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Compact or Spread-Out Cities: Urban Planning, Taxation, and the Vulnerability to Transportation Shocks

Summary

This paper shows that cities made more compact by transportation taxation are more robust than spread-out cities to shocks in transportation costs. Such a shock, indeed, entails negative transition effects that are caused by housing infrastructure inertia and are magnified in low-density cities. Distortions due to a transportation tax, however, have in absence of shock detrimental consequences that need to be accounted for. The range of beneficial tax levels can, therefore, be identified as a function of the possible magnitude of future shocks in transportation costs. These taxation levels, which can reach significant values, reduce city vulnerability and prevent lock-ins in under-optimal situations.

Keywords: Urban transportation, Housing, Inertia, Vulnerability, Transportation Taxation

JEL Classification: R21, R48, H23, H31

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1 Introduction

Coordinating housing needs and mobility practices in cities with high vs. low densities constitutes the centre of a major controversy in architecture and urban planning; compact cities found with Le Corbusier (1924) their most fervent partisan, while extreme dispersion of housing was advocated by F. L. Wright (see Jenks et al., 1996). As urban sprawl became a strong tendency in developed countries, economists entered this debate, and began to analyze density in terms of environmental consequences and energy consumption: Newman and Kenworthy (1989) for instance found a negative relationship between density and per capita energy consumption. This seminal paper was the origin of a lively debate in the economic literature, and these results were challenged, for example by Gordon and Richardson (1995).

While this literature focused on long term relationships, the first innovation of our paper is that it concentrates on short- and medium-run evolutions: we argue that, over those timescales, spread-out cities are more vulnerable than compact cities when confronted with an abrupt increase in their transportation costs. This vulnerability arises from the facts (i) that urban forms are adapted to transportation systems and costs (Brueckner and Fansler (1983), Yacovissi and Kern (1995), Song and Zenou (2006)), and (ii) that housing infrastructures have a strong inertia (Mayer and Somerville, 2000). As a consequence, any change in transportation costs induces a slow change in urban infrastructures, which can only take place over very long time scales. Gusdorf and Hallegatte (2007), hereafter referred to as GH07, show that, as long as housing capital has not been adapted, the transition that takes place has significant impacts on households and landowners.

Moreover, energy shocks and climate policies are characterized by imperfect foresight at the timescales relevant to building turnover, which makes the design of urban policies particularly difficult. Here, therefore, we make the case for using robustness in face of multiple scenarios, instead of efficiency in one scenario, as the criterion to manage urbanism. This method could help cities to face the future and uncertain challenges related to constraints on fossil energy resources, to geopolitical instability in oil producing countries, or to climate policies. Transport policies leading to more compact cities, *e.g.* transport taxation or speed limitation, can be seen as an insurance in this context of imperfect foresight. For instance, Akerman and Hojer (2006) indicate that climate policies call for a change in built-up areas, and that an appropriate transport policy shall be flexible enough to allow for adaptation when more information is made available on the climate.

In this perspective, the impacts of transportation taxes are more than ever a crucial issue for policy makers. A robust finding of prospective energy models is that abatement costs of CO_2 emissions will be much higher in the transportation sector than in other sectors (Parry, 2006). Indeed, efficiency gains of vehicle trigger an important rebound effect on gasoline demand. Also, as transportation amounts to 19.3% of the average American household's expenditures (O'Toole, 2003), welfare consequences of taxing gasoline can rapidly become significant. Economic agents have little room to adapt their behavior to an increase in oil costs: first, it is difficult to find alternative less carbon-intensive transportation technologies. Second, housing prices, firms localizations (Schafer, 1998), behavioral regularities (Schafer, 2000) and previous infrastructure choices (Crassous et al., 2006) constrain the transportation needs. Hourcade and Gilotte (2000) mention the importance of urban forms for the design of appropriate carbon taxes, but do not represent the spatial effects of such a tax. A second originality of our paper is that it fills in this gap.

Using urban microeconomic modeling and numerical simulations, we show that: (1) cities with pre-existing high transportation tax levels are less vulnerable to energy shocks, and better prepared to future climate policies; in other cities, housing inertia will induce significant transition effects, such as a fall in utility level, a decrease in landowners' incomes, and unintended redistributive effects between households and landowners; (2) if housing infrastructures are rigid, early taxation can prevent the lock-in of cities in detrimental urban forms. From a normative point of view, we follow Lempert (2006) who claims that decision-makers should be provided with information on the robustness of their strategies with respect to the risks that they are wiling to take or to reject. In this framework, we show that (3) due to redistributive effects between categories of actors, and between generations, the tax level a government may choose is strongly dependent on the nature of the optimality criterion (utilitarian vs. Rawlsian), and on the weight attributed to each category of actors; (4) the implementation of transportation tax is itself an event that may induce negative transition effects, which can, to a certain extent, be avoided thanks to a smooth implementation path.

In the following, we set a theoretical framework suited to the analysis of transportation shocks in Section 2. Following GH07, we explicitly represent housing inertia so as to analyse the effects of such a shock. The basic urban model is only briefly reproduced, since its main features have been well studied in the economic literature. In Section 3, we use this model to evaluate the effects of a shock on transportation prices, and show that cities with high preexisting taxation levels are more robust to shocks. In Section 4, we characterize the tax levels that should be chosen by a welfare-maximizing government. Finally, Section 5 concludes on the consequences for mitigation policies, and provides insights for future research.

2 The model

We use a standard urban economics modeling framework *à la* Von Thuenen, (Von Thuenen, 1826), as adapted by Alonso (1964), Mills (1967) and Muth (1969). More precisely, we use the close city model with absentee landowners specified in Fujita (1989), and the housing production function introduced by Muth. Since the basic properties of this model, and the relationships on which it relies, have been presented in other papers (*e.g.* Wheaton, 1974), we do not provide here an extensive description of those characteristics. We briefly present in Section 2.1.2 the behavior of the economic agents, and list in Section 2.1.3 the relationships defining the equilibriums we introduce in Section 2.1.4. A nomenclature is provided to the reader in Section 2.1.1.

2.1 The Closed City Model with taxation

2.1.1 Nomenclature

CBD	Central Business District, where firms are located	r	distance from CBD
q	housing service per household	s	land area per household
k	housing capital per household	z	composite good
$\mathsf{Land}(r)$	available land surface at distance r	K	capital
$n(r)$	density of households at distance r	$T(r)$	transportation costs
Y	income per capita	r_f	city frontier
$R_H(r)$	unit housing service rent	R_a	agricultural land rent
$H(r)$	total housing service at distance r	$h(r)$	housing service density
$U(z,q)$	utility function of a household	u	utility level
θ	tax level	σ	discount factor
$x^*(r)$	optimal capital-to-land ratio	ρ	capital price
$F(K,L)$	housing service production function	π	tax product

Table 1
Symbols and variables

The variables and functions used in this modeling are listed in Tab. 1 with their significations. Among this set of variables, we specify the housing service density $h(r) = H(r)/\mathsf{Land}(r) = f(x^*(r))$, where the function f is defined by $f(x) = F(1,x)$.

