Urban Structure and Environmental Externalities

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Abstract

The objective of this paper is to analyze the impact of pollution on the structure of cities. We base our analysis on the paper of Ogawa and Fujita (1982), which offers a proper theoretical framework of non-monocentric urban land use using static microeconomic theory. We show that households internalize the effects of industrial air pollution in their choice of localization, which consequently reinforces spatialization within the city. We demonstrate that it impacts directly the emissions of pollution by commuting and we analyze policy instruments in order to achieve optimal land use pattern.

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1 Introduction

In a world were distance is almost eliminated by innovations in telecommunication, people live closer and closer from each other. Indeed, the United Nations report in a recent study : "The world reaches an invisible but momentous Milestone : for the first time in history, more than half its human population, 3.3 billion people, will be living in urban areas"(UNFPA, 2007). Cities are the heart of any economic activities and an essential element for people's interactions. However, a recent study conducted by the World Health Organization shows that air pollution lowers life expectancy by seven months for a thirty-year-old individual in Paris (Declercq et al., 2012). A study conducted by the European Commission also shows that pollution is responsible for forty-two thousand deaths per year in European cities (Watkiss et al., 2009). The fast expansion of cities is today correlated with an environmental concern regarding the quality of urban air. The goal of this paper is to introduce the environment into spatial economics models in order to assess the impact of environmental issues such as air pollution on the city structure, and to analyze the inverse connection : the impact of the city structure on the environment and the use of space as a mean to control pollution. The link between environmental and spatial issue has been studied at a regional scale (Lange and Quaas, 2007; Van Marrewijk, 2005; Gaigné et al., 2012) and at a urban scale (Henderson, 1977; Robson, 1976). In this paper we choose to study the effect of air pollution at a urban level, that is why we will focus here on the literature studying the internal structure of cities where industry and households compete for scarce land to locate. More precisely, this paper studies the interaction of two forms of air pollution: point source pollution coming from industry, and non-point source pollution coming from car traffic.

Urban economic studies focuses generally on only one type of environmental externality inside cities. A part of economic literature is dedicated to the study of pollution caused by industry, while the other is related to the study of pollution caused by transport. Henderson (1977) is the first to study air pollution caused by industrial sources in a monocentric setting. Arnott et al. (2008) and Kyriakopoulou and Xepapadeas (2011) extend the study of industrial pollution to non-monocentric cities. In both papers all possible location combinations of housing and industry are considered. Both papers consider also a constant return to scale production function, in order to identify only the effect of pollution on agent's choice of localization and they don't take into account the agglomeration externalities existing among firms. This type of externalities is an important part of the study of city structure, Lucas and Rossi-Hansberg (2002) demonstrate the importance of this externalities in the resulting equilibrium land use pattern : the existence of agglomeration economies justifies the monocentric city pattern. The introduction of environmental externalities in a model with agglomerations economies can change the well-known monocentric city result (Kyriakopoulou and Xepapadeas, 2013). Moreover, regarding policy purposes, the pursuit of environmental goals may sometimes stimulate agglomeration economies whereas one would have expected the reverse in a non-spatial setting (Verhoef and Nijkamp, 2002). The important result shared by all the papers previously cited is the existence of defensive behavior by households : as they dislike pollution, households choose to locate farther from polluting firms. Problems can arise when there is an excessive defensive behavior by households : the tendency to choose a more remote location entails for example larger travel cost and increased car use. The use of cars as a means of transportation is also directly responsible for emissions of pollution in cities.

Economists have also been concerned by the effect of car use in cities. The equilibrium land use pattern is distorted from optimum because of transport pollution (Robson, 1976). Then policy instruments, such as a tax on commuting, should be implemented to decentralize optimum, (McConnell and Malhon, 1982; Robson, 1976; Verhoef and Nijkamp, 2003; Le Boennec, 2012). A tax on commuting rises the transport cost borne by households and increases its centripetal effect. At equilibrium, the city is more concentrated and the level of pollution caused by cars is lower.

To the best of our knowledge, interactions between industrial pollution and transport pollution have not been explicitly examined yet in the economic literature. However the study of these two types of pollution may lead to conflicting results. Indeed air pollution resulting from industry's emissions affect the locational decision of households by pushing them away from polluting firms, while an optimal policy instrument in the case of pollution from commuting leads to more concentrated cities. If we take into account both types of pollution into a same model the conclusion may likely be different and the effect of a tax on transport may be in contradiction with the defensive behavior by households of industrial pollution. Viguié and Hallegatte (2012) and McEvoy et al. (2006) feature the possible conflicts arising between different policy goals inside cities.

The goals of this paper is then : (i) to identity the effect of industry pollution on household choice of localization when neither employment nor residential location are specified a priori, (ii) to assess the level of transport pollution resulting from the equilibrium city structure, (iii) and to find the optimal policy mix to manage both industrial and transport pollutions. To do so we will first present the structure of the model, based on Ogawa and Fujita (1982) model of linear city with endogenous center. After having derived conditions for equilibrium land use pattern in section 3, we analyze in section 4 the possibility of an optimal policy mix, composed of a tax on emissions paid by firms and a tax on commuting paid by households.

2 Structure of the model

We assume a linear city on a uni-dimensional space $X =]-\infty, +\infty[$. In each location $x \in X$, the quantity of available land is equal to one. Two types of agents interact inside the city : firms and households. Land is owned by absentee landlords and firms by absentee shareholders. Each household provides one unit of labor to one firm, and receives a wage in exchange. Firms produce a good using a polluting technology and export it outside the city. Households consume a good z imported from outside and are affected by firms' pollution. In addition, both types of agents compete for land, either for residential or production purposes. These interactions take place through labor and land markets, both of which are assumed to be perfectly competitive in each point $x \in X$ of the city. There is no market for pollution. Firms undertake actions which have a cost for households without monetary compensation : pollution is a negative externality.

