$ represents the wage difference betwen CBD and SBD, that we assume should not exceed $1/2$ as in the actual world. Then, given $\frac{K}{\phi} < 1/2$:

- $T > 0$ for $\beta_1 > \frac{6\frac{K}{\phi}}{4\frac{K}{\phi}+1}$ and $\beta_2 < \bar{\beta}_2 = \frac{2\frac{K}{\phi} - \beta_1 + 4\frac{K}{\phi}(1-\beta_1)}{2\frac{K}{\phi} - \beta_1 - h_{us}(1-\beta_1)}$;
- $T < 0$ otherwise.

In most cases, in particular when communication costs are very high, peri-urban transport costs and h_{pc} tend to favor polycentricity. Under medium or low communication costs, it takes a very large primary city and a larger peri-urban secondary belt to ensure that increasing the cost of transportation or the lot size h_{pc} induces a more monocentric metropolis.

Finally, the following expression defines the impact of h_{us}, which captures the lot size difference between the cities of the primary and the secondary urban areas :

$$\frac{\partial \alpha^*}{\partial h_{us}} = \frac{2\beta_2}{D^2} \left[\beta_1 + (1-\beta_1)\theta h_{pc} - 2\frac{K}{\phi} \right] \tag{18}$$

Except when the wage difference is very high, the expression within brackets is positive : an increase of the lot size in the secondary city, that is less LPG available, favors monocentricity.

□

In Appendix 3 we derive the optimal repartition of population between the city and the peri-urban belt in each urban area, assuming a fixed level of polycentricity. However, given our interest in the links between polycentricity and the environment, we want to endogeneize this level of polycentricy. It is possible to derive the three optimal share parameters α^*, β_1^* and β_2^* - however their cumbersome analytical expressions make it difficult to derive conclusive results on their impact on the environmental performance of the metropolis. In the remainder of this paper, we assume that the repartitions of households between the cities and the peri-urban belts are exogenous since considered as administrative limits of historical nature that govern the share of population to be accomodated in the urban area.

In the following section, we analyse the impact of the level of polycentricity on two environmental variables, GHG emissions and land consumption. This allows us to derive the impact of the various components of the model (transport cost, communication costs, lot sizes, urban/peri-urban repartition of the population) on these environmental variables. Some components have an indirect impact only, in the sense that they affect the equilibrium polycentricity level only; while others have both an indirect and a direct impact.

4. The environmental impact of polycentricity

This section is devoted to analysing under which conditions the polycentric structure may be conducive to less land consumed and aggregate distances travelled. We focus on these two environmental variables as they capture important debates relating to urban development and the same features of the urban structures impact on them : residential lot size, peri-urban belt width and polycentricity level. However, as we will show, these environmental features may still arise as conflicting objectives.

The impacts of firm and household related parameters on the environmental performance of the metropolis are derived analytically. However, for the sake of clarity of the paper, we illustrate a selection of results with empirical data from the French context. The data is presented in Section 4.1. Then Sections 4.2 and 4.3 treat each environmental issue separately. Section 4.4 illustrate how the urban structure, as defined by its polycentricity, may have conflicting impacts on these issues.

4.1. Some empirical evidence from France

The model depends on several exogenous parameters, such as the communication costs, the lot sizes, the peri-urban transport costs and the repartition of urban versus peri-urban dwellers. Therefore, the complete analytical discussion of the model is cumbersome as it requires to distinguish numerous cases according to the values of these parameters. Nevertheless, from an empirical viewpoint, not all cases are realistic. For instance, the CBD is greater than the SBDs, so that $\alpha > 1/3$. Likewise, the residential lots of the secondary city are generally greater than those of the primary city ($h_{us} \geq 1$) and peri-urban lots are even greater ($h_{pc} \geq h_{us}$). Finally, the share of the population of the primary area housed in the city is usually lower than the corresponding share in the secondary area ($\beta_1 \leq \beta_2$).

What situations are realistic in the French case? Our modeling framework does not assume any particular geographical scale of analysis. However, there are two important assumptions : no cross-commuting and existence of communication costs incurred by firms of the SBD. The second condition is ensured by the proximity of the SBDs to the CBD. The first condition amounts to excluding little villages around rural towns and SBDs within an aire urbaine (as defined by the INSEE). Apart from these two types of exclusions, various scales of CBD/SBD interactions are relevant within the framework of our model.

Regarding the French statistical partition by the INSEE (2010), a primary urban area may correspond to a large regional metropolis and its peri-urban belt, such as Toulouse, surrounded by smaller autonomous secondary urban areas that attract most of the workers residing around them : Montauban, Auch, St Gaudens, Pamiers, Castelnaudary, Castres, Albi. In this case, cross-commuting is rare, and firms of these SBDs use the central services located in Toulouse (airport, banking, etc.) on a regular basis. Another configuration is the case of Caen, a medium-sized metropolis, surrounded by smaller urban areas (Bayeux, St Lo, Vire, Flers, Lisieux, Dives-sur-mer). Finally, the model can also apply to the French "petites aires" (1460 communes), that accomodate between 1,500 and 5,000 jobs, and are satellites of "poles moyens" (447 communes) with 5,000 to 10,000 jobs. Petites aires are defined by few commuters to a larger urban area and the use of the services of these larger urban areas [29]. These examples are only provided to illustrate, and allow an easier discussion of, the main cases identified analytically. A more rigorous empirical application is outside the scope of this paper and would call for a specific one.