The function $T(r)$ represents generalized transportation costs, that take into account the cost of transportation itself as well as the cost of the time spent in commuting, which could have been devoted to work. Marginal transportation cost is assumed to be constant, and no congestion is taken into account, even though it is an important phenomenon (see *e.g.* Mayeres and Proost, 2001).

We assume that the government sets a tax level per km of commuting $\theta T(r)$. The product [3] of such a tax is given by

$$\pi = \theta \int_0^{r_f} T(r) n(r) r \, dr \tag{1}$$

and we will assume that it is lump-sum redistributed to all workers. This tax level is not intended to pay for investments and infrastructure operating, which we assume to be included in transportation costs $T(r)$.

As a consequence, the new transportation price and the new income of those workers are, giving the subscript "$_a$" to ancient parameters:

$$\begin{aligned} T(r) &= T_a(r)(1+\theta) \\ Y &= Y_a + \pi/N \end{aligned} \tag{2}$$

2.1.2 Economic agents

The households

Each household is composed of one worker commuting every day to the CBD. All workers earn the same income Y, and enjoy utility from a composite good z and a housing service q. All workers share the same utility function $U(z,q)$. Each worker chooses his/her housing location r in the city, where the unit price of housing service at location r is $R_H(r)$. He/she maximizes his/her utility level under a budget constraint:

$$\max_{r,z,q} U(z,q) \text{ s.t. } z + R_H(r)q \leq Y - T(r) \tag{3}$$

Absentee landowners

A landowner allocates his/her amount of land L to agricultural use or to residential use. In the first case, the rent drawn from the land will be $R_a.L$. In the second case, the landowner invests in housing capital K to produce a housing service H. Function F is assumed to have constant returns to scale.

[3] Note that while $T(r)$ is a generalized transportation cost (*i.e.* including the cost of time), the tax $\theta T(r)$ is fully monetary.

The investment decision of a landowner who owns land surface L at location r, is given by:

$$\mathsf{max}_K \ \frac{1}{1-\sigma}[R_H(r)F(L,K)-\rho K] \tag{4}$$

The Aggregate Landowners' Income (ALI) is the income earned by landowners following their investments:

$$ALI = \int_0^{r_f} \mathsf{Land}(r)\Big[R_H(r)f(\frac{K}{L}(r)) - \rho\frac{K}{L}(r)\Big]dr \tag{5}$$

2.1.3 Formal relationships

We define two kinds of static equilibriums that are likely to emerge, depending on whether housing supply is endogenous or exogenous. Several relationships characterize those equilibriums.

If housing supply is exogenous:

$$\begin{aligned}
&\text{all consumers throughout the city have the same utility level } u\\
&R_H(r) = \begin{cases} \mathsf{max}_{q\geq 0} \ \frac{Y-T(r)-Z(q,u)}{q} & \text{for } r \leq r_f \\ 0 & \text{for } r \geq r_f \end{cases}\\
&n(r) = \begin{cases} H(r)/q(r,u) & \text{for } r \leq r_f \\ 0 & \text{for } r \geq r_f \end{cases}\\
&N = \int_0^{r_f} n(r)dr\\
&R_H(r_f,u) \geq 0
\end{aligned} \tag{6}$$

If housing supply is endogenous, we need to add:

$$\begin{aligned}
&x^*(r) = \arg\max_x \ [R_H(r)f(x) - \rho x]\\
&r_f = \mathsf{max}[r, R_H(r)f(x^*(r)) - \rho x^*(r) \geq R_a]\\
&H(r) = \begin{cases} \mathsf{Land}(r)\cdot f(x^*(r)) & \text{for } r \leq r_f \\ 0 & \text{for } r \geq r_f \end{cases}\\
&R_H(r_f)H(r_f) - \rho K^*(r) = R_a\mathsf{Land}(r_f)
\end{aligned} \tag{7}$$

2.1.4 Definitions

Definition 1 (CSExt) ***A competitive equilibrium with tax and exogenous housing*** *(or CSExt) is reached in the city when, for a given set of parameters N, Y_a, R_A, θ, and for given functions $H(r)$, and $T_a(r)$, one can find parameters and functions u, Y, π, r_f, $n(r)$, $T(r)$, $R_H(r)$, and $z(r)$ verifying Eqs. (1), (2) and (6).*

Definition 2 (CSEnt) ***A competitive static equilibrium with tax and endogenous housing*** *(or CSEnt) is reached in the city when, for a given set of parameters N, Y_a, R_A, θ, and for given functions $\mathsf{Land}(r)$ and $T_a(r)$ and $F(L,K)$, one can find parameters and functions u, Y, π, r_f, $n(r)$, $T(r)$, $R_H(r)$, $z(r)$ and $H(r)$ verifying Eqs. (1), (2), (6) and (7).*

2.2 The city structure

A transportation tax has two effects on urban sprawl, namely on r_f, and on consumers welfare. On the one hand, if a positive tax is implemented, transportation prices are higher, which shrinks the city boundary, and reduce households' utility (see also Wheaton, 1974). On the other hand, the product of this tax is positive, and is lump-sum distributed to consumers. Thus, the income of the representative household increases, which improves consumers utility and expands the city outwards.

Brueckner (2005) shows that the first effect is the strongest on urban sprawl: a positive tax shrinks the city boundary. What is the optimal subsidy or taxation level on commuting for consumers utility level? Brueckner asks the question but cannot tell whether optimal taxation is positive or negative; he recommends exploring the question with specific functional forms, beginning with CES and Cobb-Douglas. We do such an analysis with Cobb-Douglas functions, and show that there is an optimal subsidy for households' utility level, partly answering Brueckner's questioning.

To do so, we use the following functional forms, classically used in urban economics (see *e.g.* Fujita, 1989)[4]:

$$
\begin{aligned}
&U(z,q) = z^{\alpha} q^{\beta} \text{ where } \alpha,\ \beta\ > 0 \text{ and } \alpha + \beta = 1\\
&F(s,k) = A s^{a} k^{b} \text{ where } a,\ b,\ A\ > 0 \text{ and } a + b = 1\\
&T(r) = p.r\\
&\mathsf{Land}(r) = l.r\\
&R_a = 0
\end{aligned}
\tag{8}
$$

For the numerical simulations presented in this paper, we calibrated our model on the Los Angeles agglomeration: 4.3 million workers earn a $\$20,700$ yearly income (data U.S. Census Bureau 1999). We use an estimate of transportation price using 1999 gasoline prices (*i.e.* 32 cents per km on average, data American Automobile Association 1999), which is a lower bound of transportation costs. Coefficient β, introduced in Eq. (8), represents the share of households budget devoted to housing and related expenses (housing equipment, heating, ...), which we set at 25%. For the construction function, we lack robust empirical evaluation, and used $A = 1$ and $a = 0.5$. To assess the robustness of our results, we carried out systematic sensitivity analyses that show that all qualitative results of the model remain the same in the range of reasonable parameter values.

