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ARE NIMBY'S COMMUTERS?

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Are NIMBY's commuters?

Bert Saveyn

Abstract

This paper considers a metropolitan area where residents can commute between several jurisdictions. These residents show NIMBY behavior (Not-In-My-Backyard). They try to preserve their living quality by pushing the polluting economic activity to the neighboring jurisdictions and keep their labor income as commuters. This induces a race-to-the-top among jurisdictions. Fiercer competition due to a higher number of jurisdictions intensifies this race-to-the-top; whereas commuting costs, pollution taxes, payroll taxes and bigger jurisdictions increase the incentive for more pollution.

Keywords: Commuting, NIMBY, interjurisdictional competition, environmental federalism

JEL-classification: H, Q, R

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1. INTRODUCTION

We present a theoretical model that can be used to study the environmental policy of small jurisdictions. We highlight the application of the model to the occurrence of NIMBY's (not-in-my-backyard behavior) in (sub-) metropolitan jurisdictions. NIMBY behavior is often observed in projects involving local pollution[1,2], such as the location of a waste incinerators, landfills, big industrial plants or airports, etc. We show that NIMBY behavior and a race-to-the-top among jurisdictions may originate from inter-jurisdictional commuting. Jurisdictions may set too stringent environmental regulations in a common labor market. As the residents of a jurisdiction can commute at a low cost, they do not fully depend on the local economic activity for their income. They will try to preserve their environmental quality in their home jurisdiction by pushing the polluting economic activity to the neighboring jurisdictions and keep their labor income as commuters. Moreover, this behavior is exacerbated when the rents of local pollution do not fully accrue to the residents, but leak (partially) to other jurisdictions. Jurisdictions may thus face a prisoners' dilemma, in which, they all push for too high local environmental quality (race-to-the-top). Further we show that local payroll taxes (i.e. source-based wage taxes), pollution taxes, positive commuting costs or bigger jurisdictions may increase the pollution level.

The race-to-the-top result of this paper is in strong contrast to the "business tax models"[3] where jurisdictions competing for capital in a world economy tend to allow for too much pollution if only a source-based capital tax is available (race-to-the-bottom). Jurisdictions fear that environmental gains will be more than offset by movement of capital to jurisdictions with lower standards. If each jurisdiction reasons the same way, all will adopt lower standards of environmental quality than they would prefer if they could cooperate in setting higher standards. The desire to coordinate policies motivates the centralized control in the US and EU over environmental policy.

A first theoretical exception to the race-to-the-bottom has been made by Oates and Schwab (1988). They show that decentralized regulation may be efficient when the distorting capital

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[1] Frey *et al.* (1996) define NIMBY projects as all undertakings that increase overall welfare (public good) but impose net costs on the individuals living in the host community (private bad).

[2] Local pollution includes e.g. noise, smell, local air pollution as root and dust, decrease of scenic value, etc.

[3] Among others, Oates and Schwab (1988), and more generally for local public goods, Wilson (1986) and Zodrow and Mieszkowski (1986)

taxes are set to zero and a residence-based lump-sum tax can be used. This result, however, hinges on the assumption that all pollution rents are distributed back to the residents of the jurisdiction. This rent distribution assumption parallels a perfect Pigouvian emissions tax and interferes with the command-and-control policy (Levinson, 1997). Second, Wellisch (1995) recognizes that pollution rents are in general not confined to jurisdictions, as they are captured by firms also owned by non-residents. The residents bear the entire burden of the pollution and gain few benefits. He concludes that decentralized command-and-control regulation leads to environmental overprotection. Kunce and Shogren (2005a) also allow for non-resident ownership of polluting firms. They state, however, that local governments, facing fiscal constraints (and no Pigouvian or first-best fiscal instruments are available), adopt capital tax structures that exacerbate inefficiencies of decentralized command-and-control, reducing the overprotection and possibly even leading to a race-to-the-bottom. In a third exception, Glazer (1999) presumes that the benefits gained from firms locating to a jurisdiction are sufficiently small and are over-whelmed by the additional environmental costs. His model for two identical jurisdictions shows that each jurisdiction tries to shift the environmental damage to the other jurisdiction. This happens even when residents of a single jurisdiction own all firms of that jurisdiction.

Empirical evidence for a race-to-the-bottom is weak at best, and some studies rather suggest a race-to-the-top. Fredriksson and Millimet (2002) find evidence of strategic environmental policy across U.S. states but are unable to conclude if the evidence supports a race-to-the-top or race-to-the-bottom. Fredriksson and Gaston (1999), examine the votes on environmental legislation in the U.S. in state legislatures as well as at the congressional level. They find no tendency for state politicians to vote against environmental measures. List and Gerking (2000) and Millimet (2003) analyze the decentralization of environmental policy under Reagan. List and Gerking (2000) conclude that a race-to-the-bottom in environmental quality did not materialize in the 1980’s. Moreover, Millimet (2003) finds strong evidence that decentralized environmental policy contributed to a race-to-the-top in abatement expenditures. Fredriksson *et al.* (2004), however, point out that the previous literature considers strategic interaction in a uni-dimensional framework. Jurisdictions may respond to a more lenient environmental policy of their neighbors not only by lowering their environmental standards, but also by lowering state-level taxation or increasing infrastructure spending. Their result suggests that important own- and cross-policy interactions exist. They conclude that the literature with uni-dimensional frameworks presents lower bound estimates of the degree of strategic interaction.

The previous theoretical papers focus on firm and capital mobility in the tradition of the business-tax models. NIMBY behavior and the environmental quality in residential areas and commuting belts, however, have received less attention. Fischel (2001a, 2001b) argues that greater decentralization may lead to a NIMBY reaction of homeowners. A home is the largest asset most people own and owners cannot insure against devaluation by neighborhood effects. As their assets would be devalued by pollution, local governments are cautious in admitting new industries and developments. Frey *et al.* (1996) analyze why compensation schemes dealing with NIMBY behavior, frequently fail. They state that traditional economic theory of compensation is incomplete because it neglects the influence of moral principles. In the political decision making such moral considerations weaken the effects of price incentives. Levinson (1999) studies state taxes on hazardous waste disposal. Hazardous waste disposal confers few benefits on local jurisdictions and has high perceived costs. States have an incentive to set waste tax levels too high. Further, Levinson shows empirically that state hazardous waste taxes matter. He concludes that devolved environmental policy is inefficient. Fredriksson (2000) develops a political economy model for the siting of hazardous waste disposal facilities in a federal system with many small jurisdictions. He concludes that the lower government levels in federations should get the authority over siting decisions. The centralized government faces a greater obstacle in the compensation effort, as each jurisdiction has an incentive to favor capacity in the other jurisdictions. Feinerman *et al.* (2004) develop a model where the government of a two-city economy determines the location of a noxious facility. The government is subject to political pressures by city-level lobbies of landowners. In the empirical section, they asses the prospects of the political system for resolving the NIMBY conflict for locating a landfill-site in a multiple-city region in Israel. Cavailhès *et al.* (2004) study the periurban belt around poles of economic activity. They explain that households value rural amenities and hence, may live close to farmers. These households commute to their jobs.

Our paper explains how the very nature of commuting may induce a race-to-the-top/ NIMBY behavior between small jurisdictions. So far, most NIMBY studies have focused on hazardous waste, landfills and other noxious installations. We believe that our paper is suitable for a wider range of local environmental problems. Methodologically, the model builds on the model of Braid (1996). In his analysis of tax competition in metropolitan areas, commuting takes the form of factor movement, i.e. jurisdictions compete for labor force. This approach differs from most commuting papers which focus on congestion or firm-worker matching on the labor market[4].

Our model has three main features. First, the model has three levels. We discuss a metropolitan area in a world economy, and this metropolitan area has a number of jurisdictions[5]. These jurisdictions have Nash interactions, using the local environmental quality as strategic variable. The metropolitan government is merely a referee, guaranteeing the legal order. Second, output is produced using labor and pollution. Jurisdictions produce a single good, which is sold on the world market for a normalized price of 1. We assume that pollution is local and does not cross the jurisdictional borders[6]. Third, the most important feature of the model is that Nash interactions occur in the common labor market. Residential locations are fixed[7], but the consumers who live in one jurisdiction can commute to work in any of the other jurisdictions. Thus each jurisdiction is able to influence the wage of the common labor market.

Section 2 develops a symmetric model. Section 3 gives the socially optimal outcome. In section 4 we find that the model without taxes leads to a race-to-the-top. Section 5 discusses the effect of lump-sum, payroll and pollution taxes on the environmental policy of jurisdictions. In section 6 we look to positive commuting costs and non-identical jurisdictions. We conclude in section 7.

2. MODEL

We consider a metropolitan area in a world economy with *n* identical jurisdictions (indexed by *i*). In each jurisdiction we find a single industry, comprised of fixed number of identical polluting firms[8]. Industry output is produced using mobile labor (N_i) and local pollution (P_i). N_i is the endogenous number of workers in jurisdiction *i*, each supplying one unit of labor; whereas N_0

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[4] Papers analyzing congestion or labor market in presence of commuting include, among others, Anas and Xu (1999), Zenou (2000), De Borger and Van Dender (2003), Borck and Wrede (2005) and de Palma and Proost (forthcoming).

[5] Jurisdictions are defined as counties, municipalities and districts in metropolitan areas.

[6] For more on transboundary pollution see, e.g. Baumol and Oates (1988) or Silva and Caplan (1997)

[7] This assumption is realistic in cases where transaction costs of moving are high due to the tax structure on the housing market, most European countries being examples.

[8] The number of firms in the jurisdictions is fixed and large. Kunce and Shogren (2005b) point out that a fixed number of firms correspond to a long-run equilibrium.

represents the fixed number of residents in each jurisdiction. The residents can not migrate to other jurisdictions. We treat pollution in a jurisdiction (P_i) as an input to local production. The pollution externalities hurt only the residents in the jurisdiction where they are created. Contrary to most of the inter-jurisdictional competition literature, this model concentrates on location choices of labor rather than on firm, capital or population mobility.

The total production of the identical firms in jurisdiction *i* is determined by the constant-returns-to-scale neo-classical production function $F(N_i, P_i)$, which is homogeneous of degree one. We assume that F_N, F_P and F_{NP} are positive[9], and that F_{NN} and F_{PP} are negative. This guarantees that a perfect competition solution exists.

3. SOCIAL OPTIMUM

Social optimum requires the maximization of the residents' utility in jurisdiction 1 (1)[10]. We assume that (1) is a strictly quasi-concave function, decreasing in aggregate emissions ($U_P<0$), and increasing in per-capita consumption per capita ($U_C>0$). This maximization problem is subject to 3 constraints. First, the utility of all other jurisdictions remains constant[11]. Second, the aggregate consumption equals the aggregate production (3). Third, total labor demand equals total available labor (4). The social optimum becomes[12]

$$\max_{N_1, C_1, P_1} U^1(C_1, P_1) \tag{1}$$

Subject to
$$U^2(C_2, P_2) = \overline{U}^2 \tag{2}$$

$$F(N_1, P_1) + (n-1)F(N_2, P_2) = N_0\left[C_1 + (n-1)C_2\right] \tag{3}$$

$$N_1 + (n-1)N_2 = nN_0 \tag{4}$$

We ignore the corner solutions (i.e. $N_1>0$ and $N_2>0$) and the following optimal conditions characterize a social optimum.

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9 A positive F_{NP} means that labor and pollution are complements. This is realistic with strongly aggregated inputs as in this model. For more properties of the production function F(N,P), see Appendix A.

10 The representative jurisdiction is denoted as jurisdiction 1; the other jurisdictions are represented by jurisdiction 2.

11 Wellisch (1995) and Kunce and Shogren (2005a,b) use a similar approach for the social optimum. We implicitly assume perfect redistribution possibilities across jurisdictions. Under this condition, it is sufficient to maximize utility of jurisdiction 1 keeping the utilities of the other jurisdictions constant.