Table 1 shows the values of the observed population shares and lot sizes in the three cases detailed above.

	City/peri-urban belt		Lot sizes	
	β_1	β_2	h_{us}	h_{pc}
Toulouse	0.73	0.68	0.87	1.31
Caen	0.51	0.63	2.12	3.21
Petites aires	0.84	0.93	1.07	2.08

Table 1: French data used in the simulations

4.2. Land consumption

The first environmental criteria we analyse is the level of land consumption, noted S, which is the total width of the (half) city we study:

$$S = x_{pse} = \alpha[\beta_1 + h_{pc}(1-\beta_1)] + (1-\alpha)[h_{us}\beta_2 + h_{pc}(1-\beta_2)] \tag{19}$$

The higher S, the higher the detrimental impact of urban development on surrounding natural and agricultural land.

Proposition 2. *Polycentricity may either increase of decrease the pressure of the metropolis on land ressources, depending on the relative width of the peri-urban belts. Communication and transport costs affect land ressource through their impact on the equilibrium polycentricity level. Lot sizes have both a clear positive direct impact - larger lots induce more consumption- and an indirect impact -which may be positive or negative- through their effect on polycentricity.*

Corollary 1. *Caen is an example where monocentricity entails less land consumption : given the distribution of urban/peri-urban dwellers and the lot size differences, reducing sprawl would necessitates a more monocentric structure. The French petites aires and Toulouse are instances where the reverse applies : reducing the hold on land ressources goes with more polycentric structures.*

Proof. Signing the impact of the level of polycentricity is straightforward :

$$\frac{\partial S}{\partial \alpha} = \beta_1(1-h_{pc}) - \beta_2(h_{us} - h_{pc}) \tag{20}$$

The above expression is positive, under the assumption that $h_{pc} > h_{us}$, if the following applies :

$$\beta_2 > \beta_1 \frac{h_{pc} - 1}{h_{pc} - h_{us}} \tag{C3}$$

The impact of polycentricity on land ressources depends on the relative differences in urban/peri-urban lot sizes and population repartition between the primary and the secondary urban areas. Monocentricity entails more land consumption when (C3) holds, ie when the city of the secondary urban area is large compared to the peri-urban belt and lot sizes between primary and secondary city are fairly close. This applies to the case of the petites aires where the secondary city is home to a sufficently high share of urban dwellers to ensure that increasing the level of polycentricity reduces land consumption. It also applies to the case of Toulouse where the lot size of secondary cities is sufficiently small, even if the proportion of urban dwellers is not as high as in the case of the petites aires. In Caen, the share of peri-urban dwellers is fairly high in both primary and secondary cities, and both h_{us} and h_{pc} are high : (C3) doesn't apply, which means that a more monocentric structure is compatible with less land consumed.

Communication costs impact on land consumption through their effect on the equilibrium polycentricity level :

$$\frac{\partial S}{\partial K} = \frac{\beta_1(1-h_{pc}) - \beta_2(h_{us}-h_{pc})}{h_{pc}\theta(3-\beta_1-\beta_2) + 2\beta_1 + h_{us}\beta_2} \tag{21}$$

The denominator of the above expression is positive and its numerator is akin to condition (C3); situations where (C3) applies are also those in which increasing communication costs entails a higher pressure on land ressources - this follows from the fact that communication costs have a non ambiguous impact on the degree of polycentricity.

Peri-urban transport costs also have an (indirect) impact on S, through their influence on the equilibrium polycentricity level α^* : $\partial S/\partial\theta = \partial S/\partial\alpha \, . \, \partial\alpha^*/\partial\theta$. Both terms of this equation have been analysed previously (Equations (17) and (20)). To sum up the results, when communication costs are high, the results are driven by β_2 : with a very urban secondary center, increasing transport costs entails a lower pressure on land ressources. When communication costs are low, so that it is more attractive for firms to settle in the secondary center, low transport costs tend to decrease the amount of land consumed when the *primary* center is very urban. In all the cases we analyse, increasing peri-urban transport costs tends to favor polycentrism. Then the resulting impact on land consumption depends on condition (C3) which has been analysed just above.

The impact of the residential lot sizes can is expressed as follows :

$$\frac{\partial S}{\partial h_{us}} = \frac{1}{2}\beta_2 - \frac{1}{2}\alpha^* + \frac{1}{2}\frac{\partial S}{\partial\alpha}\frac{\partial\alpha^*}{\partial h_{us}} \tag{22}$$

$$\frac{\partial S}{\partial h_{pc}} = \frac{1}{2}(1-\beta_2) + \frac{1}{2}\alpha^*(\beta_2-\beta_1) + \frac{1}{2}\frac{\partial S}{\partial\alpha}\frac{\partial\alpha^*}{\partial h_{pc}} \tag{23}$$

Both lot sizes have a direct impact on S. However, they also impact on the level of land consumption through their effect on the equilibrium polycentricity level, which is given by the third terms on the RHS of the above-equations. In all our empirical cases, the aggregate effect is positive : increasing lot sizes unambiguously increases land consumption.

□

4.3. Commuting distances

The aggregate length of commuting L is the second environmental variable we study. Through this variable we capture the impact in terms of GHG emissions of the various urban forms. Hence we assume that there is a fixed linear relation between the distance travelled and the level of emissions[5].

$$L = 2\sum_i\sum_j\int_{x\in X_{ji}}\frac{1}{h_{ji}}x\,dx = \frac{h_{pc}}{4} - \frac{h_{pc}-h_{us}}{4}(1-\alpha)^2\beta_2 - \frac{h_{pc}-1}{4}\alpha\beta_1(2-\alpha\beta_1) \tag{24}$$

[5]Consequently, we abstain from the consideration of the effect of congestion on the intensity of emissions, for instance.