2.2.1 Tax effect on the city

A high tax level, which increases the transportation price, makes locations far from the CBD less sought after, and those close to the CBD more sought after: consumers agree to pay higher rents to get closer to the CBD, even if it means that they have to put up with smaller flats. Therefore, the rent curve is steeper, and landowners invest accordingly. Figure 2.2.1 shows that, through this mechanism, taxation level influences strongly urban structure.

2.2.2 Landowners

At the aggregate level, landowners are insensitive to transportation prices, but they are sensitive to the level of taxation:

$$ALI = \frac{NY_a(1+\theta)}{(\gamma+3)+\theta(\gamma+1)} \tag{9}$$

[4] We analytically show in Appendix 6.2.2 that, with these functional forms, there is both existence and uniqueness of a CSEnt and a CSExt.

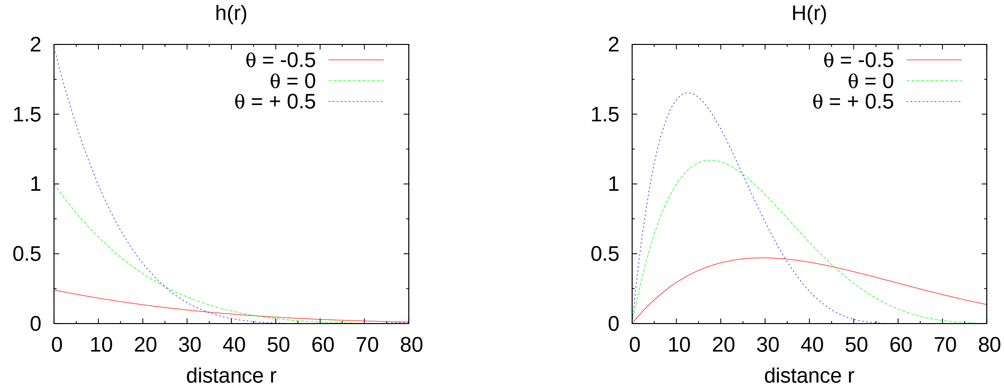

Fig. 1. Left: housing density $h(r)$ corresponding to different tax levels θ (index $h(0) = 1$ for zero tax). Right: housing structure $H(r)$ as a function of the tax level (index $H(10) = 1$ for zero tax).

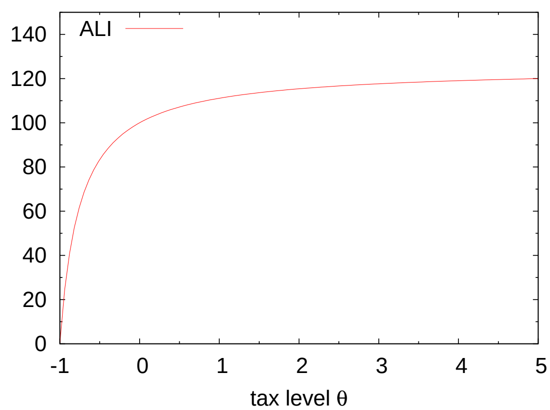

Fig. 2. The Aggregate Land Income, corresponding to different tax levels (index $ALI = 1$ for zero tax).

A tax on transportation creates a market distortion: it gives households an incentive to commute less and to spend a larger share of their budget on housing services and other consumer goods. Figure 2 shows that a tax on transportation increases aggregate landowners' income.

2.2.3 Tax effects on households

Each tax level θ is associated with a unique utility level, given by:

$$u^{\gamma+1}\frac{(\gamma+2)N}{lB} = \frac{Y^{\gamma+2}}{p^2}(1+\theta)^{\gamma}\Big(\frac{\gamma+3}{(\gamma+3)+\theta(\gamma+1)}\Big)^{\gamma+2} \tag{10}$$

The tax or subsidy has two effects on households' utility. On the one hand, a tax increases transportation price, which decreases utility. On the other hand, its product increases the income of consumers, which increases utility.

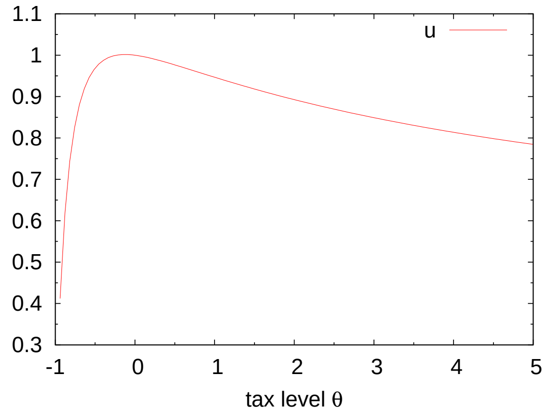

Fig. 3. Impact of a tax θ on utility u (index $u = 1$ for $\theta = 0$).

Of course, the two effects are exactly opposite when the tax is a subsidy. With the functional forms we use, the optimal balance between these two effects is reached for a unique subsidy level, corresponding to the maximum of the utility level given by Eq. (10):

$$\theta^* = -\frac{1}{\gamma + 1} = -a\beta \tag{11}$$

It is noteworthy that the optimal tax level is strictly negative: households are given an incentive to commute more, and spend less money on housing [5] .

We now introduce a monetary equivalent to consumers' utility [6] :

Definition 3 (Equivalent income) *In a city where the income is $Y_{equi}(u, T(r))$, where the transportation cost function is given by $T(r)$, and where the government sets the optimal tax level $\theta = \theta^*$, consumers reach the utility level u.*

This monetary equivalent will be useful in the analysis of government's decisions. A utilitarian government taking into account absentee landowners would maximize a Static Global Welfare ($SGW(u, T(r))$) expressed in monetary terms as the sum of landowners' income and of the equivalent income of consumers:

$$SGW(u, T(r)) = N.Y_{equi}(u, T(r)) + ALI \tag{12}$$

[5] This subsidy can for instance consist in the free access to roads and highways financed by a tax independent of individual transportation behavior.

[6] We prefer not to use the criterion specified by Herbert and Stevens (1960): as energy shocks may have an influence on all cities as well as on rural population, we do not want to depend on the existence of a reservation utility. Therefore, we rather define an equivalent income.

If the optimal tax level is defined as the level that maximizes SGW, and if ALI is lump-sum redistributed to consumers, we find (see Appendix 6.1.5) that the optimal tax level is zero [7].

3 Compared vulnerability to external transportation shocks

Since our goal is to investigate the vulnerability of cities to shocks in transportation costs, we assume in this section that at one point in time, the transportation costs increase instantaneously from an initial value p_i to a final value p_f.