2.1 Households

We assume that there are N identical households in the city, where N is exogenously determined. We focus on a closed-city model, useful to study the internal structure of cities. All households have identical preferences for composite good, land, and environmental quality. The household utility function is expressed as follows :

$$U = U(Z, S_h, E)$$

where U is the utility level, Z is the amount of composite good consumed by the household, S_h is the amount of land consumed by the household, and E is environmental quality perceived by the household at its residential location. For simplicity, the amount of land consumed by each household is assumed to be given exogenously. Utility level U is increasing with the consumption of the composite good, of land, and with environmental quality. We choose a quasi-linear functional form :

$$U(Z, S_h, E) = Z + E + \gamma \ln(S_h) \tag{2.1}$$

Households choose a residential location and a job site to maximize their utility under a budget constraint. Each household provides one unit of labor to a business firm located in x_w and earns a wage $W(x_w)$. Each household uses this wage to pay a land rent $R(x)$, and to consume composite commodity. The composite commodity is chosen as a numéraire so price $p_z = 1$. In addition each household commutes to the firm everyday at a cost t per kilometer travelled between residential location x and job site x_w. Since all households are assumed to be identical, in equilibrium they must all achieve the same maximum utility level, independent of location. The common maximum utility level, called the *equilibrium utility* and denoted U^*, is the solution of the following program:

$$\begin{cases} \max\limits_{x, x_w} & U(Z, S_h, E) \\ s.t. & W(x_w) = R(x)S + Z + t|x - x_w| \end{cases}$$

In order to avoid unnecessary intricate analytic computation, we choose to define environmental quality as a linear function[1]. The environmental quality function is defined at each

[1] The choice of a linear function allows us to analytically compute in a comprehensible manner the following results. Until a given point, similar results can be found using exponential functional form.

point x by :

$$E(x) = \bar{E} - \int_X [\varepsilon - \eta|x-y|]\, b(y)dy \tag{2.2}$$

Where $b(y)$ is the density function of firms at location y, $|x-y|$ is the distance between households located at x and firms located at y, ε represents the quantity of pollution emitted by one firm and η is a measure of dispersion of pollution into the atmosphere. Household located in x suffer from a negative effect of pollution emitted by firms located at y. As emissions disperse into the atmosphere at a constant rate, households can choose to benefit from a better environmental quality if they locate far away from firms. However, by choosing a location farther from firms, households will bear a higher transport cost. Transport cost acts as a centripetal force, while pollution acts as a centrifugal one. Households will make trade-off between better environmental quality and lower commuting cost. These trade-off appear in the *bid-rent function* of households, which is a generalized form of the bid rent function originally defined by (Alonso, 1964) in the context of a monocentric city. The individual bid-rent function of households located at x gives the highest price that they are willing to pay for one unit of land at x while deriving the utility level U^* and given the wage profile $W(x_w)$. The bid-rent function is expressed as follows

$$\Psi(x) \equiv \quad \Psi(x|W(x_w), U^*) = \quad \max_{x_w} \left\{ \frac{1}{S_h} \left[W(x_w) - t|x - x_w| - Z^*(S, E, U^*) \right] \right\}$$

Where $Z^*(S_h, E, U^*)$ is the solution to $U(Z, S_h, E) = U^*$ and represents the amount of composite good necessary to achieve equilibrium utility level U^* when lot size is equal to S_h and environmental quality to E. With the specified utility function defined in (2.1) we obtain:

$$\Psi^*(x) = \max_{x_w} \left\{ \frac{1}{S_h} \left[W(x_w) - t|x - x_w| - U^* + E(x) + \gamma \ln(S_h) \right] \right\}$$

Note that here, each household locating at x optimally chooses its job site x_w, considering the trade-off between commuting cost $t|x - x_w|$ and wage $W(x_w)$. (Ogawa and Fujita, 1980) prove that a first property of any equilibrium is no cross-commuting. Using this property they show that if commuting takes place in the equilibrium city, the equilibrium wage profile must be a linear function of distance to the center. Proof of these two propositions can be found in (Ogawa and Fujita, 1982)[2]. The equilibrium wage profile is given by :

$$W(x) = W(0) - tx \tag{2.3}$$

Then, using (2.3) we conclude that at equilibrium the bid-rent function of households is written :

$$\Psi^*(x) = \frac{1}{S_h} \left[W(x) - U^* + E(x) + \gamma \ln(S_h) \right] \tag{2.4}$$

[2]The introduction of industrial pollution in the model does not alter the proves of these propositions as the consumption of environmental externalities does not enter into the budget constraint and the net income remains the same.

The bid-rent of households depends positively on wage and on environmental quality, but negatively on transport cost.

2.2 Business firms

We suppose that there are M identical firms. Each firm produces one good using land and labor, and a polluting technology that allows to reduce production costs. Production output is exported from the city at price 1. Following (Ogawa and Fujita, 1982), we assume that the amounts of land and labor used for production by each firm are fixed. The amount of land is denoted S_b and the amount of labor is L_b. We assume that there is no unemployment in the city. Then at equilibrium we have the following relation :

$$M = N/L_b$$

Firms benefit from agglomeration economies, measured by the locational potential function F(x) defined by

$$F(x) = \int_X \left[\alpha - \tau|x-y|\right] b(y)dy \tag{2.5}$$

Where $b(y)$ is density of business firm at y, and $|x-y|$ is distance between firms locating at x and y. Each firm wants to maximize profit and solves the following program

$$\max_x \quad \pi = F(x) - R(x)S_b - W(x)L_b + \varepsilon$$

Where ε represents cost saved by using a polluting technology. We assume for simplicity that the total cost saved is equivalent to the amount of pollution emissions, and that it is fixed for each firm. From the maximization problem we can define the bid-rent function of the firm. It is the maximum land rent that a business firm could pay at location x while deriving a profit π^* and given the distribution of firms $b(x)$. It is written as follows

$$\Phi^*(x) \equiv \quad \Phi(x|b(x), W(x), \pi^*) = \quad \frac{F(x) - \pi^* - W(x)L_b + \varepsilon}{S_b}$$

Markets are perfectly competitive then at equilibrium profit is driven to zero, so the bid-rent function is rewritten as

$$\Phi^*(x) = \frac{F(x) - W(x)L_b + \varepsilon}{S_b} \tag{2.6}$$

The bid rend function of firms depends positively on the locational potential and on costs saving thanks to polluting technology, but negatively on wage.