12 For more detail see Appendix B

$$-N_0 \frac{U_P^i}{U_C^i} = F_P^i \qquad \forall \text{i=1,2} \tag{5}$$

$$F_N^1 = F_N^2 \tag{6}$$

Equation (5) says that the each jurisdiction chooses the consumption and pollution level such that the marginal rate of substitution between the two, summed over all jurisdictional residents equals the marginal product of environment (F_P). This corresponds to the Samuelson Rule for optimal pollution, where the left-hand side of the equation equals the marginal willingness to pay for the environment. If it did not hold in some jurisdiction, then it would be possible to change the pollution level in that jurisdiction so as to increase welfare. Equation (6) shows that the marginal product of labor is equal across jurisdictions. If this did not hold, it would be possible to increase welfare by commuters moving from a jurisdiction where the marginal product of labor is low to a jurisdiction where it is high.

4. NASH EQUILIBRIUM WITHOUT TAXES

We are interested in a symmetric Nash equilibrium[13] with the local pollution level as the strategic variable. Following the command-and-control strategy of Oates and Schwab (1988) and Kunce and Shogren (2005a,b), each jurisdiction sets the aggregate local pollution level, P_i. In order to derive the equilibrium, it is sufficient to consider the environmental policy of a representative jurisdiction, denoted as jurisdiction 1, subject to the exogenous environmental policy of the other n-1 identical jurisdictions, denoted as jurisdiction 2. The location choice of labor in the jurisdictions is endogenous.

Jurisdiction 1 chooses P_1 to maximize the utility of a representative resident (7) subject to its budget constraint (8) and taking P_2 as given. The consumption of all residents in jurisdiction 1 consists of the wage (w) and their share in the pollution rents of the metropolitan area (R_i). We assume that the residents of all jurisdictions own an equal share of all firms. Hence, the

[13] The Nash equilibrium is the standard equilibrium concept in fiscal competition. Its existence and uniqueness is among the most persisting problems in fiscal federalism. Most authors merely assume the existence of the equilibrium. The few authors dealing with the existence problem have encountered very demanding assumptions (e.g. Bucovetsky, 1991; Laussel and Le Breton, 1998). Bayindir-Upmann and Ziad (2005), however, relax the demanding assumptions of the Nash equilibrium, using the concept of 2nd-order locally consistent equilibrium (2-LCE) for the Zodrow and Mieskowski fiscal competition model. The 2-LCE concept ensures that a set of local maxima is reached in equilibrium. No jurisdiction faces an incentive to deviate unilaterally from its equilibrium strategy by some small readjustment of its strategy variable. Whether these relaxed assumptions also apply for this model is a topic for future research.

pollution rents generated in the metropolitan area are distributed equally across all residents of all jurisdictions. In this stage we have not yet incorporated the local non-environmental public goods provided by the local government. We introduce them in section 5.

$$\max_{P_1} U(C_1, P_1) \tag{7}$$

Such that
$$N_0 C_1 = N_0 w + \frac{R_1 + (n-1)R_2}{n} \tag{8}$$

The basic equilibrium conditions determine w, N_i and R_i as function of P_i[14]

$$N_1 + (n-1)N_2 = nN_0 \tag{4}$$

$$w = F_N(N_i, P_i) \tag{9}$$

$$R_i = F_P(N_i, P_i) \bullet P_i \geq 0 \tag{10}$$

The total number of residents in each jurisdiction is fixed (4). Workers can commute between jurisdictions at zero cost[15]. This assures that the same endogenous net wage rate, w, prevails across all jurisdictions (9). The firms use environmental resources for production at zero cost and, hence, pollution generates pollution rents[16], R_i (10). As labor can commute freely the equilibrium need to observe (4) and (9). The comparative-static derivative of labor in a jurisdiction (9) w.r.t. local pollution level and evaluated at the symmetric equilibrium gives the following result[17]

LEMMA 1: In a symmetric Nash equilibrium (N_e,P_e), the equilibrium quantity of labor in a jurisdiction is related to the local pollution level as follows

$$\frac{\partial N_1}{\partial P_1} = -\frac{n-1}{n}\frac{F_{NP}}{F_{NN}} \tag{11}$$

Equation (11) states that an increase of the local pollution level attracts more labor to jurisdiction 1. Obviously, eq. (11) becomes zero for a unique jurisdiction (n=1). For an infinitely

[14] The non-index subscripts denote partial derivatives.
[15] For the sake of simplicity, we assume costless commuting. We relax this in section 6.
[16] From the linear homogeneity of production
[17] For more details see Appendix C.

high number of jurisdictions ($n \rightarrow +\infty$), it converges to $-F_{NP}/F_{NN}$, the marginal rate of substitution of pollution for labor.

We illustrate the inefficiencies arising with decentralized decision-making. In a symmetric equilibrium all endogenous variables are identical for all n jurisdictions[18]. The symmetric Nash-equilibrium values of the pollution levels for jurisdictions are[19]

PROPOSITION 1: In a symmetric Nash equilibrium (N_e,P_e), a jurisdiction, chooses a pollution level, P_e, such that

$$-N_0 \frac{U_P}{U_C} = \frac{F_P}{n} \tag{12}$$

Equation (12) shows that the decentralized environmental policy differs from the social environmental efficiency (5). In the symmetric Nash equilibrium, every jurisdiction reduces marginal environmental damage to a too low level. It considers only 1/n of the marginal product of pollution, instead of the full marginal product. The full benefits of pollution do not accrue to the residents due to two leakages. First, as firms are not fully locally owned, pollution rents leak to the other jurisdictions. Second, and more interestingly, wages leak to other jurisdictions too due to commuting. Stated differently, jurisdictions are not fully dependent on the economic activity within their borders. The residents of jurisdictions benefit little from local pollution, but they carry the full burden of the local pollution. The jurisdictions have incentives to set too restrictive pollution standards.

Number of jurisdictions

The degree of competition among jurisdictions depends on the number of jurisdictions, *n*, in the metropolitan area. A higher number of jurisdictions induce more competition. In order to make our point clear, we look at two extreme cases, a single-jurisdiction metropolitan area (n=1) and a metropolitan area with an infinite high number of jurisdictions ($n \rightarrow +\infty$).

COROLLARY 1: A single-jurisdiction metropolitan area, chooses an optimal pollution level, P_e, such that,

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[18] In the symmetric equilibrium (N_e, P_e) we find that $N_0=N_1=N_2=N_e$, $R_1=R_2=R_e$ and $P_1=P_2=P_e$

[19] Appendix D gives more details

$$-N_0 \frac{U_P}{U_C} = F_P \tag{13}$$

And, in a symmetric Nash equilibrium (N_e,P_e), a jurisdiction in a metropolitan area with an infinite number of jurisdictions, chooses a pollution level P_e, such that

$$-N_0 \frac{U_P}{U_C} \to 0 \tag{14}$$

In a single-jurisdiction metropolitan area there is no commuting and the firms are fully locally owned. Hence, there are no leakages and the local government chooses the socially efficient level of pollution (13). With an infinite number of jurisdictions, a single jurisdiction is a price-taker on the common labor market. It does not have any market power and its environmental policy does not influence the common net wage. Moreover, the pollution rents are dissipated across all jurisdictions. Hence, the leakages reduce the benefits of local pollution to zero, whereas the residents of the jurisdiction still carry the full burden of local pollution. The local government behaves like an extreme NIMBY and it sets the pollution level at zero (14).

5. NASH EQUILIBRIUM WITH TAXES

We discuss the effect of taxes on the environmental policy of jurisdictions. We look, successively, at three types of taxes, a resident-based income tax (a_i), a source-based pay-roll tax (b_i) and a pollution tax (t_i). We assume, for the sake of simplicity, that the tax revenues are distributed in a lump-sum way to the jurisdiction's residents. Implicitly, this presumes that non-environmental public goods are provided efficiently (i.e. the marginal rate of substitution between public and private consumption is 1). In the symmetric equilibrium, the tax rates are equal across the jurisdictions, a_1=a_2=a_0, b_1=b_2=b_0, t_1=t_2=t_0.

Income Tax

The residence-based income tax, a_i, is equivalent to a lump-sum tax since residents do not migrate and labor-leisure choice is ignored in this paper. There is no way to avoid this labor income tax. This tax does not change the basic equilibrium conditions (4), (9) and (10), and the total income of all residents in jurisdiction 1 is identical to eq. (8). The analysis get the same results as for the symmetric model without taxes (12). Again, a single-jurisdiction metropolitan area provides the socially efficient level of pollution (13), whereas with an infinite number of jurisdictions there is no pollution admitted (14).

Pay-roll Tax

The source-based pay-roll tax, b_i, is distorting as the pay-roll tax can be avoided through commuting. Basic equilibrium condition (9), determining the wage level, changes into

$$w = (1 - b_i) F_N (N_i, P_i) \tag{15}$$

Now, the consumption of all residents in jurisdiction 1 consists of the net wage of these residents, their share in the pollution rents of the metropolitan area and the local payroll tax revenues.

$$N_0 C_1 = N_0 w + \frac{R_1 + (n-1) R_2}{n} + b_1 F_N N_1 \tag{16}$$

Jurisdiction 1 chooses P_1 and b_1 to maximize the utility of a representative resident (7) subject to its budget constraint (16) and taking P_2 and b_2 as given. The first-order conditions for the jurisdiction's problem are[20]

$$-N_0 \frac{U_P}{U_C} = \frac{F_P}{n} - \frac{\text{n-1}}{\text{n}} b_1 \frac{F_N F_{NP}}{F_{NN}} \tag{17}$$

$$b_1 = -\frac{F_{NN}}{F_N} N_0 \tag{18}$$

Combining (17) and (18), results in

PROPOSITION 2: In a symmetric Nash equilibrium (N_e,P_e), a jurisdiction, using a payroll tax, chooses a pollution level, P_e, such that

$$-N_0 \frac{U_P}{U_C} = \frac{F_P}{n} + \frac{\text{n-1}}{\text{n}} F_{NP} N_0 \tag{19}$$

Equation (19) shows that the payroll tax reduces the race-to-the-top. Moreover, with $N_0 F_{NP} > F_P$, the pollution level is higher than the social efficiency. The payroll tax alleviates the leakage of wage income through commuting, as all workers (incl. commuters) contribute to the budget of the jurisdiction where the firm is located. The leakage of pollution rents, however, persists. The payroll tax gives an incentive to increase the pollution level. The local government sets less restrictive pollution standards than with a lump-sum tax, but this may still be lower than the optimal level.

COROLLARY 2: A single-jurisdiction metropolitan area, using a pay-roll tax, chooses pollution levels, P_e, such that,

$$-N_0 \frac{U_P}{U_C} = F_P \tag{20}$$

And, in a symmetric Nash equilibrium (N_e,P_e), a jurisdiction in a metropolitan area with an infinite number of jurisdictions, using a payroll tax, chooses pollution level P_e, such that

$$-N_0 \frac{U_P}{U_C} \to F_{NP} N_0 \tag{21}$$

A single-jurisdiction metropolitan area provides the socially efficient level of pollution (20). With an infinite number of jurisdictions, the government sets the pollution level higher than zero (21).

Pollution Tax

The pollution tax is an alternative instrument to the pollution standard. The local governments specify a tax that firms pay for pollution. The first best optimal tax for pollution becomes

$$F_P = t_i \tag{22}$$

Firms consider the pollution tax, t_i, as a parameter and pollute to the point where the marginal product of pollution equals the pollution tax. Basic equilibrium condition (10), determining the rent, changes into

$$R_i = F_P P_i - t_i P_i \tag{23}$$

The local government returns the pollution tax revenues to its residents in a lump-sum way. The income constraint for the residents becomes

$$N_0 C_1 = N_0 w + \frac{R_1 + (n-1) R_2}{n} + t_1 P_1 \tag{24}$$

[20] Appendix E gives more details

This income consists of the net wage of these residents, the pollution tax revenues and their share in the pollution rents of the metropolitan area. These pollution rents, however, are zero as every jurisdiction taxes them away. Jurisdiction 1 chooses t_1 to maximize the utility of a representative resident (7) subject to its budget constraint (24). The pollution level, P_i, is not exogenously set, it is determined indirectly through the jurisdiction's choice of t_i. The symmetric values of the pollution levels for jurisdictions are [21]

PROPOSITION 3: In a symmetric Nash equilibrium (N_e,P_e), a jurisdiction, using a pollution tax, chooses a pollution level, P_e, such that

$$-N_0 \frac{U_P}{U_C} = F_P \tag{25}$$

We see that when all jurisdictions of the metropolitan area use a pollution tax to regulate the pollution level, these jurisdictions provide the socially optimal level of environmental quality. If the pollution tax revenues are distributed among the jurisdictional residents, the rent from local pollution is internalized. The jurisdictions have incentives to increase the pollution level. As all jurisdictions increase the pollution level, this has a positive effect on the common labor market wage. The combined effect leads to the socially efficient pollution level. We conclude that the pollution tax, t_i, is a Pigouvian instrument to realign the overprotection result of devolved environmental policy. This result is similar to the outcomes of Wellisch (1995) and Kunce and Shogren (2005a). In these papers the pollution tax only corrects for one leakage, namely, the non-resident ownership of mobile firms. In this paper, however, the pollution tax corrects two leakages, namely, the foreign-ownership of the firms and the leakage through commuting.