If housing capital is fixed, GH07 show that the transportation shock effects are worse than under the malleability assumption (in the latter case, housing infrastructures adapt instantaneously). They find that this worsening is not negligible, and entails also important distributive effects between landowners and households, and among landowners. They do not account, however, for the effects of taxation levels. In the remaining of this section, we analyze a situation where households and landowners adopt a myopic behavior, in a city where a pre-existing taxation level θ has been implemented. To analyze cities with different taxation levels, we compare the medium-run situation with a long run equilibrium where the optimal taxation level θ^* is implemented. We use this final period as a common reference to study the medium-run effects of different values of θ_i, the initial value of the tax.

3.1 Accounting for inertia during the transition

We consider three periods: (1) the *initial* period, before the shock, during which the city is assumed to be at its long-run equilibrium with a transportation price p and a tax level θ_i. (2) The *final* period, during which the city is at its new long-run equilibrium, fully adapted to the new transportation price p_f and a tax level θ^*. This period takes place a long time after the shock, at least several decades: based on Jin and Zeng (2004), the buildings turnover in an American city is complete in 60 to 70 years. (3) An intermediary period, or *medium* period. Goodwin et al. (2004) review the literature on the response to transportation cost changes, and find a short-term response taking place within approximately 5 to 10 years after the shock [8]. Thus, the medium pe-

[7] This also the optimal tax level that Brueckner (2005) finds for a classical Herbert-Stevens criterion.

[8] Due to the timescales we consider, what we call here a “short-term” response is for Goodwin et al. (2004) a long-term response.

riod takes place approximately between one decade after the shock and a few decades after the shock.

During the medium period, the housing-supply structure is not adapted to the new transportation price, because of the long adjustment delay in buildings and city structure. Households, on the other hand, have adjusted their behavior to the new transportation price and the available housing infrastructure (see GH07).

Variables and parameters corresponding to these periods will be characterized by a subscript i, f, or m. In the initial period, households and landowners make their decisions as if p_i should not change. We test different values of θ_i so as to evaluate the potential for anticipation through a tax in the initial period.

Hence,

(1) initial period is characterized by a CSEnt with transportation price p_i and a tax level θ_i;
(2) medium period is characterized by a CSExt with transportation price p_f, a tax level $\theta_f = \theta^*$ and a housing structure inherited from the initial period: $H_m(r) = H_i(r)$.
(3) final period is characterized by a CSEnt with transportation price p_f and a tax level $\theta_f = \theta^*$;

3.2 Effects on landowners

Section 2.2.2 established that, in the initial period, landowners' income unambiguously gets larger as θ_i increases. In the medium run, however, a larger θ_i has two effects on ALI_m:

(i) initial investment is higher, which decreases ALI_m;
(ii) housing is more and more concentrated towards the CBD (see Eq. (17)), where people devote less money to commuting, and more to housing. As a consequence, the aggregate housing rent is also larger in the medium run, which increases ALI_m.

What is the balance between those two effects? Figure 4 shows that ALI_m decreases with respect to θ_i when $\theta_i < 0.2$; above this value, a larger θ_i induces a higher ALI_m. Thus, there is a worst value of initial tax level for landowners during the medium period. In that case, ALI_m is 21% lower than ALI_f. Beyond this worst value, a larger θ_i induces higher aggregate income in both the initial and the medium periods.

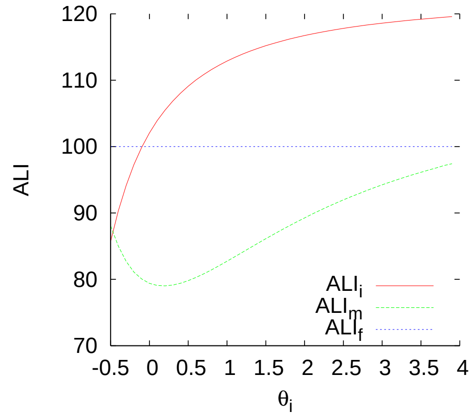

Fig. 4. For a doubling of transportation price, impact of θ_i on ALI (index $ALI_f = 100$).

3.3 Effects on households

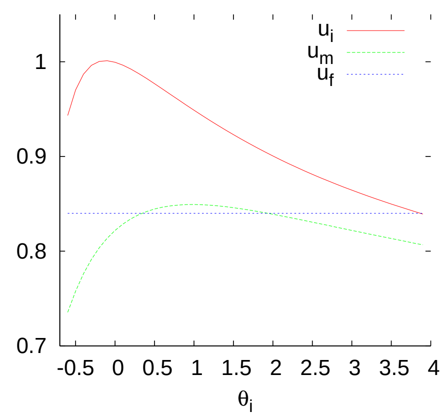

Fig. 5. For a doubling of transportation price, the impact of tax levels θ_i on utility levels u_i, u_m and u_f (index $u_i = 1$ for $\theta_i = \theta^*$).

In the medium run, Fig. 5 shows that, for $\theta_i < 1$, consumers benefit from a larger θ_i. Beyond this value, they lose from it. When the taxation level in the initial period increases beyond this threshold, consumers utility decreases both in the initial and in the medium period. Thus, the situation of households is the opposite to that of landowners.

3.4 Vulnerable and robust cities

Previous results suggest that cities' vulnerability is not a concept that can be handled without distinguishing between several categories of agents. For instance, for a shock corresponding to a doubling of transportation prices, Tab. 2 shows the diverging interests of landowners and households:

results are in %	$\theta_i = \theta^* < 0$	$\theta_i = 1$	$\theta_i = 2$
$\frac{ALI_m - ALI_f}{ALI_f}$ (Landowners)	-20	-17.2	-10.8
$\frac{u_m - u_f}{u_f}$ (Households)	-3.4	$+1.1$	0

Table 2
For a doubling of transportation price, the situation of agents in the medium run, relative to the final situation, for various levels of θ_i.

A city with an initial subsidy to commuting ($\theta_i = \theta^*$) is very vulnerable over the medium run to a transportation price shock: households support a -3.4% utility loss compared to the final period, while landowners suffer from a -20% decrease in their income compared to the final period. Those losses would be reduced in a city where preexisting taxation levels are higher: for $\theta_i = 1$, landowners' aggregate loss is reduced to -17.2%, while households are actually better off during the transition than at the final stage. An even higher θ_i would be preferred by landowners, but is detrimental to households.

Thus, if a government decides to send a signal price to economic actors so as to anticipate the possibility of a future shock in transportation prices, our results indicate that there are positive tax levels that lead to less vulnerable cities.