2.3 Equilibrium conditions

Equilibrium land use describes a state of the urban system that shows no propensity to change. It implies that there are no utility to gain by changing location, neither for firms or for households. Absentee landowners want to obtain the maximum amount of money from the rent of their land. Then at equilibrium they offer land to the highest bidder. Beyond the city's limit, there is only agricultural land, and the agricultural rent is exogenous and given by R_a. Each equilibrium spatial structure of the city is described by a system where the unknowns are the household density function $h(x)$, the firm density function $b(x)$, the land rent profile $R(x)$, the wage profile $W(x)$, the commuting pattern $P(x, x_w)$, and the utility level U^*, with

$$P(x, x_w) = \frac{\text{number of household locating at } x \text{ and commuting to job site } x_w}{\text{total number } h(x) \text{ of household locating at } x}$$

The necessary and sufficient conditions for the system to be an equilibrium land use pattern are summarized as follows :

(i) Land market equilibrium conditions at each x :

$$\begin{aligned}
&R(x) = \max\{\Psi^*(x), \Phi^*(x), R_a\}\\
&R(x) = \Psi^*(x) \quad \text{if} \quad h(x) \geq 0\\
&R(x) = \Phi^*(x) \quad \text{if} \quad b(x) \geq 0\\
&R(x) = R_a \quad \text{on the urban fringe}\\
&S_h h(x) + S_b b(x) \leq 1\\
&S_h h(x) + S_b b(x) = 1 \quad \text{if} \quad R(x) > R_a
\end{aligned}$$

(ii) Labor market equilibrium condition at each x

$$b(x)L_b = \int_X h(y)P(y, x)dy$$

(iii) Total unit number constraints :

$$\int_X h(x)dx = N, \quad \int_X b(x)dx = NL_b$$

(iv) Non-negativity constraints :

$$h(x) \geq 0, \quad b(x) \geq 0, \quad R(x) \geq 0, W(x) \geq 0, \quad 1 \geq P(x, x_w) \geq 0,$$
$$\int_X P(x, x_w)dx_w = 1$$

3 Equilibrium land use pattern

In this section we examine each urban configuration and the conditions under which they are the equilibrium market outcome, given the fact that household internalized pollution caused by industries in their choice of localization. The methodology used is similar as in (Ogawa and

Fujita, 1980), then the full derivation of conditions will not appear in this paper.We will also analyzed the total travelled distance in each urban configuration, to understand the intensity of car pollution in each case.

3.1 Monocentric urban configuration

First of all, we start with the basic monocentric configuration. This type of configuration corresponds to a case where the majority of households leaves in suburbs while firms occupy the city center. Formally, we assume that the origin is the center of the city. All firms are located around 0 between -f_1 and f_1. We call this section the *business district* (BD). Households are located in two zones, between -f_1 and -f_2 and f_1 and f_2. We call these sections the *residential areas* (RA). Beyond urban fringes -f_2 and f_2 there are only agricultural lands. We assume that the city is perfectly symmetric, then it is sufficient to examine the equilibrium conditions on the right-half of the city, where $x \geq 0$. We have the following density functions:

$$h(x) = 1/S_h, \quad b(x) = 0, \quad \forall x \in RA$$

$$h(x) = 0, \quad b(x) = 1/S_b, \quad \forall x \in BD$$

Thanks to the total unit number constraints and the full employment assumptions, we can derive the center boundary f_1 and the urban fringe f_2 as follow :

$$f_1 = \frac{S_b M}{2}, \quad f_2 = \frac{M}{2}(S_b + L_b S_h)$$

To define environmental quality in the monocentric configuration, we use equation (2.2) and equations of business density. We obtain the following environmental quality function :

$$E(x) = \begin{cases} \bar{E} - \varepsilon M + \frac{\eta}{S_b}(f_1^2 + x^2) & \text{if} \quad x \in [0, f_1] \\ \bar{E} - \varepsilon M + \frac{2\eta}{S_b} x f_1 & \text{if} \quad x \in [f_1, f_2] \end{cases} \tag{3.1}$$

Environmental quality perceived by household located in x is inversely correlated with the aggregation of pollution emitted by all firms in the city, given by εM. However it increases with the distance to the center because pollution disperses into the atmosphere at rate η. $E(x)$ is increasing and convex with x on BD and increasing and linear on RA.
The potential location function acts as a centripetal force for firms, and using definition (2.5), we obtain $F(x)$ in the monocentric city :

$$F(x) = \begin{cases} \alpha M - \frac{\tau}{S_b}(f_1^2 + x^2) & \text{if} \quad x \in [0, f_1] \\ \alpha M - \frac{2\tau}{S_b} x f_1 & \text{if} \quad x \in [f_1, f_2] \end{cases} \tag{3.2}$$

$F(x)$ is decreasing and concave with x on BD and decreasing and linear on RA, meaning that agglomeration externalities are stronger when firms are close to each other.

The total distance travelled in a monocentric configuration is given by the aggregation of each household's ride. Formally, it is given by the following function :

$$D_M(x, x_w) = \int_0^{f_1} \int_{f_1}^{f_2} P(x, x_w)(x - x_w) dx dx_w \tag{3.3}$$

Using the definition of the commuting pattern $P(x, x_w)$, we rewrite it as follows :

$$P(x, x_w) = \frac{(f_2 - f_1)/S_h}{f_1/S_b} \cdot \frac{1}{1/S_h}$$

Plugging this expression into (3.3), we obtain the following measure of the total distance travelled :

$$D_M(x) = \frac{1}{2} S_b f_2 (f_2 - f_1)^2$$

The property of no cross-commuting is also useful to rewrite the equilibrium conditions in the land market as follows :

$$R(x) = \Phi^*(x) \geq \Psi^*(x) \quad \forall x \in [0, f_1] \tag{3.4a}$$

$$R(x) = \Phi^*(x) = \Psi^*(x) \quad \text{at} \quad x = f_1 \tag{3.4b}$$

$$R(x) = \Psi^*(x) \geq \Phi^*(x) \quad \forall x \in [f_1, f_2] \tag{3.4c}$$

$$R(x) = \Psi^*(x) = R_a \quad \text{at} \quad x = f_2 \tag{3.4d}$$

Where $\Psi^*(x)$ and $\Phi^*(x)$ are given respectively by equation (2.4) and (4.2). Equation (3.4d) must be satisfied, which implies that the household bid-rent function must be a decreasing function of x. Then it implies :

$$|W'(x)| \geq |\beta E q'(x)| \tag{3.5a}$$

$$\Leftrightarrow \quad t \geq E q'(x) \tag{3.5b}$$

$$\Leftrightarrow \quad \tfrac{t}{\eta} \geq M \tag{3.5c}$$

Conditions (3.5b) means that the cost of one more unit of distance travelled, measured by the transport cost t, must be greater than the benefit of this additional unit travelled, measured by the variation of environmental quality $E'(x)$. If the marginal benefit is greater than the marginal cost, household have an incentive to locate farther from the center and the bid-rent function is increasing, which cannot lead to any spatial equilibrium. Hence, if (3.5b) is satisfied $\Psi^*(x)$ is a decreasing and concave function of x. We know that $\Phi^*(x)$ is also always decreasing and concave because of the functional form of $F(x)$. Then equilibrium conditions on the land market can be rewritten as follow :