Proposition 3. *Increasing the level of polycentricity may induce a higher or a lower aggregated distance travelled by commuters. Polycentricity is favorable to less distance travelled when the secondary urban area is less peri-urbanized.*

Corollary 2. *Caen and the petites aires are cases where monocentricity entails less kilometers travelled : given the distribution of urban/peri-urban dwellers and the lot size differences, reducing commuting distances would necessitate more monocentric structures. In the case of Toulouse, the reverse applies : polycentricity is compatible with a GHG reduction target.*

Proof. To study the impact of city structure on aggregate distance travelled, consider the following :

$$\frac{\partial L}{\partial \alpha} = \beta_2(1-\alpha)\frac{h_{pc}-h_{us}}{2} - \beta_1(1-\alpha\beta_1)\frac{h_{pc}-1}{2} \tag{25}$$

If $\beta_2 \leq \bar{\beta_2}$, then the above expression is positive if $\alpha \geq \bar{\alpha}$; otherwise, aggregate commuting distance increases with monocentricity when $\alpha \leq \bar{\alpha}$, with :

$$\bar{\alpha} = \frac{\beta_1(h_{pc}-1) - \beta_2(h_{pc}-h_{us})}{\beta_1^2(h_{pc}-1) - \beta_2(h_{pc}-h_{us})} \quad \text{and} \quad \bar{\beta_2} = \beta_1^2\frac{h_{pc}-1}{h_{pc}-h_{us}} \tag{26}$$

In all our applications, $\beta_2 \geq \bar{\beta_2}$ so that the impact of the degree of polycentricity will depend on whether $\alpha \leq \bar{\alpha}$. In the case of Caen, $\bar{\alpha} < 0$: increasing monocentricity always entails less kilometers travelled. In the case of Toulouse and the petites aires, the direction of the impact of polycentrism on distance travelled depends on the current α, since $\bar{\alpha} > 0$. However, in the case of the petits aires, $\bar{\alpha}$ has a very low value, due to the high share of urban dwellers in the secondary city, that makes the case of a detrimental impact of monocentricity on distance less probable. In the case of Toulouse, this treshold is within a reasonable range, but lower that the calculated α^* : polycentricity entails less kilometers travelled. □

As for land consumption, to derive the impact of the other parameters of the model, we assume that the degree of polycentricity is endogenously set at its equilibrium value α^*.

Corollary 3. *In Toulouse, a reduction of commuting distances is achieved by decreasing communication costs and generally achieved by increasing transport costs.*

Proof. The following applies : $\frac{\partial L}{\partial \theta} = \frac{\partial L}{\partial \alpha}\frac{\partial \alpha^*}{\partial \theta}$, $\frac{\partial L}{\partial K} = \frac{\partial L}{\partial \alpha}\frac{\partial \alpha^*}{\partial K}$. Then, the impact of communication costs is clear-cut, since they decrease the equilibrium degree of polycentricity. Transport costs generally induce a more polycentric city, except when communication costs are low, the primary center less peri-urbanized and the secondary more peri-urbanized (see Equation (17). Then any alteration of the parameters that is compatible with a more polycentric urban structure ensures that less kilometers are travelled. □

Corollary 4. *Increasing the residential lot sizes may have a positive or a negative effect on the aggregate distance travelled.*

Proof. Residential lot sizes have both a direct and an indirect impact on kilometers travelled :

$$\frac{\partial L}{\partial h_{us}} = \frac{\partial L}{\partial \alpha}\frac{\partial \alpha^*}{\partial h_{us}} + \frac{1}{4}\beta_2(1-\alpha^*)^2 \tag{27}$$

$$\frac{\partial L}{\partial h_{pc}} = \frac{\partial L}{\partial \alpha}\frac{\partial \alpha^*}{\partial h_{pc}} + \frac{1}{4}(1-\beta_2) + \frac{1}{2}\alpha^*(\beta_2-\beta_1) + \frac{1}{4}\alpha^{*2}(\beta_1^2-\beta_2) \tag{28}$$

Increasing h_{us} unambiguously increases the total amount of kilometers travelled by commuters through a direct effect independant of the equilibrium urban structure : the more urban dwellers in the secondary city, the more additionnal kilometers travelled when their lot sizes increase. The impact of increasing h_{pc} is more difficult to track since it affects both primary and secondary cities - the larger β_2 and β_1, the lower the number of peri-urban dwellers. Their indirect impacts depend on how polycentricity affects the aggregate distance travelled, and on how they impact on the equilibrium polycentricity level. The resulting aggregate impact is difficult to sign analytically. □

4.4. The possibility of conflicting environmental objectives

Proposition 4. *Depending on the relative values of the lot sizes in the different segments of the metropolis and on the share of population in peri-urban areas, the impact of the urban structure on GHG emissions and land consumption can be characterized by three cases only :*

- *polycentricity as the win-win solution*
- *monocentricity as the win-win solution*
- *polycentricity as a land preserving solution, at the expense of increased GHG emissions*

Proof. Let's rewrite the condition for $\frac{\partial L}{\partial \alpha} > 0$:

$$\beta_2 > \beta_1 \frac{1 - \alpha\beta_1}{1 - \alpha} \frac{h_{pc} - 1}{h_{pc} - h_{us}} \tag{C4}$$