Choosing θ_i, therefore, influences the urban form (spread-out vs. compact) in a crucial manner. A lock-in effect is likely to happen with low transportation costs and no taxation. Once the city has gone through an urban sprawl process, turning back to a more compact urbanism is a long and costly transition. Moreover, the larger the inertia of housing capital, the most important for welfare is the medium period, since initial tax level θ_i shapes then the urban forms for a longer period of time.

4 Normative aspects

The normative evaluation shall take into account not only the medium run period following the shock, but also the effects of θ_i on the initial, pre-shock, period. Furthermore, actors that are to be taken into account in these criteria may also differ according to local institutions.

4.1 Robust vs. vulnerable strategies

In view of Sections 3.2 and 3.3, the determination of a socially optimal tax θ_i proves difficult:

(i) For a same actor (a household, or a landowner), changing θ_i may have opposite effects in the initial period and in the medium period.
(ii) In a given period, changing θ_i may have opposite effects on two categories of actors.

Furthermore, the uncertainty in future transportation costs, and the subsequent impossibility of perfect foresight, makes this situation even more complex. Lempert et al. (2004), for example, claim that the deep uncertainties surrounding climate change issues should lead decision-makers to choose strategies with the most acceptable vulnerabilities. Here, we have to assume that the government does not know several decades in advance the magnitude of the shock(s) that it will have to face. In such a situation, it may be more useful not to look for an optimal tax, but rather to characterize the situations in which a given tax level θ_i has a positive impact on the welfare criterion, compared with the "do-nothing" strategy $\theta_i = 0$. To do so, we will assess, for each shock amplitude, which tax levels are beneficial or detrimental.

In what follows, we present a utilitarian and a Rawlsian criterion, which, as we will see, lead to different recommendations for policy action.

The utilitarian criterion

If only consumers utility is accounted for, the utilitarian government's welfare criterion is represented by:

$$W_C^U = \lambda u_i + (1 - \lambda) u_m$$

where λ and $(1 - \lambda)$ are the relative weights the government places on the situations in period i and m. The actual value of λ depends on the time at which the shock will occur and on the preference for the present. In the following, we assume that the time of the shock is known (*i.e.* λ is known), while its magnitude is uncertain. Adding uncertainty on time is possible within our framework, but it does not change the qualitative results of our study.

If the government takes into account not only the well-being of households, but also the wealth of landowners, the optimality criterion is modified accordingly, taking into account SGW as defined in Eq. (12). The government maximizes then an Intertemporal Global Welfare (IGW) over the initial and the medium period:

$$W_{CL}^U = IGW = \lambda SGW(u_i, p_i) + (1 - \lambda) SGW(u_m, p_m)$$

Let us set $\mu = p_f / p_i$ as the magnitude of the shock. Figure 6 shows, for the utilitarian criterion and for each shock μ, the tax levels θ_i that have beneficial consequences compared with no pre-existing taxation. Two cases are studied,

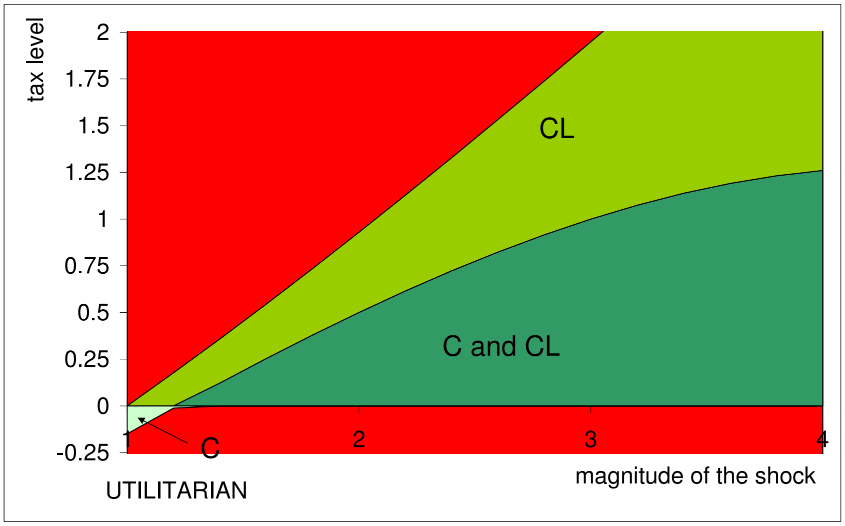

Fig. 6. Impact of θ_i for a utilitarian government ($\lambda = 1/2$): green areas correspond to the couples (θ_i,μ) that ensure a better outcome than (0,μ) for W_C^U (C) and W_{CL}^U (CL) respectively. In red areas, both criteria perform worse than $\theta_i = 0$.

depending on the weight that is attributed to landowners' income. It appears that a subsidy to commuting is never beneficial for W_{CL}^U, and is beneficial for W_C^U only for low values of μ: this property emphasizes that very spread-out cities are particularly vulnerable to transportation shocks.

If a value $\theta_i > 0$ is beneficial for W_C^U, then it is also beneficial for W_{CL}^U, but the opposite is not true. Two reasons explain this asymmetry: first, low initial (positive) values of θ_i profit to consumers in both periods, while they induce gains for landowners in the initial period that are sufficient to compensate for their losses in the medium run. Second, high values of θ_i induce smaller utility levels for consumers, but larger landowners' income in both initial and medium periods (see Figs. 4 and 5 for example, which illustrate the case $\mu = 2$).

The rawlsian criterion

This criterion is an intertemporal maximin: the government's behavior is described either by:

$$W_C^R = \mathsf{max}_{\theta_i}\Big(\,\mathsf{min}[u_i, u_m]\Big)$$

if only consumers are taken into account, or by

$$W_{CL}^R = \mathsf{max}_{\theta_i}\Big(\,\mathsf{min}[SGW_i, SGW_m]\Big)$$

if landowners' income is also taken into account.

Corresponding results are presented in Fig. 7. As in the utilitarian case, the choice of θ_i is more restricted for W_C than for W_{CL}. Also, compared to the

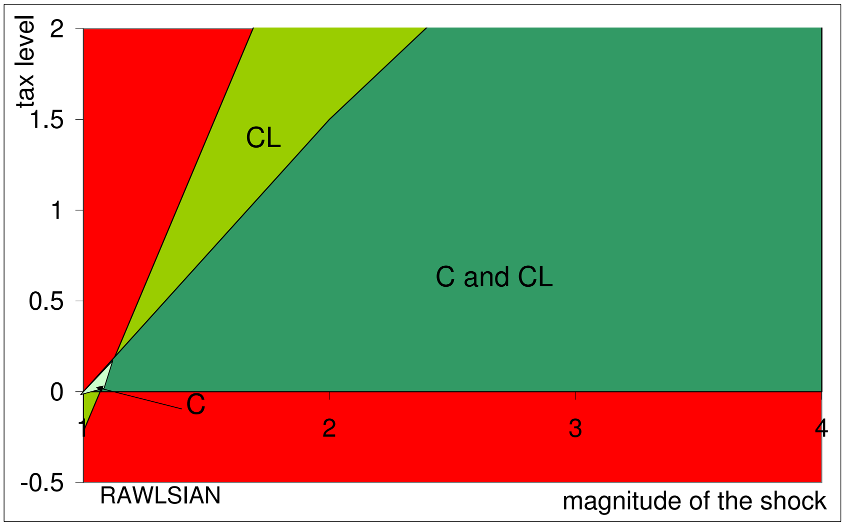

Fig. 7. Impact of θ_i for a utilitarian government ($\lambda = 1/2$): green areas correspond to the couples (θ_i,μ) that ensure a better outcome than (0,μ) for W_C^R (C), and for W_{CL}^R (CL) respectively. In red areas, both criteria perform worse than $\theta_i = 0$.

utilitarian case, high tax levels are a more robust choice in this Rawlsian case. This is so because an intertemporal maximin takes into account only the medium period, where consumers utility is always lower than in the initial period, at least fot the values of θ_i and μ that we explored.