$$R(0) = \Phi^*(0) \geq \Psi^*(0)$$

$$R(f_1) = \Phi^*(f_1) = \Psi^*(f_1)$$

$$R(f_2) = R_a = \Psi^*(f_2) \geq \Phi^*(f_2)$$

Which implies

$$\Phi^*(0) - \Phi^*(f_1) \geq \Psi^*(0) - \Psi^*(f_1) \tag{3.6}$$

$$\Phi^*(f_1) - \Phi^*(f_2) \geq \Psi^*(f_1) - \Psi^*(f_2) \tag{3.7}$$

Using equations (2.4) and (4.2), we can rewrite (3.6) and (3.7) as follows :

$$t \leq \underbrace{\frac{S_h}{S_b + S_h L_b} \cdot \frac{(F(0) - F(f_1))}{f_1}}_{A} + \underbrace{\frac{S_b}{S_b + S_h L_b} \cdot \frac{(E(f_1) - E(0))}{f_1}}_{B} \tag{3.8a}$$

$$t \leq \underbrace{\frac{S_h}{S_b + S_h L_b} \cdot \frac{(F(f_1) - F(f_2))}{(f_2 - f_1)}}_{A_1} + \underbrace{\frac{S_b}{S_b + S_h L_b} \cdot \frac{(E(f_2) - E(f_1))}{(f_2 - f_1)}}_{B_1} \tag{3.8b}$$

Parts A and A_1 correspond to the conditions derived (Ogawa and Fujita, 1982) when there is no environmental externality. Part B and B_1 appear when we introduce pollution in the model. They are positive constants, which means that the condition on t is easier to sustain. The presence of environmental externalities pushes households to locate farther from the business district, and leads to more spatialisation of activities.
Using equation the functional form of $E(x)$ and $F(x)$ given by (3.1) and (4.1), we obtain only one conditions on t :

$$t \leq \frac{(S_h \tau + S_b \eta) N}{2 L_b (S_b + S_h L_b)} \tag{3.9}$$

Proposition 1 : With the presence of a negative environmental externality caused by industrial pollution, the monocentric configuration is more likely an equilibrium.

3.2 Completely mixed urban configuration

Now we analyze a situation where households and firms coexist at every point x in the city. Therefore, households' residential location and job site are the same, and there is no commuting implying $x = x_w$. This type of configuration may be considered as analogous to a high densified city in a model with endogenous lot size. Indeed firms and households are close to each other and both types of configuration present the same characteristics.

The limit of the city is given by the frontiers $-f_1$ and f_1 and their is only one zone between these two limits called the *integrated district* (ID). As there is no commuting, the equilibrium condition in the labor market is satisfied, and the total distance travelled is equal to zero. Under this configuration, the density function of firms and households are :

$$h(x) = \frac{L_b}{S_b + S_h L_b}, \qquad b(x) = \frac{1}{S_b + S_h L_b}, \qquad \forall x \in [-f_1, f_1]$$

We focus again only on the right hand side of the city where $x \geq 0$. Environmental quality perceived by households located at x is given by :

$$E(x) = \bar{E} - \varepsilon M + \frac{\eta}{S_b + S_h L_b}(f_1^2 + x^2) \quad \forall x \in [0, f_1] \tag{3.10}$$

Environmental quality is always increasing and convex inside ID. The locational potential function is expressed as follow :

$$F(x) = \alpha M - \frac{\tau}{S_b + S_h L_b}(f_1^2 + x^2) \quad \forall x \in [0, f_1] \tag{3.11}$$

The locational potential function is decreasing and concave inside ID.

In the land market the equilibrium conditions are given by:

$$R(x) = \Psi^*(x) = \Phi^*(x) \quad \forall x \in [0, f_1] \tag{3.12a}$$

$$R(x) = R_a \qquad \text{at} \quad x = f_1 \tag{3.12b}$$

From (2.4), (4.2) and (3.12a) we obtain the wage profile :

$$W(x) = \frac{S_h F(x) + S_b(U^* - \gamma \ln S_h) + \overbrace{S_h \varepsilon - S_b E(x)}^{C}}{S_b + S_h L_b} \tag{3.13}$$

Part C is due to the introduction of environmental externalities in the model. Wage is decreasing with environmental quality. As in this configuration, households cannot internalize the pollution damage by choosing a location farther from firms, firms must offer a higher wage to provide an incentive to households to locate where there is low environmental quality. Plugging (3.13) into (2.4) or (4.2), we obtain the equilibrium land rent :

$$R(x) = \frac{F(x) - L_b(U^* - \gamma \ln S_h) + \varepsilon + L_b E(x)}{S_b + S_h L_b} \tag{3.14}$$

Again, the rent function is increasing with the level of environmental quality, and environmental quality is an increasing function of distance. The existence of an equilibrium implies that the bid-rent function must be decreasing with x in order to satisfy condition (3.12b) . Then the following condition must hold :

$$R'(x) \leq 0 \tag{3.15a}$$

$$\Leftrightarrow \quad |F'(x)| \geq |L_b E'(x)| \tag{3.15b}$$

$$\Leftrightarrow \quad \left| \frac{-2\tau x}{S_b + S_h L_b} \right| \geq \left| \frac{2 L_b \eta x}{S_b + S_h L_b} \right| \tag{3.15c}$$

$$\Leftrightarrow \quad \tau \geq \eta L_b \tag{3.15d}$$

The firm's loss caused by one additional unit of distance, which is represented by the variation in locational potential, must be higher than the benefit of this additional unit of distance for household, measured by the variation of environmental quality. If the benefit is higher than the loss, bid-rent function is increasing and there is no feasible equilibrium. We should notice here that if condition (3.15d) is satisfied, the absolute value of the second-derivative of $F(x)$ is greater than the second-derivative of $E(x)$. As $F(x)$ is convex and $E(x)$ is concave, the bid-rent $R(x)$ is a concave function on ID. Moreover, $W(x)$ is positively correlated with $F(x)$ and negatively correlated with $E(x)$. It implies that the wage $W(x)$ is a strictly concave function of x. As there is no commuting in the completely mixed configuration, households have no incentive to change their job site only if $|W'(x)| \leq t$. This condition is equivalent to $W'(f_1) \geq -t$ because of the strict concavity of $W(x)$. Then, from this condition and with equations (3.10) and (3.11) we obtain :

$$t \geq \underbrace{\frac{N\tau S_h}{(S_b + S_h L_b)L_b}}_{A_2} + \underbrace{\frac{N\eta S_b}{(S_b + S_h L_b)L_b}}_{B_2} \tag{3.16}$$