6. COMMUTING COSTS AND ASYMMETRIC JURISDICTIONS

We introduce a fixed positive commuting cost ($c \geq 0$) and asymmetric jurisdictions, respectively.

Non-zero commuting cost

With a non-zero commuting cost, the commuters lose a part of the wage they earn in other jurisdictions. Hence, they prefer to look for a job in their own jurisdiction at the first place. Equations (26) and (27) describe the relations between the wages in the jurisdictions. The

[21] Appendix F gives more details

commuting cost spans the gap between the wages in jurisdictions. These relations hold only as long as all wages are positive ($w_2=w_1-c\geq 0$ or $w_1=w_2-c\geq 0$). If c is high ($w_1-c<0$ or $w_2-c<0$), there is no longer commuting and eq. (26) and (27) do not longer hold. The wages are independent from the other jurisdictions.

$$w_1 = w_2 - c \geq 0 \quad \text{if } N_1 < N_0 < N_2 \tag{26}$$

$$w_2 = w_1 - c \geq 0 \quad \text{if } N_2 < N_0 < N_1 \tag{27}$$

If $w_2-c\geq 0$, the consumption of all residents in jurisdiction 1 consists of the wage of the residents working in jurisdiction 1, the wage of the residents working in jurisdiction 2 (if any) and their share in the pollution rents of the metropolitan area.

$$N_0 C_1 = N_1 w_1 + \left(N_0 - N_1\right)\left(w_2 - c\right) + \frac{R_1 + (n-1)R_2}{n} \tag{28}$$

If $w_2-c<0$, the commuting cost is too high and the residents in jurisdiction 1 do not commute. Consumption in jurisdiction 1 consists of the wage of the residents working in jurisdiction 1 and their share in the pollution rents of the metropolitan area.

$$N_0 C_1 = N_0 w_1 + \frac{R_1 + (n-1)R_2}{n} \tag{29}$$

Jurisdiction 1 chooses P_1 to maximize the utility of a representative resident (7) subject to its budget constraint (28) or (29) and taking P_2 as given. The symmetric Nash-equilibrium values of the pollution levels are[22]

PROPOSITION 4: In a symmetric Nash equilibrium (N_e,P_e) and with a positive commuting cost ($c\geq 0$), a jurisdiction, chooses a pollution level, P_e, such that

If $w_1=w_2-c\geq 0$,

$$-N_0 \frac{U_P}{U_C} = \frac{F_P}{n} - \frac{n-1}{n}\frac{F_{NP}}{F_{NN}}c \tag{30}$$

Or if $w_1=w_2-c<0$,

[22] Appendix G gives more details

$$-N_0 \frac{U_P}{U_C} = \frac{F_P}{n} + \frac{n-1}{n} N_0 F_{NP} \tag{31}$$

Equation (30) equals (31), if

$$c = -N_0 F_{NN} \tag{32}$$

Equations (30) and (31) are generalizations of the conventional result (12). Setting the commuting cost to zero (c=0) in (30) results in F_P/n. With n=1, we find the social optimum, the conventional result for a single-jurisdiction metropolitan area (13). Without commuting (31), there is only one leakage left, the redistribution of the pollution rents. Indeed, very high commuting costs give the same pollution levels as the equilibrium with a payroll tax (19). The policy implication is that low commuting costs (e.g. through subsidies) enhance NIMBY behavior and may lead to inefficiently low levels of pollution.

Asymmetric model

In the real world, urban areas typically consist of a central city surrounded by small suburbs. In many metropolitan areas in the US, the central city has about 25-30% of the metropolitan population (Braid, 2005). We construct an asymmetric model with jurisdiction 1 of size β=m and (n-m) jurisdictions 2 of size β=1. Basic equilibrium condition (4) changes into

$$mN_1 + (n-m)N_2 = nN_0 \tag{33}$$

The consumption of the residents in jurisdiction i (34) consists of the wage of the residents and their share in the pollution rents of the metropolitan area.

$$\beta N_0 C_i = \beta N_0 w_i + \beta \frac{R_1 + (n-m)R_2}{n} \tag{34}$$

Jurisdiction i chooses P_i to maximize the utility of a representative resident (7) subject to its budget constraint (34) and taking the pollution of the other jurisdictions as given. The Nash-equilibrium value of the pollution level for jurisdiction i is[23]

PROPOSITION 5: In an asymmetric Nash equilibrium (N_i,P_i), jurisdiction i of size β chooses a pollution level, P_i, such that

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[23] Appendix H gives more details

$$-\beta N_0 \frac{U_P^i}{U_C^i} = \frac{\beta}{n} F_P^i \tag{35}$$

Equation (35) is a generalization from the result for a symmetric model (12). Both small and big jurisdictions set their pollution level, respecting eq. (35). If jurisdiction i is of size β =1, then we get a result identical to the symmetric model (12). Bigger jurisdictions (β >1) allow for more pollution. With size β =n, we get the socially optimal level of pollution, F_P. In appendix G, we show that for models with two different sizes of jurisdictions, the Nash equilibrium is independent from the size of the other jurisdictions in the metropolitan area.

The asymmetric model responds better to the reality of a metropolitan area. Here, we often observe a big core with a commuting belt or sleeping towns around it. Most economic activity happens in the core, whereas the sleeping towns care more about their living quality. Our result also suggests that we may solve NIMBY problems by bringing the jurisdictions under a common metropolitan government. This solution is an alternative to the use of taxes.

7. CONCLUSIONS

This paper helps to explain why NIMBY behavior is still observed in the “green” sleeping towns or commuter belt with a high proportion of active participants in the economy. Our paper considers inter-jurisdictional competition where the jurisdictions interact through a common labor market. The main results differ in character from those of the traditional “business-tax competition models”. The inter-jurisdictional competition on the labor market leads to a race-to-the-top, as commuters prefer to work in the other jurisdictions, while preserving a high environmental quality in their home jurisdiction. Fiercer competition due to an increasing number of jurisdictions intensifies this race-to-the-top.

It is useful to finish by discussing the policy implications of the results in the real world. First, we show that jurisdictions can (imperfectly) correct this race-to-the-top using payroll taxes and pollution taxes. The payroll tax corrects the wage leakage through commuting. The loss of pollution rents, however, persists. Although, the use of payroll taxes leads to higher pollution levels, the optimal level is not guaranteed. The pollution tax, however, is a Pigouvian instrument, leading to the socially efficient pollution levels. In most countries, the higher-governments limit the tax instruments that local governments can use, thereby possibly reducing the scope for alleviating NIMBY behavior through taxes. In e.g. Japan, Germany, Sweden and Denmark, income taxes make up most of the local tax revenue. In the US, however, only 16 out of the 50 states allow local governments to use wage or income taxes. Payroll taxes are merely used in 5 states. In the Anglo-Saxon world property taxes are by far the most important source of local tax revenue[24] (Braid, 2005). In other countries, the local tax revenues are more balanced between different taxes. In Belgium, municipalities levy, on average, around 20 different taxes. Taxes account for about 47% of the local budget; the remainder being covered (mainly) by dividends from gas and electricity utilities (9%) and transfers from higher government levels (40%). The residence-based income taxes and property taxes make up about 20% of the total municipal budget each. Taxes on firm profits or environmental taxes (2% and 3% of total local budget, respectively) are relatively insignificant on the lowest government level.

Further, we find that low commuting costs enhance the NIMBY behavior of small jurisdictions. Positive commuting costs have a similar effect as the payroll tax. They limit or stop wage leakage through commuting but the leakage of pollution rents persist. This result adds to the discussion about the goods and the ills of subsidizing commuting. Many countries subsidize commuting to work. In most countries, commuters may not pay their full costs since transport is subsidized in many ways. Moreover, countries like Germany, France and Belgium example, allow taxpayers to deduct commuting expenses from their income tax liability (Borck and Wrede, 2005).

Finally, we find that bigger jurisdictions are less prone to race-to-the-top competition, as they can keep higher shares of the benefits, wages and pollution rents, within their borders. One may solve the inefficiencies by fusing jurisdictions or transferring the environmental competencies to the metropolitan government. Apart from the institutional complications that this measure would cause; it is very unlikely however, that this would solve the existence of geographically well-defined NIMBY groups within the metropolitan area.

[24] To make our point clear, the paper does not include the capture of the market for fixed or mobile industrial property/capital.

The interesting results of this paper open the scope for future research. Empirical evidence is needed to show whether intensive commuting corresponds to a race-to-the-top in environmental quality, or, whether jurisdictions with a high share of commuters in their labor force have a different reaction function to the environmental policy of other jurisdictions. Moreover, there is an interesting task to reconcile the race-to-the-top of this paper with the race-to-the-bottom of the traditional business tax models. An obvious approach is to include capital and property in the production functions and to study a two-level government, e.g. a metropolitan area with sub-metropolitan jurisdictions. The sub-metropolitan jurisdictions take into account the effect of commuting as in this paper. The government of the metropolitan area, however, considers commuting as an intra-metropolitan affair and behaves like the jurisdictions in the tax business models.

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APPENDIX A: PROPERTIES OF PRODUCTION FUNCTION

In this appendix we write out some useful properties of the production function F(N, P).

As F(N, P) is homogeneous of degree one we know that (Euler's Theorem)

$$NF_N + PF_P = F \tag{36}$$

Deriving (36) w.r.t. N and P results in, respectively,

$$NF_{NN} + PF_{PN} = 0 \tag{37}$$

$$NF_{NP} + PF_{PP} = 0 \tag{38}$$

With (37) and (38), we can show that $F_{NP}>0$.

$$d^2F(N,P) = \begin{bmatrix} F_{NN} & F_{NP} \\ F_{PN} & F_{PP} \end{bmatrix} \tag{39}$$

$d^2F(N,P)$ is the Hessian of F(N,P). With (37) and (38), we further can show that the determinant of the Hessian equals zero.

$$F_{NN}F_{PP} = F_{NP}F_{PN} \tag{40}$$

This results in the useful equation which we will use in the following derivations.

$$F_{NN}F_{PP} = F_{NP}F_{PN} \tag{41}$$

APPENDIX B: COMPARATIVE-STATIC DERIVATIVES

In the paper, we are interested in a symmetric equilibrium in which the endogenous variables are the same in all *n* jurisdictions. All partial derivatives of F are evaluated at the following symmetric equilibrium: $N_0=N_1=N_2=N_e$, $P_1=P_2=P_e$. Consequently, we assume that in (N_e,P_e)

$$
\begin{aligned}
&F(N_e,P_e)=F^1(N_e,P_e)=F^2(N_e,P_e)\\
&F_N(N_e,P_e)=F_N^1(N_e,P_e)=F_N^2(N_e,P_e)\\
&F_P(N_e,P_e)=F_P^1(N_e,P_e)=F_P^2(N_e,P_e)\\
&F_{NN}(N_e,P_e)=F_{NN}^1(N_e,P_e)=F_{NN}^2(N_e,P_e)\\
&F_{PP}(N_e,P_e)=F_{PP}^1(N_e,P_e)=F_{PP}^2(N_e,P_e)\\
&F_{NP}(N_e,P_e)=F_{NP}^1(N_e,P_e)=F_{NP}^2(N_e,P_e)
\end{aligned} \tag{42}
$$