Following the Lempert's methodology, therefore, we showed, for each possible future transportation price, the first-period tax levels that are beneficial, for two possible criteria. We claim that, based on these results, decision-makers can implement informed policies, as a function of their beliefs on future changes and of political parameters and value judgments.

4.2 The implementation of a transportation tax

Our results have pragmatic policy implications: it is possible to make a city more robust with respect to future possible changes in transportation prices. Taxing in advance transportation sends to consumers and landowners an appropriate signal-price. In particular, cities that are being built now (as is the case in developing countries where demography is increasing at a tremendous pace) should take into account the possibility of future price increases. They should thus build housing infrastructures that are more robust to the possibility of an increase in energy prices. Implementing an appropriate tax is a way to do so.

In cities where housing is already adapted to low energy prices, such as northern American cities, however, reaching a less vulnerable equilibrium shall be done with caution: implementing abruptly a new transportation tax is also a shock that can be detrimental. Nevertheless, a shock due to a tax is different from a shock due to an increase in energy prices, since the tax product is lump-sum redistributed to consumers. Thus, they pay higher transportation prices, but the tax product is added to their income [9] . As shown in Fig. 8, this difference influences significantly the consequences of the shock.

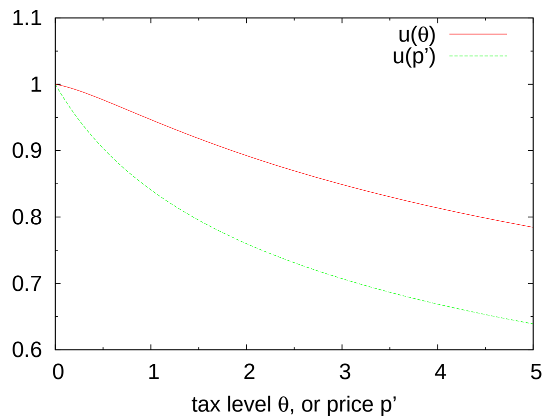

Fig. 8. Impact of a tax θ vs. a price $p' = p(1+\theta)$ on utility u (index $u = 1$ for $\theta = 0$).

Nevertheless, we show in this section that a tax implementation induces a transition period that also calls for anticipation. In a new numerical experiment, the transportation price p is constant while the tax level is the only changing variable. Again, we consider three periods: the *initial* period when the tax level is $\theta_i = \theta^*$; the *medium* period where the chosen tax level θ_f has already been set, but housing infrastructure is not adapted yet $(H_m(r) = H_i(r))$; and a *final* period, where the tax level is θ_f, and where housing infrastructure is adapted to this new signal-price.

Households: starting from a CSEnt where $\theta_i = \theta^*$, households cannot gain from a change in tax levels as long as transportation price p stays at the same level. Figure 9 shows that this deterioration of their situation can be deepened during the medium period. Since the tax product is lump-sum redistributed, however, the consequences of a shock remain limited. [10]

Landowners: setting a transportation tax creates a market distortion, which leads households to choose locations where they have to commute less, but pay higher rents. Rents close to the CBD increase, and they decrease far from the CBD. In the long run, this mechanism increases aggregate housing rents,

[9] Figure 8 shows for instance that a doubling of the price through a tax $\theta = p$ induces a 10% loss of utility, while a transportation cost $p' = 2p$ induces a 16% loss.
[10] For instance, for $\theta_f = 1$, households are better off during the transition. For $\theta_f = 2$, the amplification of consumers utility losses during the transition is 3.7%.

and aggregate housing capital stock. Thus, two effects impact ALI_m compared to ALI_f: on the one hand, there is under-investment in the medium period, while rents have already increased. This should push ALI_m above ALI_f. On the other hand, the investments performed to adapt housing in the final period lead to higher aggregate rents, which pushes ALI_f above ALI_m. Both effects increase with respect to the taxation level θ_f. The right side of Fig. 9 shows that the first effect is the strongest for high θ_f. However, these effects of the transition on landowners remain limited in amplitude. [11]

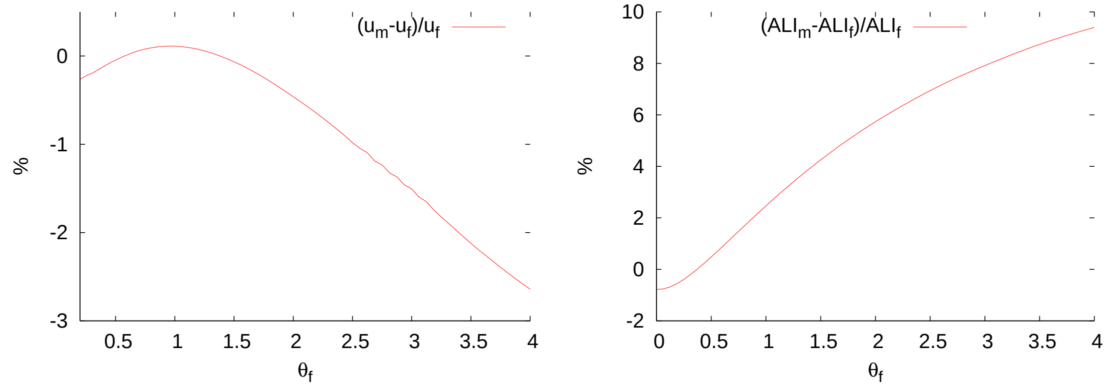

Fig. 9. Impact of tax levels θ_f on - Left: utility levels u_m and u_f. -Right: ALI_m compared to ALI_f.

Our theoretical framework is not complex enough to treat the question of the optimal path of the signal price. A follow-up paper using a continuous-time model will cope with this question. Our results suggest, however, that the implementation of a new tax level induces a transition that has contrasted effects for households and landowners, even though these impacts remain limited compared with the effects of a shock in transportation costs.