Part A_2 is the condition without pollution as in (Ogawa and Fujita, 1982). Part B_2 is due to the introduction of pollution in the model. B_2 is a positive constant so the condition on t is stronger. Even if the locational potential τ is very low, the completely mixed urban configuration might not be an equilibrium because of the presence of a negative environmental externality, which pushes households far from polluting firms.
Proposition 2 : With the presence of a negative environmental externality caused by industrial pollution, the completely mixed urban configuration is less likely an equilibrium.

3.3 Incompletely mixed urban configuration

An incompletely mixed urban configuration is a generalization of the monocentric and the completely mixed configuration. This type of configuration is representative of a certain number of French agglomerations : a part of households lives in the city center where firms are also established, while an other part lives in suburbs. There are three section in the city. As the city is perfectly symmetric we focus only on the right side. Between 0 and $f1$, firms and households are mixed and we called it the integrated district (ID). Between f_1 and f_2, there are only firms, and it is the business district (BD). Between f_2 and f_3, there are only households in the residential area (RA). The city boundaries are given by :

$$f_1 \in \left(0, \frac{S_b + S_h L_b}{2L_b} N\right), \quad f_2 = \frac{S_h L_b}{S_b + S_h L_b} f_1 + \frac{S_b N}{2L_b}, \quad f_3 = \frac{S_b + S_h L_b}{2L_b} N.$$

It is easy to see that the incompletely mixed urban configuration tends to be a monocentric configuration as f_1 tends to zero, and it tends to be a completely mixed configuration as f_1 tends to $((S_b + S_h L_b)/2L_b)N$.

Each segment of the city is characterized by the following functions:

- In the integrated district :

$h(x) = \frac{L_b}{S_b+S_hL_b}, \quad b(x) = \frac{1}{S_b+S_hL_b}$
$E(x) = \bar{E} - \varepsilon M + \left\{ \frac{\eta}{S_b}(f_2^2 - f_1^2) + \frac{\eta}{S_b+S_hL_b}(f_1^2 + x^2) \right\}$
$F(x) = \alpha M - \left\{ \frac{\tau}{S_b}(f_2^2 - f_1^2) + \frac{\tau}{S_b+S_hL_b}(f_1^2 + x^2) \right\}$

- In the business district :
  $h(x) = 0, \quad b(x) = \frac{1}{S_b}$
  $E(x) = \bar{E} - \varepsilon M + \left\{ \frac{\eta}{S_b}(f_2^2 - 2f_1x + x^2) + \frac{2\eta}{S_b+S_hL_b} f_1 x \right\}$
  $F(x) = \alpha M - \left\{ \frac{\tau}{S_b}(f_2^2 - 2f_1x + x^2) + \frac{2\tau}{S_b+S_hL_b} f_1 x \right\}$

- In the residential area :
  $h(x) = \frac{1}{S_h}, \quad b(x) = 0$
  $E(x) = \bar{E} - \varepsilon M + \left\{ \frac{2\eta}{S_b}(f_2 - f_1)x + \frac{2\eta}{S_b+S_hL_b} f_1 x \right\}$
  $F(x) = \alpha M - \left\{ \frac{2\tau}{S_b}(f_2^2 - f_1)x + \frac{2\tau}{S_b+S_hL_b} f_1 x \right\}$

The total distance travelled is given by the following function :

$$D_I(x, x_w) = \int_{f_1}^{f_2} \int_{f_2}^{f_3} P(x, x_w)(x - x_w) dx dx_w \tag{3.17}$$

Following the same reasoning as in section (3.1), the commuting pattern is written :

$$P(x, x_w) = \frac{(f_3 - f_2)/S_h}{(f_2 - f_1)/S_b} \cdot \frac{1}{1/S_h} \tag{3.18}$$

Then using this expression into (3.17) gives the total distance travelled in the incompletely mixed configuration :

$$D_I(x) = \frac{1}{2}(f_3 - f_2)^2 (f_3 - f_1) S_b$$

The equilibrium conditions in the land market for the incompletely mixed urban configuration are summarized, for $x \geq 0$ as follow :

$$R(x) = \Phi^*(x) = \Psi^*(x) \quad \forall x \in [0, f_1] \tag{3.19a}$$
$$R(x) = \Phi^*(x) \geq \Psi^*(x) \quad \forall x \in [f_1, f_2] \tag{3.19b}$$
$$R(x) = \Phi^*(x) = \Psi^*(x) \quad \text{at} \quad x = f_2 \tag{3.19c}$$
$$R(x) = \Psi^*(x) \geq \Phi^*(x) \quad \forall x \in [f_2, f_3] \tag{3.19d}$$
$$R(x) = \Psi^*(x) = R_a \quad \text{at} \quad x = f_3 \tag{3.19e}$$

Where $\Psi^*(x)$ and $\Phi^*(x)$ are given by (2.4) and (4.2) respectively. As in the case of a completely mixed urban configuration, from (2.4), (4.2) and (3.19a), we obtain the wage profile $W(x)$

in the integrated district. On the residential area, the wage profile is a linear function of distance. To summarize, the wage profile in the city is given by :

$$W(x) = \begin{cases} \frac{S_h F(x) + S_b(U^* - \gamma \ln S_h) + S_h \varepsilon - S_b E(x)}{S_b + S_h L_b} & \text{if} \quad x \in [0, f_1] \\ W(f_1) - t(x - f_1) & \text{if} \quad x \in [f_1, f_3] \end{cases} \tag{3.20}$$

Using (2.4) and the second part of (3.20), we can compute the value of $W(x)$ in f_1 depending on the equilibrium utility U^*. Knowing that this value must be equal to the value in the first part of (3.20), we can determine the equilibrium utility level U^* as a function of f_1 and f_3:

$$U^* = \frac{F(f_1) + \varepsilon}{L_b} + \frac{S_b(E(f_3) - E(f_1)) - (S_b + S_h L_b)(S_h R_a + t(f_3 - f_1))}{S_h L_b} + \gamma \ln S_h + Eq(f_3) \tag{3.21}$$