Pollution

The equilibrium quantity of labor (11) can be found by deriving (4) and (9) w.r.t. P_1, finding

$$\frac{\partial N_1}{\partial P_1}+(n-1)\frac{\partial N_2}{\partial P_1}=0 \tag{43}$$

$$\frac{\partial w_1}{\partial P_1}=\left[F_{NN}^1\frac{\partial N_1}{\partial P_1}+F_{NP}^1\right] \tag{44}$$

$$\frac{\partial w_2}{\partial P_1}=F_{NN}^2\frac{\partial N_2}{\partial P_1} \tag{45}$$

Equating the right-hand sides of (44) and (45), and using (42) and (43) at symmetric equilibrium, we find

$$\frac{\partial N_1}{\partial P_1}=-\frac{n-1}{n}\frac{F_{NP}}{F_{NN}} \tag{11}$$

Payroll Tax

The equilibrium quantity of labor (49) can be found by deriving (4) and (15) w.r.t. b_1 (and P_1 is exogenous as it is still determined by the jurisdictional government) finding

$$\frac{\partial N_1}{\partial b_1}+(n-1)\frac{\partial N_2}{\partial b_1}=0 \tag{46}$$

$$\frac{\partial w_1}{\partial b_1} = -F_N^1 + (1-b_1)F_{NN}^1 \frac{\partial N_1}{\partial b_1} \tag{47}$$

$$\frac{\partial w_2}{\partial b_1} = (1-b_2)F_{NN}^2 \frac{\partial N_2}{\partial b_1} \tag{48}$$

Equating the right-hand sides of (47) and (48), and using (42) and (46) at symmetric equilibrium, we find

$$\frac{\partial N_1}{\partial b_1} = \frac{1}{(1-b_0)} \frac{n-1}{n} \frac{F_N}{F_{NN}} \tag{49}$$

Pollution Tax

The equilibrium quantity of pollution (55) can be found by deriving (4) and (9) w.r.t. t_1 (and P_1 is endogenous) finding

$$\frac{\partial N_1}{\partial t_1} + (n-1)\frac{\partial N_2}{\partial t_1} = 0 \tag{50}$$

$$\frac{\partial w}{\partial t_1} = F_{NN}^1 \frac{\partial N_1}{\partial t_1} + F_{NP}^1 \frac{\partial P_1}{\partial t_1} \tag{51}$$

$$\frac{\partial w}{\partial t_1} = F_{NN}^2 \frac{\partial N_2}{\partial t_1} \tag{52}$$

Combining (51) and (52), using (42) at symmetric equilibrium, results in

$$-\frac{n}{n-1} F_{NN} \frac{\partial N_1}{\partial t_1} = F_{NP} \frac{\partial P_1}{\partial t_1} \tag{53}$$

We know that

$$F_P = t_1 \tag{22}$$

Differentiating (22) w.r.t. t_1 gives

$$F_{PN} \frac{\partial N_1}{\partial t_1} + F_{PP} \frac{\partial P_1}{\partial t_1} = 1 \tag{54}$$

Combining (53) and (54) results in

$$\frac{\partial P_1}{\partial t_1} = \frac{n}{F_{PP}} \tag{55}$$

APPENDIX C: SOCIAL OPTIMUM

We get the social optimum optimum by

$$\max_{N_1, C_1, P_1} U(C_1, P_1) \tag{56}$$

Subject to

$$U(C_2, P_2) = \overline{U} \tag{57}$$

$$F(N_1, P_1) + (n-1)F(N_2, P_2) = N_0\left[C_1 + (n-1)C_2\right] \tag{58}$$

$$N_1 + (n-1)N_2 = nN_0 \tag{4}$$

The Lagrangian becomes

$$\begin{aligned}\Psi \leftrightarrow \max_{N_i, C_i, P_i} U(C_1, P_1) - \lambda_1\left(U(C_2, P_2) - \overline{U}\right) \\ -\lambda_2\left(F(N_1, P_1) + (n-1)F(N_2, P_2) - N_0\left[C_1 + (n-1)C_2\right]\right) \\ -\lambda_3\left(N_1 + (n-1)N_2 - nN_0\right)\end{aligned} \tag{59}$$

and

$$\frac{\partial \Psi}{\partial P_1} \leftrightarrow U_P - \lambda_2 F_P = 0 \tag{60}$$

$$\frac{\partial \Psi}{\partial C_1} \leftrightarrow U_C + \lambda_2 N_0 = 0 \tag{61}$$

$$\frac{\partial \Psi}{\partial N_1} \leftrightarrow -\lambda_2 F_N - \lambda_3 = 0 \tag{62}$$

For a symmetric equilibrium this results in

$$-N_0 \frac{U_P^i}{U_C^i} = F_P^i \qquad \forall \mathrm{i} \tag{5}$$

$$F_N^1 = F_N^2 \tag{6}$$

APPENDIX D: CONVENTIONAL MODEL

Residents get:

- wage
- proportional share of pollution rents of all n jurisdictions
- commuting

$$\underset{P}{Max}\ \mathrm{U}(\mathrm{C}_1, P_1) \tag{7}$$

S.t.

$$N_0 C_1 = N_0 w + \frac{R_1 + (n-1)R_2}{n} \tag{8}$$

And

$$w = F_N^i \tag{9}$$

$$R_i = P_i F_P^i \tag{10}$$

The Lagrangian becomes

$$\Psi \leftrightarrow U\left(C_1, P_1\right) - \lambda_1 \left(N_0 F_N + \frac{R_1 + (n-1)R_2}{n} - N_0 C_1 \right) \tag{63}$$

Or, using (10) and (36),

$$\Psi \leftrightarrow U\left(C_1, P_1\right) - \lambda_1 \left[\underset{\text{A}}{\left(F_1 - P_1 F_P\right)} + \underset{\text{B}}{\left(N_0 - N_1\right) F_N} + \underset{\text{C}}{\sum_{i=1}^{n} \frac{P_i F_P}{n}} - \underset{\text{D}}{N_0 C_1} \right] \tag{64}$$

A is the total wage sum paid in jurisdiction 1

B is the correction for the commuters' wages

C is the revenue from the polluting rents in all jurisdictions

D is the total cost of consumption in jurisdiction 1

FOC for consumption

$$\frac{\partial \Psi}{\partial C_1} \leftrightarrow \frac{\partial U}{\partial C_1} + \lambda_1 N_0 = 0 \tag{65}$$

FOC for pollution

$$\frac{\partial \Psi}{\partial P_1} \leftrightarrow \frac{\partial U}{\partial P_1} - \lambda_1 \begin{bmatrix} \left(F_P^1 + F_N^1 \frac{\partial N_1}{\partial P_1} - F_P^1 - P_1 F_{PP}^1 - P_1 F_{PN}^1 \frac{\partial N_1}{\partial P_1} \right) \\ + \left(N_0 - N_1 \right) \left(F_{NP}^1 + F_{NN}^1 \frac{\partial N_1}{\partial P_1} \right) - F_N^1 \frac{\partial N_1}{\partial P_1} \\ + \dfrac{F_P^1 + P_1 \left(F_{PP}^1 + F_{PN}^1 \frac{\partial N_1}{\partial P_1} \right)}{n} \\ + \dfrac{n-1}{n} P_2 F_{PN}^2 \dfrac{\partial N_2}{\partial P_1} \end{bmatrix} = 0 \tag{66}$$

Simplifying (66), using (42) and (43) at symmetric equilibrium results in

$$\frac{\partial \Psi}{\partial P_1} \leftrightarrow \frac{\partial U}{\partial P_1} - \lambda_1 \begin{bmatrix} \left(-P_1 F_{PP} - P_1 F_{PN} \frac{\partial N_1}{\partial P_1} \right) \\ + \dfrac{F_P + P_1 \left(F_{PP} + F_{PN} \frac{\partial N_1}{\partial P_1} \right)}{n} \\ - \dfrac{P_1 F_{PN}}{n} \dfrac{\partial N_1}{\partial P_1} \end{bmatrix} = 0 \tag{67}$$

$$\frac{\partial \Psi}{\partial P_1} \leftrightarrow \frac{\partial U}{\partial P_1} - \lambda_1 \begin{bmatrix} \left(-P_1 F_{PP} - P_1 F_{PN} \frac{\partial N_1}{\partial P_1} \right) \\ + \dfrac{F_P + P_1 F_{PP}}{n} \end{bmatrix} = 0 \tag{68}$$

With (11)

$$\frac{\partial \Psi}{\partial P_1} \leftrightarrow \frac{\partial U}{\partial P_1} - \lambda_1 \begin{bmatrix} \left(-P_1 F_{PP} + \dfrac{n-1}{n} P_1 \dfrac{F_{PN} F_{PN}}{F_{NN}} \right) \\ + \dfrac{F_P}{n} + \dfrac{P_1 F_{PP}}{n} \end{bmatrix} = 0 \tag{69}$$

From (41)

$$\frac{\partial\Psi}{\partial P_1} \leftrightarrow \frac{\partial U}{\partial P_1} - \lambda_1 \begin{bmatrix} \left(-P_1 F_{PP} + \frac{n-1}{n} P_1 F_{PP} \right) \\ + \frac{F_P}{n} + \frac{P_1 F_{PP}}{n} \end{bmatrix} = 0 \tag{70}$$

$$\frac{\partial\Psi}{\partial P_1} \leftrightarrow \frac{\partial U}{\partial P_1} - \lambda_1 \frac{F_P}{n} = 0 \tag{71}$$

Resulting in

$$-N_0 \frac{U_P}{U_C} = \frac{F_P}{n} \tag{12}$$

APPENDIX E: NASH EQUILIBRIUM WITH PAYROLL TAX

Residents get:

- wage
- revenues of the payroll tax
- proportional share of pollution rents of all n jurisdictions
- commuting

$$\underset{P_1, b_1}{Max}\ \mathrm{U}(\mathrm{C}_1, P_1) \tag{7}$$

S.t.

$$N_0 C_1 = N_0 w + \frac{R_1 + (n-1)R_2}{n} + b_1 F_N N_1 \tag{16}$$

And

$$w = (1 - b_i) F_N (N_i, P_i) \tag{15}$$

$$R_i = P_i F_P^i \tag{10}$$

The Lagrangian becomes

$$\Psi \leftrightarrow U\left(C_1,P_1\right)-\lambda_1\left(N_0(1-b_1)F_N^1+N_1 b_1 F_N^1+\frac{F^1-F_N^1 N_1}{n}+\frac{(n-1)(F^2-F_N^2 N_2)}{n}-N_0 C_1\right) \quad (72)$$

FOC for consumption

$$\frac{\partial\Psi}{\partial C_1}\leftrightarrow\frac{\partial U}{\partial C_1}+\lambda_1 N_0=0 \quad (73)$$

FOC for pollution

$$\frac{\partial\Psi}{\partial P_1}\leftrightarrow\frac{\partial U}{\partial P_1}-\lambda_1\left[\begin{array}{l} N_0(1-b_1)(F_{NP}^1+F_{NN}^1\frac{\partial N_1}{\partial P_1})+b_1F_N^1\frac{\partial N_1}{\partial P_1}+b_1N_1(F_{NP}^1+F_{NN}^1\frac{\partial N_1}{\partial P_1}) \\ +\dfrac{F_P^1+F_N^1\frac{\partial N_1}{\partial P_1}-F_N^1\frac{\partial N_1}{\partial P_1}-N_1(F_{NP}^1+F_{NN}^1\frac{\partial N_1}{\partial P_1})}{n} \\ +\dfrac{n-1}{n}(F_N^2\frac{\partial N_2}{\partial P_2}-F_N^2\frac{\partial N_2}{\partial P_2}-N_2F_{NN}^2\frac{\partial N_2}{\partial P_2}) \end{array}\right]=0 \quad (74)$$