Complying with (C4) automatically implies complying with (C3), while the reverse is not true. Conditions that ensure that polycentricity reduces GHG emissions also ensure that is a solution to reduce land consumption, while the reverse is not true. The three French cases selected, Toulouse, Caen and petites aires, illustrate the three possible cases. □

The following figures illustrate Proposition 4 through the 3 French cases presented above :

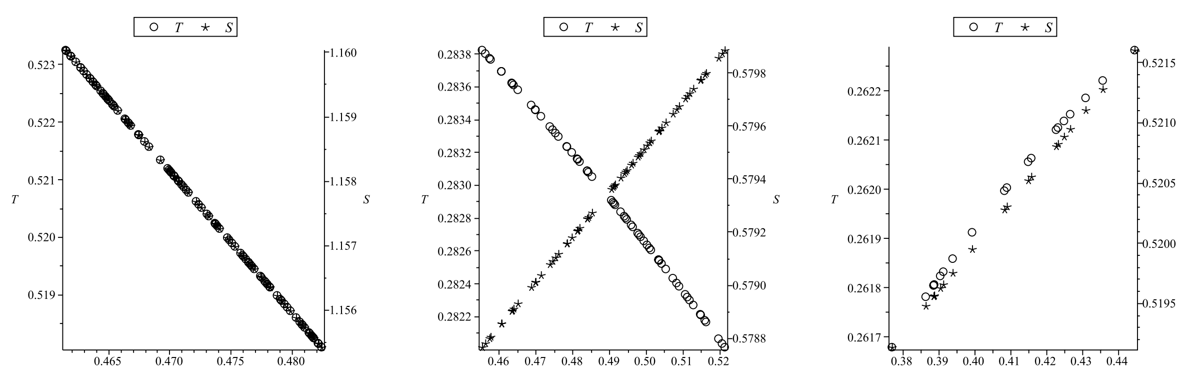

Figure 3 : Kilometers travelled and land consumption as function of the degree of polycentrism for, from left to right, Caen, petites aires and Toulouse

Both Caen and Toulouse are exemples of win-win situations where decreasing the distances travelled entails less land consumed. However the implication in terms of urban structure is different : in the case of Caen a more monocentric metropolis is the environmentally-friendly structure, while in Toulouse, the polycentric metropolis is the sustainable solution. The Toulouse example is characterized by small urban lots in the secondary city : increasing polycentricity is beneficial in terms of the two environmental variables we analyse. In the example of Caen, the primary urban area is less peti-urbanized than the secondary one, peri-urban/secondary city lot size difference is relatively small and the latters are large : monocentricity reduces both distance travelled and land consumed. Finally, in the "petites aires" case, the environmental objectives are conflicting : land consumption and distances travelled are affected in opposite directions by the level of polycentricity : the proportions of urban dwellers are very high, especially in the secondary center, and the primary and secondary city lots are very close in size. The implications in terms of public policy design are developped in the following section.

5. Public policies in a polycentric metropolis

In this section we address the design of public policies to induce compliance with an exogenously determined environmental target. Assuming that the metropolis planner is constrained by an exogenous target on the aggregate level of GHG emissions, translated in our simplified setting into a constraint of the aggregate distance travelled, we analyse efficient tax/subsidy schemes. Given the interplay between distances travelled, transport costs and communication costs, we want to assess the effectiveness of two types of policies : (i) a peri-urban transport tax and (ii) a subsidy on communication costs. In France, it is very difficult to modify the βs : the zoning policies are defined by the mayors of each "commune", with very little dialogue at the regional level. The LPG supplies, in that they determine the lot sizes, also constitute a potential basis for a policy instrument, which we will study in a subsequent paper. We assess how the efficient schemes impact on the metropolis structure, in particular on land resources consumption. We look at the design of a budget-balanced scheme, combining both a transport tax/subsidy and a communication tax/subsidy. Remember that we look at an isolated metropolis, hence we do not account for how the urban form affects its competitiveness with respect to the rest of the world. Consequently, we are only interested in how conflicting *environmental* objectives may arise, while Gaigné et al. [13] show how conflicts may arise between environmental and economic objectives.

Result 1. *A decrease of a given level of CO_2 emissions $L(\theta_{ini}) - \overline{T}$ is obtained by imposing a transport tax/subsidy : $t^{tr} = \theta^* - \theta_{ini}$. This decrease in distance travelled may necessitate either a higher or a lower level of polycentricity and it may entail more or less land consumption.*

Proof. We are looking for a value of θ^* such that an exogenous GHG target $\overline{T}$ is respected. β_1 and β_2 being considered exogenous, α is set equal to α^*. The analytical derivation of θ^* such that $L(\theta^*) = \overline{T}$ is possible but cumbersome, hence our recourse to numerical simulations. The simulations are undertaken as follows : for a given value of θ_{ini}, we calculate the resulting $L(\theta_{ini})$. Then we randomly draw values of $\overline{T} < L(\theta_{ini})$ and derive the values of θ^* that would lead the economy to that particular GHG emission target, respecting conditions (C1) and (C2) on α^*. □

A tax/subsidy on peri-urban transport costs proves an efficient urban planning strategy - within the restricted framework of our analysis, where the efficiency of a policy instrument is assessed by its capacity to induce a given level of GHG emissions. Depending on the cases illustrated by Toulouse, Caen and the petites aires, complying with the GHG target may entail more or less land consumption.