Using the functional form of $F(x)$ and $E(x)$, we can show that $F(x)$ is strictly concave on BD and linear on RA and $E(x)$ is convex on BD and linear on RA. Using condition (3.15d), we can conclude that $R(x)$ will be concave on BD and linear on RA, so the rest of the land market conditions are equivalent to :

$$\begin{aligned} R(x) &= \Phi^*(x) = \Psi^*(x) && \text{at} \quad x = f_1, f_2 \\ R(x) &= \Psi^*(x) = R_a && \text{at} \quad x = f_3 \end{aligned}$$

From these two conditions we derive :

$$t = \frac{S_h}{S_b + S_h L_b} \cdot \frac{(F(f_1) - F(f_2))}{f_2 - f_1} + \underbrace{\frac{S_b}{S_b + S_h L_b} \cdot \frac{(E(f_2) - E(f_1))}{f_2 - f_1}}_{B_3} \tag{3.22a}$$

$$t \leq \frac{S_h}{S_b + S_h L_b} \cdot \frac{(F(f_1) - F(f_3))}{(f_3 - f_1)} + \underbrace{\frac{S_b}{S_b + S_h L_b} \cdot \frac{(E(f_3) - E(f_1))}{f_3 - f_1}}_{B_4} \tag{3.22b}$$

Parts B_3 and B_4 are positive constants capturing the effect of an environmental externality on the equilibrium outcome. Finally, no commuting in ID implies again that $|W'(x)| \leq t$ for $x \in ID$, which is equivalent to the following conditions :

$$t \geq \frac{S_h}{S_b + S_h L_b} F'(f_1) + \frac{S_b}{S_b + S_h L_b} Eq'(f_1) \tag{3.23}$$

So when there is an environmental externality, a higher value of t is needed to sustain an incompletely mixed land use pattern at equilibrium.
Plugging definitions of $F(x)$ and $E(x)$ into (3.22a), we obtain the following condition :

$$t = \frac{(S_h \tau + S_b \eta) f_1}{(S_b + S_h L_b)^2} + \frac{M(S_h \tau + S_b \eta)}{2(S_b + S_h L_b)} \tag{3.24}$$

This equation allows us to compute the value of the limit of the integrated district, f_1. It is useful in order to have a better view of the difference in urban structure with and without pollution. A large f_1 means that the city is more integrated, while a low f_1 means a more spatialiazed city. We obtain the following results :

$$\tilde{f}_1 = \frac{t(S_b + S_h L_b)^2}{\tau S_h} - \frac{(S_b + S_h L_b)M}{2} \tag{3.25a}$$

$$f_1 = \frac{t(S_b + S_h L_b)^2}{\tau S_h + \eta S_b} - \frac{(S_b + S_h L_b)M}{2} \tag{3.25b}$$

Where $\tilde{f}_1$ corresponds to the limit in the no pollution case, and f_1 to the limit in the case with pollution. It is clear that with pollution, the integrated district is smaller than without pollution. Then, spatialization of activities tends to be more important with negative environmental externalities. At equilibrium land use pattern will be less integrated and more spatialized.

Proposition 3 : With the presence of a negative environmental externality caused by industrial pollution, the integrated district of an incompletely mixed city is smaller, while the business district and the residential area are larger at equilibrium.

Using equation (3.25b) into (3.22b) and (3.23) we obtain the following necessary conditions for the incompletely mixed land use pattern to be an equilibrium :

$$\frac{(\tau S_h + \eta S_b)N}{2(S_b + S_h L_b)L_b} \leq t \leq \frac{(\tau S_h + \eta S_b)N}{(S_b + S_h L_b)L_b} \tag{3.26}$$

The comparison between the original analysis of (Ogawa and Fujita, 1982) and our analysis with environmental externality is summarized in Figure 4. It appears that the domain of t in which the monocentric configuration is an equilibrium is greater with the presence of industrial pollution. This result underlines the defensive behavior of households. The problem is that the monocentric configuration results in a larger distance travelled compare to the incompletely mixed case. Indeed, plugging the definition of f_1, f_2 and f_3 in equation (3.1) and (3.3), we can easily compare the total distance travelled in each case. The ratio $\frac{D_I}{8D_M}$ is given by :

$$\frac{D_I}{8D_M} = \frac{(N(\tau S_h + \eta S_b) - tL_b(S_b + S_h L_b))}{(N(\tau S_h + \eta S_b))^3}$$

Equation (3.23) allows to say that this expression always range from 0 to 1. The total distance travelled in the monocentric case is always larger than the total distance travelled in the incompletely mixed configuration. The externality related to air pollution created by commuting is then larger because of the defensive behavior of households who locate farther from firms.

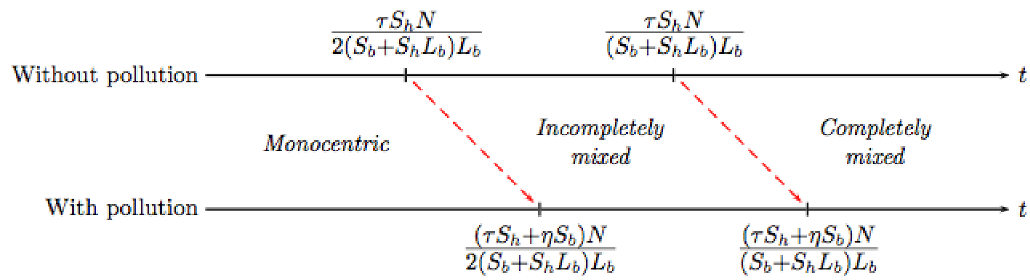

Figure 1: Comparison of equilibrium land use patterns

4 Policy issues

The presence of externalities leads to non-optimal equilibrium land use. When they maximize profits, firms do not take into account households' disutility caused by their emissions of pollution, and the defensive behavior of households is responsible for an increase in car use, hence in air pollution. We have shown that pollution has an impact on the structure of the city : it pushes household farther from firms and leads to a more spatialized city. The structure of the city also impacts directly the level of pollution : if we focus on the incompletely mixed urban configuration, the reduction of the integrated district conducts to a higher number of households in the residential area. They commute every day to work in the business district and the damage caused by emission of CO_2 by car is more important. The positive externality of agglomeration economies also causes distortion from optimal land use pattern. The achievement a first-best policy requires that the number of instruments is equal to the number of externalities. In our model, there is three externalities : the first one is due to emission of pollution by industry, the second one is a positive externality of agglomeration economics, and the the third is due to car pollution. The practical implementation of first-best policy may be too complex and may require too much cooperation between different governmental authorities (Verhoef and Nijkamp, 2003). We therefore make the hypothesis that the social planner cannot use first-best instruments, and we will consider second-best policy. The social planner which have as an objective to limit emissions of CO_2 in the atmosphere decides to implement a tax on commuting and a tax on firms emissions. From now on we will consider only the case of incompletely mixed urban configuration in order to have a global view of the impact of the taxes on pollution externalities and on the urban structure. For simplicity we will also consider only the right hand side of the city where $x \geq 0$.