Simplifying (74) and using (42) and (43) at symmetric equilibrium gives

$$\frac{\partial\Psi}{\partial P_1}\leftrightarrow\frac{\partial U}{\partial P_1}-\lambda_1\left[\begin{array}{l} N_0F_{NP}+N_0F_{NN}\frac{\partial N_1}{\partial P_1}+b_1F_N\frac{\partial N_1}{\partial P_1} \\ +\dfrac{F_P}{n}-N_1\dfrac{F_{NP}}{n} \end{array}\right]=0 \quad (75)$$

Using (11) in (75) results in

$$\frac{\partial\Psi}{\partial P_1}\leftrightarrow\frac{\partial U}{\partial P_1}-\lambda_1\left[\begin{array}{l} N_0F_{NP}-\dfrac{n-1}{n}N_0F_{NN}\dfrac{F_{NP}}{F_{NN}}-\dfrac{n-1}{n}b_1F_N\dfrac{F_{NP}}{F_{NN}} \\ +\dfrac{F_P}{n}-N_1\dfrac{F_{NP}}{n} \end{array}\right]=0 \quad (76)$$

$$\frac{\partial\Psi}{\partial P_1}\leftrightarrow\frac{\partial U}{\partial P_1}-\lambda_1\left[\frac{F_P}{n}-\frac{n-1}{n}b_1F_N\frac{F_{NP}}{F_{NN}}\right]=0 \quad (77)$$

FOC for payroll tax

$$\frac{\partial\Psi}{\partial b_1}\leftrightarrow-\lambda_1\left[\begin{array}{l}-N_0F_N^1+N_0(1-b_1)F_{NN}^1\frac{\partial N_1}{\partial b_1}+N_1F_N^1+b_1F_N^1\frac{\partial N_1}{\partial b_1}+b_1N_1F_{NN}^1\frac{\partial N_1}{\partial b_1}\\ +\frac{F_N^1\frac{\partial N_1}{\partial b_1}-N_1F_{NN}^1\frac{\partial N_1}{\partial b_1}-F_N^1\frac{\partial N_1}{\partial b_1}}{n}\\ +\frac{(n-1)}{n}\left(F_N^2\frac{\partial N_2}{\partial b_1}-N_2F_{NN}^2\frac{\partial N_2}{\partial b_1}-F_N^2\frac{\partial N_2}{\partial b_1}\right)\end{array}\right]=0 \quad (78)$$

Simplifying (78) and using (48) gives

$$\frac{\partial\Psi}{\partial b_1}\leftrightarrow-\lambda_1\left[N_0F_{NN}\frac{\partial N_1}{\partial b_1}+b_1F_N\frac{\partial N_1}{\partial b_1}\right]=0 \quad (79)$$

Resulting in

$$b_1=-N_0\frac{F_{NN}}{F_N} \quad (18)$$

Combining (73) and (77) results in

$$-N_0\frac{U_P}{U_C}=\frac{F_P}{n}-\frac{n-1}{n}b_1\frac{F_NF_{NP}}{F_{NN}} \quad (17)$$

Substituting b_0 for (18) gives

$$-N_0\frac{U_P}{U_C}=\frac{F_P}{n}+\frac{n-1}{n}N_0F_{NP} \quad (19)$$

APPENDIX F: NASH EQUILIBRIUM WITH POLLUTION TAX

Residents get:

- wage
- pollution tax
- proportional share of pollution rents of all n jurisdictions
- commuting

$$\underset{t}{Max}\ \mathrm{U}(\mathrm{C}_1, P_1) \tag{7}$$

S.t.

$$N_0 C_1 = N_0 w + \frac{R_1 + (n-1)R_2}{n} + t_1 P_1 \tag{80}$$

And

$$w^i = F_N^i \tag{9}$$

$$R_i = P_i F_P - t_i P_i \tag{81}$$

The Lagrangian becomes

$$\Psi \leftrightarrow U\left(C_1, P_1\right) - \lambda_1 \left(N_0 w + \frac{R_1 + (n-1)R_2}{n} + t_1 P_1 - N_0 C_1 \right) \tag{82}$$

Or

$$\Psi \leftrightarrow U\left(C_1, P_1\right) - \lambda_1 \left[\left(F^1 - P_1 F_P^1\right) + \left(N_0 - N_1\right) F_N^1 + \sum_{i=1}^{n} \frac{P_i F_P^i - t_i P_i}{n} + t_1 P_1 - N_0 C_1 \right] \tag{83}$$

Firms consider t as a parameter and pollute to the point in which the marginal product of emissions equals the emissions price. All revenues from this price instrument are transferred equally to the residents. The firms produce till t=F_P. Equation (83) becomes

$$\Psi \leftrightarrow U\left(C_1, P_1\right) - \lambda_1 \left[F^1 + \left(N_0 - N_1\right) F_N^1 - N_0 C_1 \right] \tag{84}$$

FOC for consumption

$$\frac{\partial \Psi}{\partial C_1} \leftrightarrow \frac{\partial U}{\partial C_1} + \lambda_1 N_0 = 0 \tag{85}$$

FOC for pollution tax

$$\frac{\partial \Psi}{\partial t_1} \leftrightarrow \frac{\partial U}{\partial P_1}\frac{\partial P_1}{\partial t_1} - \lambda_1 \begin{bmatrix} F_P^1 \frac{\partial P_1}{\partial t_1} + F_N^1 \frac{\partial N_1}{\partial P_1}\frac{\partial P_1}{\partial t_1} - F_N^1 \frac{\partial N_1}{\partial P_1}\frac{\partial P_1}{\partial t_1} \\ + \left(N_0 - N_1\right)\left(F_{NP}^1 \frac{\partial P_1}{\partial t_1} + F_{NN}^1 \frac{\partial N_1}{\partial P_1}\frac{\partial P_1}{\partial t_1} \right) \end{bmatrix} = 0 \tag{86}$$

Or simplified using (42) in a symmetric equilibrium

$$\frac{\partial \Psi}{\partial t^1} \leftrightarrow \frac{\partial U}{\partial P^1} - \lambda_1 F_P = 0 \tag{87}$$

Resulting in

$$-N_0 \frac{U_P}{U_C} = F_P \tag{25}$$

APPENDIX G: NON-ZERO COMMUTING COST

Residents get:

- wage
- proportional share of pollution rents of all n jurisdictions
- commute with positive cost (c)

$$\underset{P}{Max}\ \mathrm{U}(\mathrm{C}_1, P_1) \tag{7}$$

S.t.

If $w_2 - c \geq 0$

$$N_0 C_1 = N_1 w_1 + \left(N_0 - N_1\right)\left(w_2 - c\right) + \frac{R_1 + (n-1)R_2}{n} \tag{28}$$

If $w_2 - c < 0$

$$N_0 C_1 = N_0 w_1 + \frac{R_1 + (n-1)R_2}{n} \tag{29}$$

And

$$w_i = F_N^i \tag{9}$$

$$R_i = P_i F_P^i \tag{10}$$

$$w_1 = w_2 - c \geq 0 \text{ if } N_1 < N_0 \tag{26}$$

$$w_2 = w_1 - c \geq 0 \text{ if } N_0 < N_1 \tag{27}$$

Case1: $w_1 = w_2 - c \geq 0$

The Lagrangian becomes

$$\Psi \leftrightarrow U\left(C_1, P_1\right) - \lambda_1\left(N_1 F_N^1 + \left(N_0 - N_1\right)\left(F_N^2 - c\right) + \frac{P_1 F_P^1 + (n-1) P_2 F_P^2}{n} - N_0 C_1\right) \quad (88)$$

$$\frac{\partial \Psi}{\partial C_1} \leftrightarrow \frac{\partial U}{\partial C_1} + \lambda_1 N_0 = 0 \quad (89)$$

$$\frac{\partial \Psi}{\partial P_1} \leftrightarrow \frac{\partial U}{\partial P_1} - \lambda_1 \begin{bmatrix} \left(F_N^1 \frac{\partial N_1}{\partial P_1} + N_1\left(F_{NN}^1 \frac{\partial N_1}{\partial P_1} + F_{NP}^1\right)\right) \\ -\frac{\partial N_1}{\partial P_1}\left(F_N^2 - c\right) + \left(N_0 - N_1\right) F_{NN}^2 \frac{\partial N_2}{\partial P_1} \\ + \frac{F_P^1 + P_1\left(F_{PP}^1 + F_{PN}^1 \frac{\partial N_1}{\partial P_1}\right)}{n} \\ + \frac{n-1}{n} P_2 F_{PN}^2 \frac{\partial N_2}{\partial P_1} \end{bmatrix} = 0 \quad (90)$$

Simplifying (90), using (42) and (43) at symmetric equilibrium results in

$$\frac{\partial \Psi}{\partial P_1} \leftrightarrow \frac{\partial U}{\partial P_1} - \lambda_1 \begin{bmatrix} \frac{\partial N_1}{\partial P_1} c + N_1 F_{NN} \frac{\partial N_1}{\partial P_1} + N_1 F_{NP} \\ + \frac{F_P + P_1\left(F_{PP} + F_{PN} \frac{\partial N_1}{\partial P_1}\right)}{n} \\ -\frac{P_1 F_{PN}}{n} \frac{\partial N_1}{\partial P_1} \end{bmatrix} = 0 \quad (91)$$

Using (11)

$$\frac{\partial \Psi}{\partial P_1} \leftrightarrow \frac{\partial U}{\partial P_1} - \lambda_1 \begin{bmatrix} \frac{1}{n} N_1 F_{NP} - \frac{n-1}{n} \frac{F_{NP}}{F_{NN}} c \\ + \frac{F_P + P_1 F_{PP}}{n} \end{bmatrix} = 0 \quad (92)$$

Resulting in

$$\frac{\partial\Psi}{\partial P_1} \leftrightarrow \frac{\partial U}{\partial P_1} - \lambda_1 \begin{bmatrix} \frac{1}{n} N_1 F_{NP} - \frac{n-1}{n} \frac{F_{NP}}{F_{NN}} c \\ + \frac{F_P + P_1 F_{PP}}{n} \end{bmatrix} = 0 \tag{93}$$

$$\frac{\partial\Psi}{\partial P_1} \leftrightarrow \frac{\partial U}{\partial P_1} - \lambda_1 \left(\frac{F_P}{n} - \frac{n-1}{n} \frac{F_{NP}}{F_{NN}} c \right) = 0 \tag{94}$$

$$-N_0 \frac{U_P}{U_C} = \frac{F_P}{n} - \frac{n-1}{n} \frac{F_{NP}}{F_{NN}} c \tag{30}$$

With c=0, zero commuting cost, we get the result of the conventional model (12). With n=1, we find the result for a single-jurisdiction metropolitan area (13).

Case 2: $w_2 - c \prec 0$

The Lagrangian becomes

$$\Psi \leftrightarrow U\left(C_1, P_1\right) - \lambda_1 \left(N_0 F_N^1 + \frac{P_1 F_P^1 + (n-1) P_2 F_P^2}{n} - N_0 C_1 \right) \tag{95}$$

$$\frac{\partial\Psi}{\partial C_1} \leftrightarrow \frac{\partial U}{\partial C_1} + \lambda_1 N_0 = 0 \tag{96}$$

$$\frac{\partial\Psi}{\partial P_1} \leftrightarrow \frac{\partial U}{\partial P_1} - \lambda_1 \left[N_0 F_{NP}^1 + \frac{F_P^1 + P_1 F_{PP}^1}{n} \right] = 0 \tag{97}$$

(With $\frac{\partial N_1}{\partial P_1} = \frac{\partial N_2}{\partial P_1} = 0$)

$$\frac{\partial\Psi}{\partial P_1} \leftrightarrow \frac{\partial U}{\partial P_1} - \lambda_1 \left[\frac{F_P}{n} + \frac{n-1}{n} N_0 F_{NP} \right] = 0 \tag{98}$$

$$-N_0 \frac{U_P}{U_C} = \frac{F_P}{n} + \frac{n-1}{n} N_0 F_{NP} \tag{31}$$

With n=1, we find the result for a single-jurisdiction metropolitan area (13).