Result 2. *A decrease of a given level of CO_2 emissions $L(K_{ini})-\overline{T}$ is achievable by applying a communication tax/subsidy : $K^* - K_{ini}$. As when transport costs are the focus of policy design, the resulting decrease in distance travelled may necessitate a more or less polycentric urban structure and entail more or less land consumption.*

Proof. We apply the same simulation strategy as for the transport tax analysis to the resolution of $L(\frac{K}{2}) = \bar{T}$. □

A tax/subsidy on communication costs proves an efficient urban planning strategy. Decreasing communication costs induce firms to settle in the SBD, attracting households and conducing to a more polycentric setting. This may translate into lower commuting distances hence lower GHG emissions. The impact on the level of land consumed depends, as before, on the relative levels of public goods : when the secondary city offers a good level of public good supply, then increasing polycentricity does not necessarily have a negative impact on land ressources.

The following figures illustrate how transport costs or communication costs can be altered in order to achieve an exogenous GHG target expressed in terms of kilometers travelled in case of Caen and Toulouse.

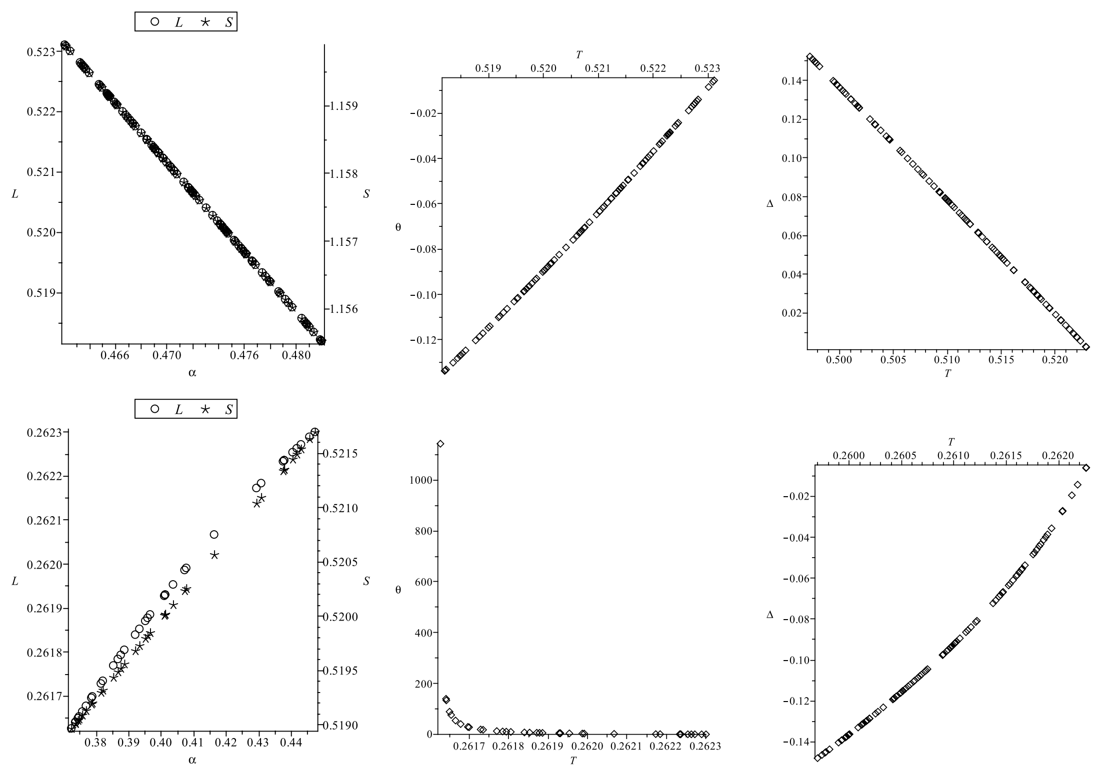

Figure 4 : Transport (center) and communication (right) management strategies allowing to reach an exogenous GHG target for Caen (up)and Toulouse (bottom)

It appears that to achieve the same double beneficial environmental impact of decreased land consumption and decreased GHG emissions, strategies are opposite in the case of Toulouse and Caen. In the former case, where polycentricity is beneficial, it is efficient to implement a tax on peri-urban transport costs, or a subsidy on communication costs. Both policies favor the settling of agents in the secondary urban area. In the case of Caen, the efficient solution is to support monocentricy, either by taxing communication costs or by subsidizing commuting costs. These conter-intuitive policies are needed when a high degree of polycentricity is the economic equilibrium that must be thwarted to obtain a more monocentric configuration. The case of the petites aires is akin to Caen, since the policy objective is distances travelled and that both cases behave the same in this respect.

Given the financial characteristics of the two instruments analysed in the previous sections, we seek a scheme that would combine both instruments and respect the condition of a balanced budget for the local planner. More precisely, the desirable scheme $s(\theta^*, K^*)$ has the property of respecting the following conditions :

$$L(s(\theta^*, K^*)) = \bar{T} \tag{CT1}$$

$$(K_{ini} - K^*)\phi(1-\alpha) + (\theta_{ini} - \theta^*)L_p(s(\theta^*, K^*)) = 0 \tag{CT2}$$

where L_p is the amount of kilometers travelled in peri-urban areas (hence subject to taxation), $\phi(1-\alpha)$ is the number of firms in the SBD. The resulting scheme is both efficient (CT1) and budget-balanced (CT2).