4.1 Designing instruments

As commuting is a non-point source of pollution, it requires too much information for the social planner to implement a spatialized tax. However, industry emission are fixed source of pollution, and the social planner can implement a spatialized tax on emission, depending on the damage created by each firms on households residing in the city. The tax on commuting,

denoted T, is then fixed and proportional to the distance travelled by each household.
The tax on firms' emissions depends on the damage created for every households. Depending on its localization firms affects differently households, because of the dispersion rate of pollution into the atmosphere. The emissions' tax have the following expression :

$$\Theta(x) = \theta \int_X (\varepsilon - \eta|x-y|)h(y)dy$$

Deriving this expression for each segment of the city, we obtain the emissions' tax as follows :

$$\Theta(x) = \begin{cases} \theta[\varepsilon M - \frac{\eta}{S_h}(f_3^2 - (f_2^t)^2) - \frac{\eta L_b}{S_b + S_h L_b}((f_1^t)^2 + x^2)] & \text{if} \quad x \in [0, f_{1t}] \\ \theta[\varepsilon M - \frac{\eta}{S_h}(f_3^2 - (f_2^t)^2) - \frac{2\eta L_b}{S_b + S_h L_b} f_1^t x] & \text{if} \quad x \in [f_{1t}, f_{2t}] \end{cases} \tag{4.1}$$

Where the limit of the integrated district $f_1^t = f_1(T, \theta)$ and the limit of the business district $f_2^t = f_2(T, \theta)$ are endogenously determined and functions of the taxes T and θ.

4.2 Taxes and equilibrium land use pattern

The tax on commuting impacts directly the budget constraint of households. It changes the utility maximization program of households and conducts to new bid-rent functions. Following the same reasoning as in section 2 and denoting the unitary tax T with $T \geq 0$, the new bid-rent function of households is written as follows :

$$\Psi^*(x) = \max_{x_w} \left\{ \frac{1}{S_h} \left[W(x_w) - (t+T)|x - x_w| - U^* + E(x) + \gamma \ln(S_h) \right] \right\}$$

The tax on firms' emission impact directly the profit function of firms. They must take into account the decrease in profit due to the introduction of the tax in their localization choice and in the bid-rend function. The new bid-rent function of firms is given by :

$$\Phi^*(x) = \frac{F(x) - W(x)L_b + \varepsilon - \Theta(x)}{S_b}$$

Households located in the residential area will have to pay a higher cost to commute to their job site because of the introduction of the tax. Then when they choose optimally job sites x_w they consider the trade-off between commuting cost which is now $(t+T)(x - x_w)$ and wage $W(x_w)$. Equilibrium wage is impacted by the increase in transport cost, and also by the increase in firms' cost due to tax on emissions. Firms will offer lower wages because a part of their profit will be allocated to the payment of the tax. The new equilibrium wage profile will be :

$$W(x) = \begin{cases} \frac{S_h F(x) + S_b(U^* - \gamma \ln S_h) + S_h \varepsilon - S_b E q(x) - S_h \Theta(x)}{S_b + S_h L_b} & \text{if} \quad x \in [0, f_1^t] \\ W(f_1) - (t+T)(x - f_1) & \text{if} \quad x \in [f_1^t, f_3] \end{cases} \tag{4.2}$$

Following the same reasoning as in section 2.3 we can determine the new equilibrium utility level, denoted U_T^* and equal to :

$$U_T^* = \frac{F(f_1^t)+\varepsilon-\Theta(f_1^t)}{L_b} + \frac{S_b(E(f_3)-E(f_1^t))-(S_b+S_hL_b)(S_hR_a+(t+T)(f_3-f_1^t))}{S_hL_b} + \gamma \ln S_h + E(f_3) \quad (4.3)$$

The utility level decreases because of the introduction of both taxes. The commuting tax increases the cost of household located in RA, and forces a part of household to relocate inside ID and to suffer from a lower environmental quality. The tax on emissions have a negative impact on wages, which lower disposable income of households. These effect involve a decrease in utility.
Using the same arguments as in section 2.3, we know that the land market conditions are equivalent to :

$$\begin{aligned} R(x) &= \Phi^*(x) = \Psi^*(x) && \text{at} \quad x = f_1^t, f_2^t \\ R(x) &= \Psi^*(x) = R_a && \text{at} \quad x = f_3 \end{aligned}$$

From these two conditions and with the new expression of $\Psi^*(x)$ we derive :

$$t+T = \frac{S_h}{S_b+S_hL_b} \cdot \frac{(F(f_1^t)-F(f_2^t)+\theta(f_1)-\theta(f_2))}{f_2^t-f_1^t} + \frac{S_b}{S_b+S_hL_b} \cdot \frac{(E(f_2^t)-E(f_1^t))}{f_2^t-f_1^t} \quad (4.4a)$$

$$t+T \leq \frac{S_h}{S_b+S_hL_b} \cdot \frac{(F(f_1^t)-F(f_3)+\theta(f_1^t))}{(f_3-f_1^t)} + \frac{S_b}{S_b+S_hL_b} \cdot \frac{(E(f_3)-E(f_1^t))}{f_3-f_1^t} \quad (4.4b)$$

The third conditions is given by the fact that no commuting in ID implies that $|W'(x)| \leq t+T$ for $x \in ID$, which is equivalent to :

$$t+T \geq \frac{S_h}{S_b+S_hL_b}(F'(f_1^t)+\theta'(f_1^t)) + \frac{S_b}{S_b+S_hL_b}E'(f_1^t) \quad (4.5)$$