5 Conclusion

Even though the controversy on compact vs. spread-out cities is far from being closed, policy makers in most European countries have decided to adopt a strong attitude on the subject, and to mitigate urban sprawl. This paper adds an argument in favor of this decision. We do not pretend to give the exact picture of the consequences of a transportation shock, but we have explored the orders of magnitude at stake. Our results suggest that cities made more compact by a transportation tax are significantly more robust than others to a shock in transportation price, in spite of the negative effect of the tax before the shock.

[11] For instance, for $\theta_f = 1$, transition gains are only 2.5% higher in the medium run than in the medium run. For $\theta_f = 2$, the difference is 6%.

The reasons for this property are that (1) a tax can be introduced progressively and its implementation can be managed, while an energy price shock cannot be controlled; (2) a shock created by the introduction of a tax is mitigated by the redistribution of the tax product while a shock on the transportation price (or speed) is only detrimental. Moreover, the lump-sum redistribution assumed in our model could, in a more realist framework, be sophisticated to take into account the pre-existing tax structure. Alleviating labor charges, for instance, could produce a so-called "double-dividend", in addition to the benefits described in this paper.

In our framework, for a doubling of the transportation costs, in a city with a high pre-existing tax level ($\theta_i = 1$), households' utility is +1.1% higher in the medium run compared to the final utility with optimal taxation, and landowners' income is decreased by −17.2%. With a lower pre-existing taxation level ($\theta_i = \theta^*$), those figures are respectively −3.4% and −20%. The importance of early taxation is even larger if housing capital is considered as fixed once it is built: low initial transportation costs determine a highly spread-out city, locked in an under-optimal situation if transportation price increases. This argument is critical in developing countries where cities experience (or will experience) a rapid growth. Those cities are, to a certain extent, still to be built, and future changes due to mitigation policies or resource constraints should be taken into account as soon as possible.

In industrialized countries, raising tax levels in vulnerable cities may be a serious problem. The reason is that housing infrastructure already exists, and represents huge investments. This factor may help understand why US government is reluctant to implement a climate policy that would lead to non negligible negative welfare effects in American particularly spread-out cities during the transition towards a more robust equilibrium. Meanwhile, it is also reasonable to think that housing inertia should not lead to inaction, but rather to early commitments and progressive action. A well conceived transportation system may be considered as an insurance against numerous risks, from energy security to climate mitigation needs.

The modelling framework we used in this paper presents several important limitations, that were already presented in GH07 (*e.g.* the absence of general equilibrium feedback mechanisms, or the assumption that the city has one unique CBD). In spite of these limitations, however, our results show significant stylised facts, which should be accounted for in more exhaustive frameworks. Follow-up papers will progressively answer to several limitations, in particular to focus on macroeconomic feedbacks and on a more realistic description of the dynamics of moves, housing investments, and rent levels.

In a more general framework, two main insights for future research can be drawn from our results. First, the use of taxation policies as a tool to anticipate uncertain future changes in presence of transition costs; in this regard, the timing of the tax implementation is an important aspect of taxation policies. Second, this paper also encourages governments to take into account future environment constraints in all domains of public policy, for instance by linking urbanism, land-use, transportation and climate policies. This view calls, therefore, for a “mainstreaming” of environmental concerns in public policy.

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6 Appendix

6.1 *Relationships in a CSEnt*

6.1.1 *Characteristics of the Urban System*

Setting $\gamma = \frac{1}{a\beta} - 1$ and $B = (Ab)^{1/a}(\alpha^\alpha\beta^\beta)^{1/a\beta}\frac{a}{b\rho^{b/a}}$, the solutions of the equilibrium problem satisfy:

$$\begin{aligned} s(r,u) &= \tfrac{u^{\gamma+1}}{B(\gamma+1)}[Y - pr]^{-\gamma} \\ r_f(u) &= Y/p \end{aligned} \qquad (13)$$

Concerning the housing service rent:

$$R_H(r,u) = \Big(\alpha^\alpha\beta^\beta\frac{Y - p(1+\theta)r}{u}\Big)^{1/\beta}$$

From this we get:

$$R_H(r,u) = Wp^{a(\gamma+3)}\Big([V(\theta)\frac{Y_a}{p} - r]\Big)^{1/\beta}\Big((1+\theta)[Y_aV(\theta)]^{-(\gamma+2)}\Big)^a$$

where $V(\theta) = \frac{\gamma+3}{(\gamma+3)+\theta(\gamma+1)}$, and $W = (\alpha^\alpha\beta^\beta)^{1/\beta}(\frac{N(\gamma+2}{lB})^a$.

6.1.2 *Utility level*

Let us first assume that there is no transportation tax set by the government. In this case, Eq. (6) on the city population implies:

$$N = \int_0^{r_f}\frac{L(r)}{s(r,u)}dr = \int_0^{r_f} lrB(\gamma+1)[Y - pr]^\gamma u^{-(\gamma+1)}dr$$

This equation gives us the relation:

$$\frac{p^2N}{lB} = -Y\frac{R_A}{B} + u\Big(\frac{R_A}{B}\Big)^{\frac{\gamma+1}{\gamma+2}}\frac{\gamma+1}{\gamma+2} + u^{-(\gamma+1)}\frac{Y^{\gamma+2}}{\gamma+2} \qquad (14)$$

Right Hand Side of relation (14) is strictly decreasing with u as soon as u is such that r_f can be positive. The interpretation of the decrease of RHS of (14) with u is that, *ceteris paribus*, an increase in u implies that N shall decrease, i.e. some people shall leave the city.

6.1.3 *Tax product*

We consider now that a tax $p\theta$ per km of commuting is levied throughout the city, thus $T(r) = p(1+\theta)r$. Thus, (13) implies:

$$\begin{aligned} \pi(u) &= p\theta \int_0^{r_f} n(r,u)r\,dr = \tfrac{p\theta lB(\gamma+1)}{u^{\gamma+1}} \int_0^{r_f} r^2[Y + \pi/N - p(1+\theta)r]^\gamma\,dr \\ r_f(\pi,u) &= \tfrac{1}{p(1+\theta)}[Y + \pi/N - (\tfrac{R_A}{B})^{\frac{1}{\gamma+1}}u] \end{aligned} \tag{15}$$

In addition, (14) can be rewritten:

$$\tfrac{N}{lB}p^2(1+\theta)^2 = -\tfrac{R_A}{B}(Y+\pi/N) + \tfrac{\gamma+1}{\gamma+2}(\tfrac{R_A}{B})^{\frac{\gamma+2}{\gamma+1}}u + \tfrac{u^{-(\gamma+1)}}{\gamma+2}(Y+\pi/N)^{-(\gamma+1)}$$

Let us assume for simplicity's sake that $R_A = 0$. Then the previous analysis gives :

$$\begin{aligned} \pi(u) &= \tfrac{2p\theta lB}{p^3(1+\theta)^3u^{\gamma+1}}\tfrac{(Y+\pi/N)^{\gamma+3}}{(\gamma+2)(\gamma+3)} \\ \tfrac{p^2(1+\theta)^2N}{lB} &= u^{-(\gamma+1)}\tfrac{(Y+\pi/N)^{\gamma+2}}{\gamma+2} \end{aligned}$$

From these relationships, we derive:

$$\frac{\pi}{N} = \frac{2\theta Y}{(\gamma+3) + \theta(\gamma+1)} \tag{16}$$

6.1.4 *Housing structure*

The construction throughout the city is given by the function:

$H(r) = n(r,\theta)q(r,\theta) = lrF(1, k(r,\theta)/s(r,\theta))$.