Result 3. *A decrease of a given level of CO_2 emissions $L(K_{ini}) - \overline{T}$ is achievable by applying a budget-balanced scheme comprising a transport tax/subsidy and a communication tax/subsidy.*

Proof. Simulations applied to the cases analysed above show that (CT1) and (CT2) are complied with various combinations of communication/transport tax/subsidy according to the values of the parameters as discussed above. Refer to figure 5. □

The budget-balanced requirement does not modify the structure of the efficient schemes in the case of Caen (or petites aires) and Toulouse : a communication tax and transport subsidy in the former case, the opposite in the latter.

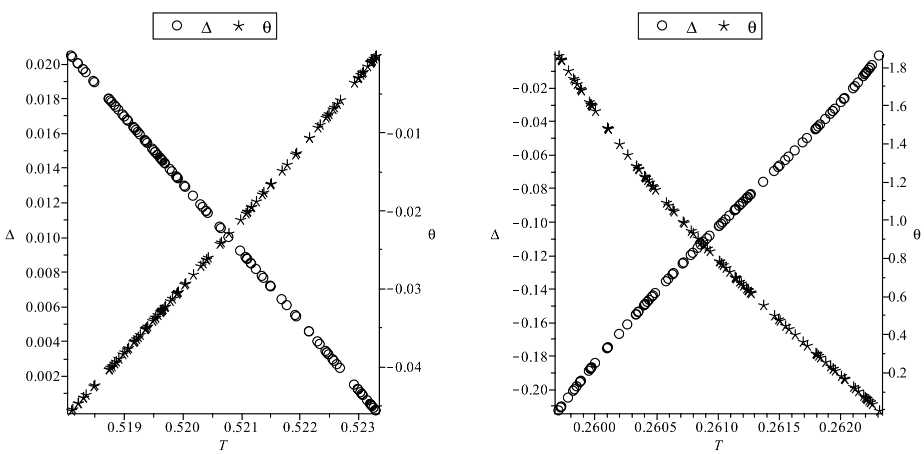

Figure 5 : Budget-balanced management strategies allowing to reach an exogenous GHG target for Caen (left)and Toulouse (right)

6. Concluding remarks

In this paper we presented an urban economics model that allows for the development of secondary business districts, given a communication cost with the central business district, and of peri-urban belts where the population density is lower than that in compact city centers and where commuting to work is faster (hence its unitary cost is lower). Thus this model relaxes the assumptions that are often relied on of a monocentric city and/or of a fixed residential lot size and/of a fixed and unitary transport cost. With this model we can analyse two environmental effects of the urban structure : the conversion of agricultural or natural resources to urban uses and the emission of GHG from commuting. The model also allows studying the effects of policy instruments on these two environmental variables : a transport tax/subsidy, a communication tax/subsidy and a budget-balanced combination of these instruments.

Polycentricity appears and increases when the communication costs decrease, which favors the decentralisation of firms, and/or when the secondary cities are well supplied in local public goods that attract households. We show that the urban form has an impact on the two environmental variables we study. The supply of LPGs of the secondary city plays an important role in this respect through its effect on equillibrium residential lot sizes. The stylized exemples of Toulouse, Caen and of the petites aires urbaines in France illustrate polar cases of the environnmental performance of the urban form : monocentrism as the win-win environmental solution (Caen), polycentricity as the win-win solution (Toulouse), and monocentricity as the way to reduce GHG emissions at the expense of more land consumed (petites aires urbaines). Polycentricity is a win win environmental solution when the secondary urban area has a small peri-urban belt, that urban lot sizes of the primary and secondary cities are close and that peri-urban lots are large. When polycentricity is a competitive economic equilibrium in inter-regional exchanges [8], it may also be environmentally beneficial.

These results suggest that a policy that modifies the structure of the metropolis can be used for environmental purposes; in this paper to limit the emissions of GHG. To restrain commuting-related GHG emissions, transport taxes are the usual suspects. We also analyse the efficiency of an instrument directly targeted at impacting on the development of secondary centers, a tax/subsidy on the communication costs that firms established in the secondary business district have to bear. This, combined with a transport tax/subsidy, provides an efficient and budget-balanced instrument. The two latter instruments consist in reducing GHG by impacting on the urban form.

This conclusion relies on the existence of attractive secondary urban areas, both for the firms (by reducing the commuting costs) and for the consumers. This motivated research in progress in two directions : theoretical, as LPGs then become another potential tool to design a sustainable urban form; and empirical, to estimate the relationship between residential lot size and LPG availability.

These developments lead to public policy recommandations, in particular, in terms of regional planning. In France, the DATAR seeks to favor an urban network constituted of regional metropolises, with a national and international level of competitiveness, linked to secondary centers structuring rural areas. Such configurations may or not be environmentally sustainable according to the transport and communication costs and the LPG supplies - all of which constitute potential bases for public policies that allow - or not - to conciliate economic and environmental objectives.

Bibliography

[1] Aguilera. A. and Mignot, Dominique,(2010) Multipolarisation des emplois et déplacements domicile-travail : une comparaison de trois aires urbaines francaises. *CJRS(Online)/RCSR(En ligne)* 33, 83-100.

[2] Ahearn. M.C. and Alig, R.J. (2006) A discussion of recent land-use trends. in Bell, K.P., Boyle, K.J. and Rubin, J. (Eds), *Economics of rural land-use change*, Aldershot, Ashgate, pp. 11-25.

[3] Anas, A., R. Arnott and K.A. Small (1998) Urban Spatial Structure. *Journal of Economic Literature* 36, 1426-1264.