Equations (30) and (31) are equal when

$$c = -N_0 F_{NN} \tag{32}$$

APPENDIX H: ASYMMETRIC JURISDICTIONS

We relax the assumption of symmetric jurisdictions. The model consists of jurisdiction 1 with size m and (n-m) jurisdictions 2 with size 1 ($n \geq m$).

Residents get:

- wage
- proportional share of pollution rents of all n jurisdictions
- commute with zero cost
- Asymmetric jurisdictions

Case 1: Jurisdiction of size m

$$\underset{P}{Max}\ \mathrm{U}(\mathrm{C}_1, P_1) \tag{7}$$

S.t.

$$mN_0 C_1 = mN_0 w_1 + m\frac{R_1 + (n-1)R_2}{n} \tag{34}$$

Equation (4) and (43) becomes

$$N_1 + (n-m)N_2 = nN_0 \tag{33}$$

And

$$\frac{\partial N_1}{\partial P_1} + (n-m)\frac{\partial N_2}{\partial P_1} = 0 \tag{99}$$

Equation (11) changes into

$$\frac{\partial N_1}{\partial P_1} = -\frac{(n-m)F_{NP}^1}{(n-m)F_{NN}^1 + F_{NN}^2} \tag{100}$$

$$\frac{\partial N_2}{\partial P_1} = \frac{F^1_{NP}}{(n-m)F^1_{NN} + F^2_{NN}} \tag{101}$$

Lagrangian becomes

$$\Psi \leftrightarrow U\left(C_1, P_1\right) - \lambda_1 \left(mN_0 F^1_N + m\frac{P_1 F^1_P + (n-m)P_2 F^2_P}{n} - mN_0 C_1 \right) \tag{102}$$

$$\Psi \leftrightarrow U\left(C_1, P_1\right) - \lambda_1 \left(mN_0 F^1_N + m\frac{\left(F^1 - N_1 F^1_N\right) + (n-m)\left(F^2 - N_2 F^2_N\right)}{n} - mN_0 C_1 \right) \tag{103}$$

$$\frac{\partial \Psi}{\partial C_1} \leftrightarrow \frac{\partial U}{\partial C_1} + \lambda_1 m N_0 = 0 \tag{104}$$

$$\frac{\partial \Psi}{\partial P_1} \leftrightarrow \frac{\partial U}{\partial P_1} - \lambda_1 \left[\begin{array}{l} mN_0 \left(F^1_{NN} \frac{\partial N_1}{\partial P_1} + F^1_{NP} \right) \\ + \frac{m}{n}\left(F^1_P + F^1_N \frac{\partial N_1}{\partial P_1} - F^1_N \frac{\partial N_1}{\partial P_1} - N_1 \left(F^1_{NN} \frac{\partial N_1}{\partial P_1} + F^1_{NP} \right) \right) \\ + \frac{m\left(n-m\right)}{n}\left(F^2_N \frac{\partial N_2}{\partial P_1} - F^2_N \frac{\partial N_2}{\partial P_1} - N_2 F^2_{NN} \frac{\partial N_2}{\partial P_1} \right) \end{array} \right] = 0 \tag{105}$$

$$\frac{\partial \Psi}{\partial P_1} \leftrightarrow \frac{\partial U}{\partial P_1} - \lambda_1 \left[\begin{array}{l} mN_0 \left(F^1_{NN} \frac{\partial N_1}{\partial P_1} + F^1_{NP} \right) \\ + \frac{m}{n}\left(F^1_P - N_1 \left(F^1_{NN} \frac{\partial N_1}{\partial P_1} + F^1_{NP} \right) \right) \\ - \frac{m\left(n-m\right)}{n} N_2 F^2_{NN} \frac{\partial N_2}{\partial P_1} \end{array} \right] = 0 \tag{106}$$

$$\frac{\partial \Psi}{\partial P_1} \leftrightarrow \frac{\partial U}{\partial P_1} - \lambda_1 \left[\begin{array}{l} \frac{m}{n} F^1_P + \frac{nmN_0 - mN_1}{n} F^1_{NP} \\ + \frac{nmN_0 - mN_1}{n} F^1_{NN} \frac{\partial N_1}{\partial P_1} \\ - \frac{m\left(n-m\right)}{n} N_2 F^2_{NN} \frac{\partial N_2}{\partial P_1} \end{array} \right] = 0 \tag{107}$$

$$\frac{\partial \Psi}{\partial P_1} \leftrightarrow \frac{\partial U}{\partial P_1} - \lambda_1 \begin{bmatrix} \frac{m}{n} F_P^1 + \frac{nmN_0 - mN_1}{n} F_{NP}^1 \\ -\frac{nmN_0 - mN_1}{n} \frac{(n-m)F_{NN}^1 F_{NP}^1}{(n-m)F_{NN}^1 + F_{NN}^2} \\ -\frac{m\left(nN_0 - N_1\right)}{n} \frac{F_{NN}^2 F_{NP}^1}{(n-m)F_{NN}^1 + F_{NN}^2} \end{bmatrix} = 0 \tag{108}$$

Leading to

$$-mN_0 \frac{U_P^1}{U_C^1} = \frac{m}{n} F_P^1 + \frac{m\left(nN_0 - N_1\right)}{n} \left(F_{NP}^1 - F_{NP}^1 \frac{(n-m)F_{NN}^1 + F_{NN}^2}{(n-m)F_{NN}^1 + F_{NN}^2} \right) \qquad 109$$

$$-mN_0 \frac{U_P^1}{U_C^1} = \frac{m}{n} F_P^1 \tag{35}$$

If m=1 eq. (35) reduces to the result of the conventional model (12).

Case 2: Jurisdiction of size 1 in an asymmetric equilibrium

$$\underset{P}{Max}\ \mathrm{U}(\mathrm{C}_1, P_1) \tag{7}$$

S.t.

$$N_0 C_2 = N_0 w_2 + \frac{R_1 + (n-1)R_2}{n} \tag{34}$$

With 1 denoting jurisdiction 1 of size m, 2 denoting the representative jurisdiction of size 1 and 3 denoting the other jurisdictions of size 1.

Equation (33) becomes

$$N_1 + N_2 + (n-m-1)N_3 = nN_0 \tag{110}$$

Deriving (9) and (33) w.r.t. P_2, results in

$$\frac{\partial N_1}{\partial P_2} + \frac{\partial N_2}{\partial P_2} + (n-m-1)\frac{\partial N_3}{\partial P_2} = 0 \tag{111}$$

$$\frac{\partial w_1}{\partial P_2} = F_{NN}^1 \frac{\partial N_1}{\partial P_2} \tag{112}$$

$$\frac{\partial w_2}{\partial P_2} = F_{NN}^2 \frac{\partial N_2}{\partial P_2} + F_{NP}^2 \tag{113}$$

$$\frac{\partial w_3}{\partial P_2} = F_{NN}^3 \frac{\partial N_3}{\partial P_2} \tag{114}$$

Equalizing (112), (113) and (114) leads to

$$\frac{\partial N_1}{\partial P_2} = \frac{F_{NN}^3}{F_{NN}^1} \frac{\partial N_3}{\partial P_2} \tag{115}$$

$$\frac{\partial N_1}{\partial P_2} = -\frac{F_{NN}^3}{F_{NN}^1 \left(n-m-1\right) + F_{NN}^3} \frac{\partial N_2}{\partial P_2} \tag{116}$$

$$\frac{\partial N_3}{\partial P_2} = -\frac{F_{NN}^1}{F_{NN}^1 \left(n-m-1\right) + F_{NN}^3} \frac{\partial N_2}{\partial P_2} \tag{117}$$

Combining (112), (113) and (116) results in

$$\frac{\partial N_2}{\partial P_2} = -\frac{F_{NP}^2 \left(F_{NN}^1 \left(n-m-1\right) + F_{NN}^3\right)}{F_{NN}^1 F_{NN}^2 \left(n-m-1\right) + F_{NN}^2 F_{NN}^3 + F_{NN}^1 F_{NN}^3} \tag{118}$$

Using (116) and (117) we find

$$\frac{\partial N_1}{\partial P_2} = \frac{F_{NP}^2 F_{NN}^3}{F_{NN}^1 F_{NN}^2 \left(n-m-1\right) + F_{NN}^2 F_{NN}^3 + F_{NN}^1 F_{NN}^3} \tag{119}$$

$$\frac{\partial N_3}{\partial P_2} = \frac{F_{NP}^2 F_{NN}^1}{F_{NN}^1 F_{NN}^2 \left(n-m-1\right) + F_{NN}^2 F_{NN}^3 + F_{NN}^1 F_{NN}^3} \tag{120}$$

Lagrangian becomes

$$\Psi \leftrightarrow U\left(C_2, P_2\right) - \lambda_2 \left(N_0 F_N^2 + \frac{P_1 F_P^1 + P_2 F_P^2 + (n-m-1) P_3 F_P^3}{n} - N_0 C_1 \right) \tag{121}$$

$$\Psi \leftrightarrow U\left(C_2,P_2\right)-\lambda_2\left(\begin{array}{l} N_0F_N^2 \\ +\dfrac{\left(F^1-N_1F_N^1\right)+\left(F^2-N_2F_N^2\right)+(n-m-1)\left(F^3-N_3F_N^3\right)}{n} \\ -N_0C_1 \end{array}\right) \quad (122)$$

$$\frac{\partial\Psi}{\partial C_2} \leftrightarrow \frac{\partial U}{\partial C_2}+\lambda_2N_0=0 \quad (123)$$

$$\frac{\partial\Psi}{\partial P_2} \leftrightarrow \frac{\partial U}{\partial P_2}-\lambda_2\left[\begin{array}{l} N_0\left(F_{NN}^2\dfrac{\partial N_2}{\partial P_2}+F_{NP}^2\right) \\ +\dfrac{1}{n}\left(F_N^1\dfrac{\partial N_1}{\partial P_2}-F_N^1\dfrac{\partial N_1}{\partial P_2}-N_1F_{NN}^1\dfrac{\partial N_1}{\partial P_2}\right) \\ +\dfrac{1}{n}\left(F_P^2+F_N^2\dfrac{\partial N_2}{\partial P_2}-F_N^2\dfrac{\partial N_2}{\partial P_2}-N_2\left(F_{NN}^2\dfrac{\partial N_2}{\partial P_2}+F_{NP}^2\right)\right) \\ +\dfrac{\left(n-m-1\right)}{n}\left(F_N^3\dfrac{\partial N_3}{\partial P_2}-F_N^3\dfrac{\partial N_3}{\partial P_2}-N_3F_{NN}^3\dfrac{\partial N_3}{\partial P_2}\right) \end{array}\right]=0 \quad (124)$$

$$\frac{\partial\Psi}{\partial P_2} \leftrightarrow \frac{\partial U}{\partial P_2}-\lambda_2\left[\begin{array}{l} \dfrac{F_P^2}{n}+\dfrac{nN_0-N_2}{n}F_{NP}^2 \\ -\dfrac{1}{n}N_1F_{NN}^1\dfrac{\partial N_1}{\partial P_2} \\ +\dfrac{nN_0-N_2}{n}F_{NN}^2\dfrac{\partial N_2}{\partial P_2} \\ -\dfrac{\left(n-m-1\right)}{n}N_3F_{NN}^3\dfrac{\partial N_3}{\partial P_2} \end{array}\right]=0 \quad (125)$$

N_1, N_2, N_3 are not necessarily equal to mN_0 and N_0 respectively.