Using (13), we have then:

$$H(r) = A'lr\Big(b\beta(\gamma+1)(\gamma+2)\frac{N}{l}(1+\theta)(\frac{Y(\gamma+3)}{(\gamma+3)+\theta(\gamma+1)})^{-(\gamma+2)}(\frac{Y(\gamma+3)}{p(\gamma+3)+p\theta(\gamma+1)} - r)^{\gamma+1}\Big)^b$$

where A' is a constant depending on the parameters of the problem.

6.1.5 *Lump-sum redistribution of ALI*

In this section, we assume $R_a = 0$. If the product of the housing industry is to be lump-sum redistributed to the city inhabitants, then Eqs. (1) , (5) and

(14) determine ALI, π and u. As a result, these variables satisfy an extended version of Eq. (15):

$$\begin{aligned} \pi &= \frac{2p\theta lB}{p^3(1+\theta)^3 u^{\gamma+1}} \frac{(Y_a+\pi/N+ALI/N)^{\gamma+3}}{(\gamma+2)(\gamma+3)} \\ \frac{p^2(1+\theta)^2 N}{lB} &= u^{-(\gamma+1)} \frac{(Y_a+\pi/N+ALI/N)^{\gamma+2}}{\gamma+2} \\ ALI &= \frac{Bl}{u^{\gamma+1}} \frac{Y^{\gamma+3}}{p^2(1+\theta)^2(\gamma+2)(\gamma+3)} \end{aligned} \quad (18)$$

As a consequence:

$$\begin{aligned} \pi &= N\frac{2\theta}{1+\theta}\frac{Y}{\gamma+3} \\ ALI &= N\frac{Y}{\gamma+3} \end{aligned}$$

From these relationships, we get: $Y = \frac{(\gamma+3)(1+\theta)}{(\gamma+2)+\theta\gamma} Y_a$

Using this value of Y in Eq. (10), we get: $u^{\gamma+1}\frac{(\gamma+2)N}{lB} = \frac{Y_a^{\gamma+2}}{p^2}(1+\theta)^\gamma \left(\frac{\gamma+3}{(\gamma+2)+\theta\gamma}\right)^{\gamma+2}$, which is maximum for $\theta = 0$.

6.2 Relationships in the medium-term equilibrium, with exogenous housing structure

6.2.1 New households density

If the government sets a transportation tax $p\theta_m$ during second period, housing service consumption is now:

$$q(u_m, r) = u_m^{1/\beta}(\alpha[Y + \pi_m/N - p_m(1+\theta_m)r])^{-\alpha/\beta}$$

and as a consequence:

$$n_m(u_m, r) = H(r)/q(u_m, r).$$

In addition, we know that π_m and u_m must verify:

$$\begin{aligned} \pi_m &= p_m\theta_m \int_0^{r_{fm}} n_m(u_m, r) r dr \\ N &= \int_0^{r_{fm}} n_m(u_m, r) dr \end{aligned}$$

where $r_{fm} = \frac{Y+\pi_m/N}{p_m(1+\theta_m)}$.

In order to simplify our notations, we write:

$\frac{1}{q(u_m,r)} = J.(K-r)^k$, where J is a number depending on u_m and θ_m, while K depends on θ_m and π_m, and $k = \alpha/\beta$. One might notice that $K = r_{fm}$.

6.2.2 Existence and uniqueness of the medium-term equilibrium

In this section, we cope with the question of the existence and uniqueness of an equilibrium and the medium-term equilibrium. A CSExt, if it exists, can be characterized by two relationships:

$$\begin{aligned} \pi_m &= p\theta_m CJ \int_0^K (D-r)^d (K-r)^k r^2 dr \\ N &= CJ \int_0^K (D-r)^d (K-r)^k r dr \end{aligned} \tag{19}$$

where J is a number depending on u_m and $p\theta_m$; $K = \frac{Y+\pi_m/N}{p(1+\theta_m)}$; $k = \alpha/\beta$; we set C, D and d so as to reformulate (17): $H(r) = C(D-r)^d$. Studying a medium-term equilibrium is then equivalent to studying a solution to the system (19), where C, D, d and k are exogenous, while J and K verify:

$J = J' u_m^{-1/\beta}$, J' being exogenous,

$0 < K = \frac{Y+\pi_m/N}{p_m(1+\theta_m)} \leq D$

In addition, all those parameters and variables are positive.

We treat this problem as a system of two equations with two unknown variables, π_m/N and u_m. We set $x = \pi_m/N$, and consider the related equation (which is in fact the ratio of the terms of the first relationship and of the second relationship):

$$x \int_0^{K(x)} (D-r)^d (K(x)-r)^k r dr = p\theta_m \int_0^{K(x)} (D-r)^d (K(x)-r)^k r^2 dr \tag{20}$$

One might note that if there is a couple (x^*, u_m^*) verifying Eq. (19), then clearly x^* must satisfy Eq. (20). Conversely, suppose there is a x^* verifying Eq. (20), then setting $u_m^* = (\frac{p\theta_m}{Nx^*} CJ' \int_0^{K^*} (D-r)^d (K^*-r)^k r^2 dr)^\beta$, one can see that (x^*, u_m^*) satisfies Eq. (19).

Thus, both existence and uniqueness of a solution to Eq. (19) are equivalent to existence and uniqueness of a solution to Eq. (20). Both sides of this relationship are continuous with respect to x. Assume for instance that $\theta_m > 0$. Then, for $x = 0$, Left Hand Side is worth 0 while Right Hand Side is strictly positive. Thus, the difference between those two sides is strictly negative. For $x = \theta_m Y$, then the difference between those two expressions is:

$$\theta_m \int_0^{K(x)} (D - r)^d (K(x) - r)^k r(Y - pr)dr \tag{21}$$

which is strictly positive. If θ_m is negative, the same conclusion applies.

Thus, there is at least one x for which Eq. (20) holds, and the existence of an equilibrium during the medium-run is proved. Furthermore, for $\theta_m > 0$ (resp. < 0), he expression in Eq. (21) is strictly increasing (resp.decreasing) with x. This proves the uniqueness of the solution to Eq. (20).

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