[4] Bento. A., S. Franco and D. Kaffineb (2006) The efficiency and distributional impacts of alternative anti-sprawl policies. *Journal of Urban Economics* 59, 121-141.

[5] Brownstone, D. and T. Golob (2009) The impact of residential density on vehicule usage and energy consumption. *Journal of Urban Economics* 65, 91-98.

[6] Burchfield M., H.G. Overman, G. Puga and M.A. Turner (2006) Causes of sprawl: a portrait from space, *Quarterly Journal of Economics* 121, 587-633.

[7] Cavailhès J., D. Peeters, E. Sekeris E. and J.F. Thisse (2004) The Periurbain City. Why to Live between the Suburbs and the Countryside? *Regional Science and Urban Economics* 34, 681-703.

[8] Cavailhès J., Gaigné C., Tabuchi T., Thisse J.F. (2007), Trade and the structure of cities, *Journal of Urban Economics*, 62 (3): 383-404.

[9] Cervero, R. and K.L. Wu (1997) Commuting and Residential Location in the San Francisco Bay Area. *Environment and Planning A* 29, 865-86.

[10] Clark, C. (1951) Urban population densities. *Journal Royal Statistical Society : Series A*, 114(4) : 490-96.

[11] European Environment Agency (2006) *Urban sprawl in Europe. The ignored challenge*. EEA Report No 10, European Commission, Directorate General, Joint Research Centre, 56 p.

[12] European Environment Agency (2007) *Greenhouse gas emission trends and projections in Europe 2007*. EEA Report No 5, COPOCE, European Union.

[13] Gaigné C., Riou S., Thisse J.F., Are conpact cities environmentally friendly? *Journal of Urban Economics*, forthcoming.

[14] Galster G., R. Hanson, M.R. Ratcliffe, H. Wolman, S. Coleman and J. Freihage (2001) Wrestling Sprawl to the Ground: Defining and Measuring an Elusive Concept *Housing Policy Debate* 12, 681-717.

[15] Giuliano, G. and A. Small (1991), Subcenters in the Los Angeles Region. *Regional Science and Urban Economics* 21, 163-82.

[16] Glaeser, E.L. and M.E. Kahn (2004) Sprawl and urban growth. In J.V. Henderson and J.-F. Thisse (eds.) *Handbook of Regional and Urban Economics*. Amsterdam, North Holland, 2481-527.

[17] Glaeser, E.L. and Kahn, M.E.(2010) The greenness of cities : carbon dioxide emissions and urban development. *Journal of Urban Economics* 67(3), 404-418.

[18] Hasse J.E., and R.G. Lathrop (2003) Land resource impact indicators of urban sprawl *Applied Geography* 23, 159-175.

[19] Henderson, V. and A. Mitra (1996) New urban landscape: developers and edge cities. *Regional Science and Urban Economics* 26, 613-43.

[20] Kahn, M.E. (2006) *Green cities : urban growth and the environment*. Washington D.C., Brooking Institution Press.

[21] Glaeser, E.L. (2008) *Cities, Agglomeration, and Spatial Equilibrium. The Lindahl lectures*. Oxford University Press.

[22] Lartigue, S. and T. Petit (2002) *Dispersion ou polarisation de l'emploi dans la grande couronne d'Ile-de-France, 1979-1998*. Paris, IAURIF.

[23] Lohse, K.A. and Newburn, D.A. and Opperman, J.J. and Merenlender, A.M. (2008), Forecasting relative impacts of land use on anadromous fish habitat to guide conservation planning, *Ecological Applications* 18, 467-82.

[24] Merenlender, A.M. and Reed, S.E. and Heise, K.L. (2009), Exurban development influences woodland bird composition. *Landscape and urban planning* 92, 255-63.

[25] McMillen, D.P. and J. F. McDonald (1998), Population Density in Suburban Chicago: A Bid-Rent Approach. *Urban Studies* 35, 1119-30.

[26] Mokhatarian P.L. (2003) Telecommunications and Travel. The case for Complementarity. *Journal of Industrial Ecology* 6, 43-57.

[27] Porter, M.E. (1995) Competitive advantage of the inner city. *Harvard Business Review*, May-June, 55-71.

[28] Schwanen, T. and F.M. Dieleman and M. DIjst (2002) The impact of metropolitan structure on commute behavior in the Netherlands - a multilevel approach. *Contributed Paper to the 42nd ERSA congress*, August 2002, Dortmund, Germany.

[29] Courtney P. and Lépicier D. and Schmitt B. (2008)Spatial patterns of production linkages in the context of Europe's small towns: How are rural firms linked to the local economy? *Regional Studies* 42(3): 355-374.

[30] Song, Y., and G.J. Knaap. (2004) Measuring Urban Form: Is Portland Winning the War on Sprawl? *Journal of the American Planning Association* 70, 210-225.

[31] Timothy, D. and W.C. Wheaton (2001) Intra-Urban Wage Variation, Employment Location and Commuting Times. *Journal of Urban Economics* 50, 338-66.

[32] Wolman H., G. Galster, R. Hanson, M. Ratcliffe, K. Furdell, and A. Sarzynsk (2005) The Fundamental Challenge in Measuring Sprawl: Which Land Should Be Considered? *The Professional Geographer* 57, 94-105.

[33] Wu J.J. (2006) Environmental amenities, urban sprawl, and community characteristics, *Journal of Environmental Economics and Management*, 52, 527-547.