$$\frac{\partial\Psi}{\partial P_2} \leftrightarrow \frac{\partial U}{\partial P_2}-\lambda_2\left[\begin{array}{l} \dfrac{F_P^2}{n}+\dfrac{nN_0-N_2}{n}F_{NP}^2 \\ -\dfrac{1}{n}N_1\dfrac{F_{NN}^1F_{NP}^2F_{NN}^3}{F_{NN}^1F_{NN}^2\left(n-m-1\right)+F_{NN}^2F_{NN}^3+F_{NN}^1F_{NN}^3} \\ -\dfrac{nN_0-N_2}{n}\dfrac{F_{NN}^2F_{NP}^2\left(F_{NN}^1\left(n-m-1\right)+F_{NN}^3\right)}{F_{NN}^1F_{NN}^2\left(n-m-1\right)+F_{NN}^2F_{NN}^3+F_{NN}^1F_{NN}^3} \\ -\dfrac{\left(n-m-1\right)}{n}N_3\dfrac{F_{NN}^1F_{NP}^2F_{NN}^3}{F_{NN}^1F_{NN}^2\left(n-m-1\right)+F_{NN}^2F_{NN}^3+F_{NN}^1F_{NN}^3} \end{array}\right]=0 \quad (126)$$

$$\frac{\partial \Psi}{\partial P_2} \leftrightarrow \frac{\partial U}{\partial P_2} - \lambda_2 \begin{bmatrix} \frac{F_P^2}{n} + \frac{nN_0 - N_2}{n} F_{NP}^2 \\ -\frac{N_1 + (n-m-1)N_3}{n} \frac{F_{NN}^1 F_{NP}^2 F_{NN}^3}{F_{NN}^1 F_{NN}^2 (n-m-1) + F_{NN}^2 F_{NN}^3 + F_{NN}^1 F_{NN}^3} \\ -\frac{nN_0 - N_2}{n} \frac{F_{NN}^1 F_{NN}^2 F_{NP}^2 (n-m-1)}{F_{NN}^1 F_{NN}^2 (n-m-1) + F_{NN}^2 F_{NN}^3 + F_{NN}^1 F_{NN}^3} \\ -\frac{nN_0 - N_2}{n} \frac{F_{NN}^2 F_{NP}^2 F_{NN}^3}{F_{NN}^1 F_{NN}^2 (n-m-1) + F_{NN}^2 F_{NN}^3 + F_{NN}^1 F_{NN}^3} \end{bmatrix} = 0 \quad (127)$$

$$\frac{\partial \Psi}{\partial P_2} \leftrightarrow \frac{\partial U}{\partial P_2} - \lambda_2 \begin{bmatrix} \frac{F_P^2}{n} + \frac{nN_0 - N_2}{n} F_{NP}^2 \\ -\frac{nN_0 - N_2}{n} \frac{F_{NN}^1 F_{NP}^2 F_{NN}^3}{F_{NN}^1 F_{NN}^2 (n-m-1) + F_{NN}^2 F_{NN}^3 + F_{NN}^1 F_{NN}^3} \\ -\frac{nN_0 - N_2}{n} \frac{F_{NN}^1 F_{NN}^2 F_{NP}^2 (n-m-1)}{F_{NN}^1 F_{NN}^2 (n-m-1) + F_{NN}^2 F_{NN}^3 + F_{NN}^1 F_{NN}^3} \\ -\frac{nN_0 - N_2}{n} \frac{F_{NN}^2 F_{NP}^2 F_{NN}^3}{F_{NN}^1 F_{NN}^2 (n-m-1) + F_{NN}^2 F_{NN}^3 + F_{NN}^1 F_{NN}^3} \end{bmatrix} = 0 \quad (128)$$

$$\frac{\partial \Psi}{\partial P_2} \leftrightarrow \frac{\partial U}{\partial P_2} - \lambda_2 \begin{bmatrix} \frac{F_P^2}{n} + \frac{nN_0 - N_2}{n} F_{NP}^2 \\ -\left(\frac{nN_0 - N_2}{n}\right) \frac{F_{NN}^1 F_{NP}^2 F_{NN}^3 + F_{NN}^1 F_{NN}^2 F_{NP}^2 (n-m-1) + F_{NN}^2 F_{NP}^2 F_{NN}^3}{F_{NN}^1 F_{NN}^2 (n-m-1) + F_{NN}^2 F_{NN}^3 + F_{NN}^1 F_{NN}^3} \end{bmatrix} = 0 \quad (129)$$

In equilibrium $F_{NN}^2 = F_{NN}^3$ and (129) reduces to

$$\frac{\partial \Psi}{\partial P_2} \leftrightarrow \frac{\partial U}{\partial P_2} - \lambda_2 \begin{bmatrix} \frac{F_P^2}{n} + \frac{nN_0 - N_2}{n} F_{NP}^2 \\ -\left(\frac{nN_0 - N_2}{n}\right) \frac{F_{NN}^1 F_{NP}^2 (n-m) + F_{NN}^2 F_{NP}^2}{F_{NN}^1 (n-m) + F_{NN}^2} \end{bmatrix} = 0 \quad (130)$$

$$-N_0 \frac{U_P^2}{U_C^2} = \frac{F_P^2}{n} + \left(\frac{nN_0 - N_2}{n}\right) F_{NP}^2 - \left(\frac{nN_0 - N_2}{n}\right) \frac{F_{NN}^1 F_{NP}^2 (n-m) + F_{NN}^2 F_{NP}^2}{F_{NN}^1 (n-m) + F_{NN}^2} \quad (131)$$

$$-N_0 \frac{U_P^2}{U_C^2} = \frac{F_P^2}{n} + \frac{nN_0 - N_2}{n} \left(F_{NP}^2 - F_{NP}^2 \frac{F_{NN}^1 (n-m) + F_{NN}^2}{F_{NN}^1 (n-m) + F_{NN}^2} \right) \quad (132)$$

$$-N_0 \frac{U_P^2}{U_C^2} = \frac{F_P^2}{n} \quad (35)$$

With m=1, all jurisdictions are equal ($F_{NN}^1 = F_{NN}^2 = F_{NN}^3$). We get the result for the symmetric equilibrium (12).

APPENDIX I: PROVISION OF NON-ENVIRONMENTAL PUBLIC GOODS

In section 5, we presumed that the non-environmental public goods are provided efficiently. The Samuelson condition for efficient public goods provision when the constant marginal production cost of public good equals one, is

$$N_0 \frac{U_G}{U_C} = 1 \tag{133}$$

Assuming efficient public consumption, however, neglects the link between two key sources of interjurisdictional competition – local taxes and environmental quality.

In this section we model this link explicitly for policies using the labor income tax, the payroll tax and the pollution tax[25]. Here, the resident's utility distinguishes between the local consumption, local pollution and local public consumption(134).

$$U(C_1, P_1, G_1) \tag{134}$$

Labor Income Tax

With a labor income, the income of the residents and the public consumption are, respectively,

$$N_0 C_1 = (1-a_1)N_0 w + \frac{R_1 + (n-1)R_2}{n} \tag{135}$$

$$G_1 = a_1 F_N N_0 \tag{136}$$

Each jurisdiction, maximizing (134) choosing P_1 and the labor income tax, a_1, subject to (135) and (136), will provide the environmental quality as in (12). With a labor income tax, public consumption can be financed in a lump-sum way. Hence the public consumption does not affect the provision of environmental quality.

Payroll Tax

With a payroll tax, the income of the residents and the public consumption are, respectively,

[25] For more details about the labor income tax, payroll tax and pollution tax, see Appendix J.

$$N_0 C_1 = N_0 w + \frac{R_1 + (n-1)R_2}{n} \tag{137}$$

$$G_1 = b_1 F_N N_1 \tag{138}$$

The first-order conditions of maximizing (134) choosing P_1 and the payroll tax, b_1, subject to (137) and (138), require

$$-N_0 \frac{U_P}{U_C} = \left(\frac{F_P}{n} - \frac{n-1}{n} b_1 \frac{F_N F_{NP}}{F_{NN}}\right) + \left(N_0 \frac{U_G}{U_C} - 1\right) b_1 \left[F_{NP} N_0 - \frac{n-1}{n} \frac{F_N F_{NP}}{F_{NN}} \right] \tag{139}$$

$$b_1 = -\frac{(n-1) F_{NN} N_0 + (N_0 \frac{U_G}{U_C} - 1) N_1 n F_{NN}}{N_0 \frac{U_G}{U_C} (n-1) F_N - (N_0 \frac{U_G}{U_C} - 1) N_1 F_{NN}} \tag{140}$$

Combining (139) and (140) yields

$$\begin{aligned}
-N_0 \frac{U_P}{U_C} = {} & \left(\frac{F_P}{n} + \frac{n-1}{n} \frac{(n-1) + (N_0 \frac{U_G}{U_C} - 1) n}{N_0 \frac{U_G}{U_C} (n-1) F_N - (N_0 \frac{U_G}{U_C} - 1) N_0 F_{NN}} N_0 F_N F_{NP}\right) \\
& -\left(N_0 \frac{U_G}{U_C} - 1\right) \frac{(n-1) F_{NN} N_0 + (N_0 \frac{U_G}{U_C} - 1) N_0 n F_{NN}}{N_0 \frac{U_G}{U_C} (n-1) F_N - (N_0 \frac{U_G}{U_C} - 1) N_0 F_{NN}} \left[F_{NP} N_0 - \frac{n-1}{n} \frac{F_N F_{NP}}{F_{NN}} \right]
\end{aligned} \tag{141}$$

Equation (141) expresses a complex relation between the environmental quality and the consumption of local public goods. It is ambiguous whether (141) will be higher or lower than (20), depending on the efficiency of local public consumption and the properties of the production function. In (139), however, we see that, *ceteris paribus*, an underprovision of local public consumption ($N_0 \frac{U_G}{U_C} > 1$) tends to allow for more pollution compared to the conventional model. If the environmental quality is provided efficiently ($N_0 \frac{U_G}{U_C} = 1$), eq. (139), (140) and (141) reduce to (17), (18) and (19), respectively. This efficient level of local public goods can be obtained by combining the labor income tax with the payroll tax.

Pollution Tax

With a pollution tax income, the income of the representative resident and the public consumption are, respectively,

$$N_0 C_1 = N_0 w \tag{142}$$

$$G_1 = t_1 P_1 \tag{143}$$

With a pollution tax, t_1, the government does not exogenously set the pollution level of the jurisdiction. Firms consider the pollution tax as a parameter and pollute to the point in which the marginal product of pollution equals the pollution tax (t_1=F_P).

The first-order conditions of maximizing (134) choosing payroll tax, t_1, subject to (142) and (143) , require

$$-N_0 \frac{U_P}{U_C} = F_P - (N_0 \frac{U_G}{U_C} - 1)(F_P - \frac{P_0 F_{PP}}{n}) \tag{144}$$

From (144), we learn that if the local public consumption is underprovided ($N_0 \frac{U_G}{U_C} > 1$), there is a race-to-the-top in environmental quality. The jurisdiction tries to finance the local public consumption with higher pollution taxes[26]. The firms react to these higher pollution taxes by polluting less. We get an efficient level of local public good and an optimal level of environmental quality when the jurisdictions are able to combine the lump-sum labor income tax with the pollution tax.