We see that the right-hand side of equations (4.4a), (4.4b) and (4.5) are equivalent to those of equations (3.22a), (3.22b), and (3.23). Only the left-hand sides of these equation are modified, meaning that the total cost of transportation, which is the addition of the transport cost and the commuting tax, should now be taken into account. Plugging definitions of $F(x)$ and $Eq(x)$ into (3.22a), we obtain the following condition :

$$t+T = \frac{(S_h\tau + S_b\eta + \theta 2\eta S_hL_b)f_1^t}{(S_b+S_hL_b)^2} + \frac{M(S_h\tau+S_b\eta)}{2(S_b+S_hL_b)} \quad (4.6)$$

Thanks to the previous result we can compute the limit of the integrated district when a tax on commuting is implemented. We obtain the following results :

$$f_1^t = \frac{2(t+T)(S_b+S_hL_b)^2-(S_b+S_hL_b)(S_h\tau+S_b\eta)M}{2(\tau S_h+\eta S_b+2\theta\eta S_hL_b)} \quad (4.7)$$

Comparing (3.25b) and (4.7), the following result appears : the implementation of a commuting tax entails an increase in the size of the integrated district, with the apparition of T in the nominator of f_1. In contradiction, the implementation of a tax on firms' emissions leads to a decrease in the size of the integrated district, with the apparition of the positive term $2\theta\eta S_h L_b$ in the denominator of f_1. Both instruments have conflicting effects on the city structure.

4.3 Taxes and pollution damages

Pollution by commuting supposes that the whole society will suffer from an environmental damage. Households located in each point x of the city generate pollution by commuting to job site x_w.The environmental damage created by commuting is then proportional to the total distance travelled in the city. If k is the unitary measure of pollution by commuting, the total environmental damage created by cars' emissions, denoted TDC is written as follows :

$$TDC(x, x_w) = kD_I(x, x_w) = k \cdot \frac{1}{2} S_b (f_3 - f_1)(f_3 - f_2)^2$$

The second source of pollution, coming from industry, is partly internalized in households preferences, as they decide to locate farther from polluting firms. However, each household only internalizes the damage created by industrial pollution at its own location, whereas pollution emitted by one firm has an impact on the whole city. Then the social cost of industrial pollution is greater than the individual cost. The total damage created by firms' pollution, denoted TDF, is the aggregation of individual damage at each point x ($x \geq 0$) of the city. It is written as follows :

$$TDF(x, x_w) = \int_0^{f_3} \int_X [\varepsilon - \eta |x - y|] b(y) dy dx$$

Simplifying this equation, we get the following expression :

$$TDF = \varepsilon M f_3 - \frac{\eta}{S_b} \left[\frac{(f_2^t)^3 - (f_1^t)^3}{3} + (f_2^t - f_1^t) f_3^2 \right] - \frac{\eta}{S_b + S_h L_b} \left[\frac{(f_1^t)^3}{3} + (f_1^t f_3)^2 \right]$$

Variation of industrial damage with taxes

We have shown that the limit of the integrated district f_1^t increases with a tax on commuting and decreases with a tax on firms' emissions. In the expression of damages, only f_1 depends on the level of taxes T and θ. Then we will now analyze the variation of the industrial damages with respect to f_1^t in order to show how this damage varies with each taxes. The first derivative of the industrial damage with respect to f_1 is given by :

$$\frac{\partial TDF}{\partial f_1^t} = \frac{S_h L_b (f_3^2 + (f_1^t)^2)}{S_b (S_b + S_h L_b)}$$

This expression is always strictly positive. Then an increase in the size of f_1^t leads to an increase in damage created by industrial pollution. Indeed, a larger number of households will suffer directly from firms' pollution.
A tax on firms' emissions reduces the size of f_1^t, then it decreases the damage created by industrial pollution. On the contrary, a tax on commuting rises the size of f_1^t, then it increases the damage created by industrial pollution.

Variation of commuting damage with taxes

Following the same reasoning, we analyze the variation of the damage created by commuting with respect to each tax. The first derivative of the industrial damage with respect to f_1^t is given by :

$$\frac{\partial TDC}{\partial f_1^t} = -\frac{1}{2}(kSb(f_3 - f_2^t)^2)$$

This expression is always negative. Then an increase in the size of f_1^t leads to a reduction in damage created by commuting. Indeed, a lower number of households will have to commute to work every day.
A tax on commuting enlarges the size of f_1^t, then it increases the damage created by industrial pollution. On the contrary, a tax on firms' emissions decreases the size of f_1^t, then it increases the damage created by commuting.

This results suggests that both types of policy instruments may have conflicting effect and it may not be appropriate to use both simultaneously. A deeper study of the variation of social welfare with respect to both taxes is now under way to obtain more advanced results.

5 Conclusion

We develop a model of city in which firms and households are free to chose were to locate. The structure of the city is nonuniform firstly because of agglomeration economies, as in (Ogawa and Fujita, 1982). They show that monocentric configuration arises only under special circumstances : when transport cost is relatively small and/or the transaction rate between firms is high. Our intention was to study wether the consideration of environmental issues can change this conclusion. Our results suggest indeed that environmental externality, under the form of industrial air pollution, reinforces the possibility of a monocentric equilibrium. More generally, we show that point-source industrial pollution leads to more spatialized city due to the defensive behavior of households. This result is consistent with the previous literature on urban environmental externalities such as papers of (Verhoef and Nijkamp, 2003) or of (Kyriakopoulou and Xepapadeas, 2013). The second part of our analysis consist in studying the policy issues raised by the existence of externalities. In this part, environmental externalities take not only the form of industrial air pollution, but also of transport-related pollution. The interesting point here is the mutual relation between pollution and the city structure : point-source pollution impacts directly the city structure because it pushes households far from firms, while the resulting spatialized city creates more important environmental damages due to car's non-point source pollution. We study the impact of a second-best policy taking the form of a commuting tax and a tax on firms' emissions. Our results show that both type of taxes have contradictory effects on the city structure and on the resulting pollution damages. It underlines the contradiction between the two types of pollution : industrial pollution is less harmful when households locate far from firms, while transport pollution is stronger in that case. Thus these results suggest that the choice of an appropriate policy instrument may depend on the relative impact of each type of pollution on the environment. Our paper is a first step in the study of mutual interactions of different sources of urban environmental externalities, however it is not yet fully satisfying because of the numerous simplifying assumptions.

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