Appendix 1 : Bid rent functions

In each segment of the city, the fixed lot size assumption applies. Then the urban costs (housing plus commuting) are equated among the households in each segment. Consequently, in each segment the slope of the bid rent function is the opposite of the ratio between the commuting cost and the lot size prevaling in the segment.

The bid rent functions for urban and periurban households, respectively Ψ and Φ, are derived under the above assumption and accounting for the following conditions : $\Psi_c(x_{uc}) = \Phi_c(x_{uc})$, $\Psi_{sl}(x_{ps}) = \Phi_{sl}(x_{ps})$, $\Psi_c(x_0) = \Psi_c(x_{pc})$, $\Psi_{sl}(x_{0s}) = \Psi_{sl}(x_{ps})$. c stands for central, s for secondary, l for left-hand side of the secondary city and r for its right-hand side.

$$\Psi_c(x) = x_{uc} + \frac{\theta}{h_{pc}}(x_{pc} - x_{uc}) - x \tag{29}$$

$$\Phi_c(x) = \frac{\theta}{h_{pc}}(x_{pc} - x) \tag{30}$$

$$\Psi_{sl}(x) = \frac{\theta}{h_{pc}}(x_{ps} - x_{pc}) + \frac{1}{h_{us}}(x - x_{ps}) \tag{31}$$

$$\Psi_{sr}(x) = \frac{\theta}{h_{pc}}(x_{ps} - x_{pc}) + \frac{1}{h_{us}}(2x_{0s} - x_{ps} - x) \tag{32}$$

$$\Phi_{sl}(x) = \frac{\theta}{h_{pc}}(x - x_{pc}) \tag{33}$$

$$\Phi_{sr}(x) = \frac{\theta}{h_{pc}}(2x_{0s} - x_{pc} - x) \tag{34}$$

Appendix 2 : Analytical expression of the zonal limits

Given the proportions of households living in each type of zone, and the lenght occupied by their residence, it is easy to provide an analytical definition of the limits of the zones :

$$x_{uc} = \frac{1}{2}\alpha\beta_1$$

$$x_{pc} = x_{uc} + h_{pc}\alpha(1-\beta_1) = x_{uc} + \frac{1}{2}h_{pc}\alpha(1-\beta_1)$$

$$x_{ps} = x_{pc} + \frac{1}{4}h_{pc}(1-\alpha)(1-\beta_2)$$

$$x_{0s} = x_{ps} + \frac{1}{4}h_{us}(1-\alpha)\beta_2$$

$$x_{us} = x_{0s} + \frac{1}{4}h_{us}(1-\alpha)\beta_2$$

$$x_{pse} = x_{us} + \frac{1}{4}h_{pc}(1-\alpha)(1-\beta_2)$$

Appendix 3 : analysis of (C2)

(i) if $\theta\mathbf{h_{us}} < \mathbf{1} < \theta\mathbf{h_{pc}}$: condition (C3) is always met since its RHS is negative and by definition $K > 0$.

(ii) if $\theta\mathbf{h_{us}} < \theta\mathbf{h_{pc}} < \mathbf{1}$: the condition is automatically met when $\beta_2 > \beta_1 \frac{1-\theta h_{pc}}{h_{us}-\theta h_{pc}}$. Otherwise, the RHS increases with β_1 and decreases with β_2 : condition (C3) is met under a more urban secondary center (and a less urban primary one).

(iii) if $\theta\mathbf{h_{pc}} > \theta\mathbf{h_{us}} > \mathbf{1}$: the condition is automatically met when $\beta_2 < \beta_1 \frac{\theta h_{pc}-1}{\theta h_{pc}-h_{us}}$. Otherwise, the RHS increases with β_2 and decreases with β_1 : a more urban primary city (a less urban secondary city) ensures that a low wage difference still complies with condition (C3).

The three cases described above illustrate various degrees of attractiveness of the peri-urban areas captured in the model. The term $h_{pc}\theta$ is the product of the parameters that make peri-urban areas different from urban areas in our model : higher lot sizes and lower transport costs. This same product equals 1 in the primary center and h_{us} in the secondary center. In case (iii), the lot size effect dominates the transport cost effect in explaining the attractivity of the peri-urban areas. Case (ii) is the reverse : the transport cost effect dominates in both primary and secondary center. Finally, case (i) offer a mixed depiction where the peri-urban lot size differential in the secondary center is not sufficient to dominate the transport cost effect. Note that under the assumption that $h_{us} > 1$, the reverse mixed case is not possible.

Appendix 4 : endogenous share of urban/periurban dwellers

In this section, we assume that the polycentrism degree is fixed, and we look at how the population within each city divides between the city and the peri-urban belt. To do so, we derive the equilibrium consumption levels by plugging the bid rent functions into the budget constraint of each zone and solving for q. These consumption levels allow us to derive the indirect utilities for each zone. Equating the urban and peri-urban ones in each city (primary and secondary), and solving for β_1 and β_2 we obtain the following :

$$\beta_1^* = 1 - \frac{2pv \ln h_{pc}}{\alpha\theta(h_{pc} - 1)} \tag{35}$$

$$\beta_2^* = 1 - \frac{pv \ln \frac{h_{pc}}{h_{us}}}{(1-\alpha)\theta(h_{pc} - h_{us})} \tag{36}$$

A more monocentric metropolis, with a higher α, induces more urban dwellers in the primary city and less urban dwellers in the secondary city. Also, increasing the preference for large lots induce lower shares of urban dwellers. Surprisingly, increasing the peri-urban lot size increases both β_1 and β_2.