APPENDIX J: LOCAL PUBLIC GOOD – ENVIRONMENT

Labor Income Tax

Residents get:

- net wage after labor income tax
- proportional share of pollution rents of all n jurisdictions

- commuting

Governments gets:

- Labor income tax revenues

$$\underset{a,P}{Max}\, U(C_1, P_1, G_1) \tag{145}$$

S.t.

$$N_0 C_1 = (1-a_1)N_0 w + \frac{R_1 + (n-1)R_2}{n} \tag{146}$$

$$G_1 = a_1 F_N^1 N_0 \tag{147}$$

And

$$w = F_N(N_i, P_i) \tag{148}$$

$$R_i = P_i F_P \tag{149}$$

The Lagrangian becomes

$$\begin{aligned}\Psi \leftrightarrow U\left(C_1, P_1, G_1\right) - \lambda_1\left((1-a_1)F_N N_0 + \frac{R_1 + (n-1)R_2}{n} - N_0 C_1\right) \\ -\lambda_2(a_1 F_N N_0 - G_1) = 0\end{aligned} \tag{150}$$

Or

$$\begin{aligned}\Psi \leftrightarrow U\left(C_1, P_1, G_1\right) - \lambda_1\left(N_0(1-a_1)F_N^1 + N_0 a_1 F_N^1 + \frac{R_1 + (n-1)R_2}{n} - N_0 C_1\right) \\ +\lambda_1 a_1 F_N^1 N_0 - \lambda_2(a_1 F_N^1 N_0 - G_1) = 0\end{aligned} \tag{151}$$

Or

$$\begin{aligned}\Psi \leftrightarrow U\left(C_1, P_1, G_1\right) - \lambda_1\left(N_0(1-a_1)F_N^1 + N_0 a_1 F_N^1 + \frac{R_1 + (n-1)R_2}{n} - N_0 C_1\right) \\ +\left(\lambda_1 - \lambda_2\right) a_1 F_N^1 N_0 + \lambda_2 G_1 = 0\end{aligned} \tag{152}$$

---

[26] Assuming that $\frac{\partial Pt}{\partial t} \succ 0$

FOC for private consumption

$$\frac{\partial \Psi}{\partial C_1} \leftrightarrow \frac{\partial U}{\partial C_1} + N_0 \lambda_1 = 0 \tag{153}$$

FOC for local public consumption

$$\frac{\partial \Psi}{\partial G_1} \leftrightarrow \frac{\partial U}{\partial G_1} + \lambda_2 = 0 \tag{154}$$

Combining (168) and (169) gives

$$N_0 \frac{U_G}{U_C} = \frac{\lambda_2}{\lambda_1} \tag{155}$$

FOC for pollution

$$\frac{\partial \Psi}{\partial P_1} \leftrightarrow \frac{\partial U}{\partial P_1} - \lambda_1 \frac{F_P^1}{n} + (\lambda_1 - \lambda_2) \frac{\partial (a_1 F_N^1 N_0)}{\partial P_1} = 0 \tag{156}$$

$$\frac{\partial \Psi}{\partial P_1} \leftrightarrow \frac{\partial U}{\partial P_1} - \lambda_1 \frac{F_P^1}{n} + (\lambda_1 - \lambda_2) a_1 N_0 \frac{F_{NP}^1}{n} = 0 \tag{157}$$

FOC for labor income tax

$$\frac{\partial \Psi}{\partial a_1} \leftrightarrow (\lambda_1 - \lambda_2) N_0 F_N^1 = 0 \tag{158}$$

$$\frac{\partial \Psi}{\partial a_1} \leftrightarrow (\lambda_1 - \lambda_2) = 0 \tag{159}$$

Hence, using (42),

$$-N_0 \frac{U_P}{U_C} = \frac{F_P}{n} \tag{12}$$

Payroll Tax

Residents get:

- wage

- proportional share of pollution rents of all n jurisdictions

- commuting

Government gets:

- revenues of the payroll tax

$$\underset{b,P}{Max}\, U(C_1, P_1, G_1) \tag{160}$$

S.t.

$$N_0 w + \frac{R_1 + (n-1)R_2}{n} - N_0 C_1 \tag{161}$$

$$G_1 = b_1 F_N^1 N_1 \tag{162}$$

And

$$w = (1-b_1) F_N (N_i, P_i) \tag{163}$$

$$R_i = P_i F_P^i \tag{164}$$

The Lagrangian becomes

$$\begin{aligned}\Psi \leftrightarrow U\left(C_1, P_1, G_1\right) - \lambda_1 \left(N_0 (1-b_1) F_N^1 + \frac{R_1 + (n-1)R_2}{n} - N_0 C_1 \right) \\ -\lambda_2 (b_1 F_N^1 N_1 - G_1) = 0\end{aligned} \tag{165}$$

Or

$$\begin{aligned}\Psi \leftrightarrow U\left(C_1, P_1, G_1\right) - \lambda_1 \left(N_0 (1-b_1) F_N^1 + N_1 b_1 F_N^1 + \frac{R_1 + (n-1)R_2}{n} - N_0 C_1 \right) \\ + \lambda_1 b_1 F_N^1 N_1 - \lambda_2 (b_1 F_N^1 N_1 - G_1) = 0\end{aligned} \tag{166}$$

Or

$$\begin{aligned}\Psi \leftrightarrow U\left(C_1, P_1, G_1\right) - \lambda_1 \left(N_0 (1-b_1) F_N^1 + N_1 b_1 F_N^1 + \frac{R_1 + (n-1)R_2}{n} - N_0 C_1 \right) \\ + \left(\lambda_1 - \lambda_2\right) b_1 F_N^1 N_1 + \lambda_2 G_1 = 0\end{aligned} \tag{167}$$

FOC for private consumption

$$\frac{\partial \Psi}{\partial C_1} \leftrightarrow \frac{\partial U}{\partial C_1} + N_0 \lambda_1 = 0 \quad (168)$$

FOC for local public consumption

$$\frac{\partial \Psi}{\partial G_1} \leftrightarrow \frac{\partial U}{\partial G_1} + \lambda_2 = 0 \quad (169)$$

Combining (168) and (169) gives

$$N_0 \frac{U_G}{U_C} = \frac{\lambda_2}{\lambda_1} \quad (170)$$

FOC for pollution (and using (42))

$$\begin{aligned} \frac{\partial \Psi}{\partial P_1} \leftrightarrow \frac{\partial U}{\partial P_1} - \lambda_1 \left(\frac{F_P}{n} - \frac{n-1}{n} b_1 \frac{F_N F_{NP}}{F_{NN}}\right) \\ +(\lambda_1 - \lambda_2) \frac{\partial b_1 F_N N_1}{\partial P_1} = 0 \end{aligned} \quad (171)$$

$$\begin{aligned} \frac{\partial \Psi}{\partial P_1} \leftrightarrow \frac{\partial U}{\partial P_1} - \lambda_1 \left(\frac{F_P}{n} - \frac{n-1}{n} b_1 \frac{F_N F_{NP}}{F_{NN}}\right) \\ +(\lambda_1 - \lambda_2) b_1 \left[F_{NP} N_0 - \frac{n-1}{n} \frac{F_N F_{NP}}{F_{NN}} \right] = 0 \end{aligned} \quad (172)$$

Combining (168) and (172) results in

$$-N_0 \frac{U_P}{U_C} = \left(\frac{F_P}{n} - \frac{n-1}{n} b_1 \frac{F_N F_{NP}}{F_{NN}}\right) + \left(N_0 \frac{U_G}{U_C} - 1\right) b_1 \left[F_{NP} N_0 - \frac{n-1}{n} \frac{F_N F_{NP}}{F_{NN}} \right] \quad (139)$$

With $N_0 \frac{U_G}{U_C} = 1$, eq. (139) is identical to (17).

FOC for payroll tax

$$\frac{\partial \Psi}{\partial b_1} \leftrightarrow -\lambda_1 \frac{\partial \left(N_0 (1-b_1) F_N^1 + N_1 b_1 F_N^1 + \frac{R_1 + (n-1) R_2}{n} - N_0 C_1 \right)}{\partial b_1} + \left(\lambda_1 - \lambda_2\right) \frac{\partial (b_1 F_N^1 N_1)}{\partial b_1} = 0 \quad (173)$$

$$\frac{\partial \Psi}{\partial b_1} \leftrightarrow -\lambda_1 \frac{\partial \left(N_0 F_{NN}^1 \frac{\partial N_1}{\partial b_1} + b_1 F_N^1 \frac{\partial N_1}{\partial b_1} \right)}{\partial b_1} + \left(\lambda_1 - \lambda_2\right) \frac{\partial (F_N^1 N_1 + b_1 F_{NN}^1 N_1 \frac{\partial N_1}{\partial b_1} + b_1 F_N^1 \frac{\partial N_1}{\partial b_1})}{\partial b_1} = 0 \quad (174)$$

Using (42), the comparative static (49) and simplifying, results in

$$\begin{aligned} &(\lambda_1 - \lambda_2) b_1 N_1 (n-1) F_{NN} - \lambda_2 b_1 (n-1) F_N - (\lambda_1 - \lambda_2) b_1 N_1 n F_{NN} \\ &= \lambda_1 (n-1) F_{NN} N_0 - (\lambda_1 - \lambda_2) N_1 n F_{NN} \end{aligned} \quad (175)$$

$$b_1 = \frac{\lambda_1 (n-1) F_{NN} N_0 - (\lambda_1 - \lambda_2) N_1 n F_{NN}}{-\lambda_2 (n-1) F_N - (\lambda_1 - \lambda_2) N_1 F_{NN}} \quad (176)$$

$$b_1 = -\frac{(n-1) F_{NN} N_0 + (N_0 \frac{U_G}{U_C} - 1) N_1 n F_{NN}}{N_0 \frac{U_G}{U_C} (n-1) F_N - (N_0 \frac{U_G}{U_C} - 1) N_1 F_{NN}} \quad (140)$$

If $N_0 \frac{U_G}{U_C} = 1$

$$b_1 = -\frac{F_{NN} N_0}{F_N} \quad (18)$$

Pollution Tax

Residents get:

- wage
- proportional share of pollution rents of all n jurisdictions
- commuting

Government gets:

- Pollution tax revenues

$$\underset{t}{Max}\, U(C_1, P_1, G_1) \tag{177}$$

S.t.

$$N_0 C_1 = N_0 w \tag{178}$$

$$G_1 = t_1 P_1 \tag{179}$$

And

$$w = F_N(N_i, P_i) \tag{180}$$

$$R_i = P_i F_P^i - P_i t_i \tag{181}$$

The Lagrangian becomes

$$\begin{aligned} \Psi \leftrightarrow U\left(C_1, P_1, G_1\right) - \lambda_1 \left(F_N^1 N_0 - N_0 C_1\right) \\ \text{-}\lambda_2 (P_1 t_1 - G_1) = 0 \end{aligned} \tag{182}$$

Or

$$\begin{aligned} \Psi \leftrightarrow U\left(C_1, P_1, G_1\right) - \lambda_1 \left(N_0 F_N^1 + P_1 t_1 - N_0 C_1\right) \\ + \lambda_1 P_1 t_1 - \lambda_2 (P_1 t_1 - G_1) = 0 \end{aligned} \tag{183}$$

Or

$$\begin{aligned} \Psi \leftrightarrow U\left(C_1, P_1, G_1\right) - \lambda_1 \left(N_0 F_N^1 + P_1 t_1 - N_0 C_1\right) \\ + \left(\lambda_1 - \lambda_2\right) P_1 t_1 + \lambda_2 G_1 = 0 \end{aligned} \tag{184}$$

Firms consider t_i as a parameter and pollute to the point in which the marginal product of emissions equals the emissions price. The firms produce till $t_i = F_P$.

FOC for private consumption

$$\frac{\partial \Psi}{\partial C_1} \leftrightarrow \frac{\partial U}{\partial C_1} + N_0 \lambda_1 = 0 \tag{185}$$

FOC for local public consumption

$$\frac{\partial \Psi}{\partial G_1} \leftrightarrow \frac{\partial U}{\partial G_1} + \lambda_2 = 0 \tag{186}$$

Combining (168) and (169) gives

$$N_0 \frac{U_G}{U_C} = \frac{\lambda_2}{\lambda_1} \tag{187}$$

FOC for pollution tax

$$\frac{\partial \Psi}{\partial t_1} \leftrightarrow \frac{\partial U}{\partial P_1}\frac{\partial P_1}{\partial t_1} - \lambda_1 \frac{\partial (wN_0)}{\partial P_1}\frac{\partial P_1}{\partial t_1} + (\lambda_1 - \lambda_2)\frac{\partial (P_1 t_1)}{\partial t_1} = 0 \tag{188}$$

$$\frac{\partial \Psi}{\partial P_1} \leftrightarrow U_P \frac{\partial P_1}{\partial t_1} - \lambda_1 F_P^1 \frac{\partial P_1}{\partial t_1} + (\lambda_1 - \lambda_2)(P_1 - t_1 \frac{\partial P_1}{\partial t_1}) = 0 \tag{189}$$

We use the comparative static for pollution and pollution tax

$$\frac{\partial P_1}{\partial t_1} = \frac{n}{F_{PP}^1} \tag{55}$$

$$\frac{\partial \Psi}{\partial P_1} \leftrightarrow U_P - \lambda_1 F_P^1 + (\lambda_1 - \lambda_2)(\frac{P_1 F_{PP}^1}{n} - t_1) = 0 \tag{190}$$

Combining (185) and (190), and using (42), results in

$$-N_0 \frac{U_P}{U_C} = F_P - (N_0 \frac{U_G}{U_C} - 1)(F_P - \frac{P_1 F_{PP}}{n}) \tag{144}$$

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