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Congestion, Land Use, and Job Dispersion: A General Equilibrium Model[1]

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In dispersed cities, congestion tolls would drive up central wages and rents and would induce centrally located producers to want to disperse closer to their workers and their customers, paying lower rents and realizing productivity gains from land to labor substitution. But the tolls would also induce residents to want to locate more centrally in order to economize on commuting and shopping travel. In a computable general equilibrium model, we find that the centralizing effect of tolls on residences dominates on the decentralizing effect of tolls on firms, causing the dispersed city to have more centralized job and population densities. Under stylized parameters, we find that efficiency gains from levying congestion tolls on work and shopping travel are 3.0% of average income. About 80% of such gains come from road planning and 20% from tolls. © 1999 Academic Press

1. INTRODUCTION

This paper has two related goals. The first, a technical goal, is to develop and present a fully closed computable general equilibrium model of urban land use without any predetermined employment locations and with endogenous traffic congestion. In this model, the locations of firms and

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consumers are interdependent and, at equilibrium, firms and consumers are dispersed everywhere within the urban area. The study of such a model is motivated by the fact that the standard monocentric model of urban land use assumes that all employment is located in the Central Business District (CBD) and that all travel is to the CBD and is work related. This standard model has lost its relevance as the weakening of agglomeration economies continues to cause urban land uses to evolve towards a higher degree of polycentricity and employment dispersion.[2]

The paper's second goal is to solve the computable general equilibrium model in order to examine how the imposition of congestion tolls would modify land use patterns in the dispersed urban form. This focus is motivated by the fact that theoretical analyses of the effects of congestion tolls have relied almost exclusively on the standard monocentric model.[3] Hence, the numerous analyses published do not shed light on how the imposition of tolls would change the *dispersion* of jobs and residences within an urban area.

In order to illustrate our limited understanding of how tolls affect land use, it is useful to start reasoning from the monocentric model and then gradually broaden our intuition. The predictions based on the monocentric model are straightforward. If residents commuting to the CBD are tolled for their contribution to congestion, the residential apron around the CBD becomes more compact and residents move closer to the CBD to offset the burden of the tolls. Welfare is improved, since the distortion initially caused by the congestion externality is offset by the Pigouvian tolls. These predictions are based on assuming no response whatsoever from employers in the CBD.

A fuller but still limited picture of how congestion tolls would affect land use in a monocentric city can be pieced together from an extension of the comparative static analysis of the standard closed-in-population partial equilibrium model (see Wheaton [26]). To see this, consider first that commuters engage in a labor-leisure trade-off, which is ignored in the standard model. Then, imposing congestion tolls would *inter alia* cause

[2] See Gordon and Richardson [8] for a discussion of recent trends in employment dispersion.

[3] Advocacy of congestion pricing dates back to the contributions of Walters [25] and Vickrey [24]. The first analysis of the land use effects of congestion pricing is by Strotz [20]. Some early analytical results are due to Mills and DeFerranti [15], Henderson [10] and Arnott and MacKinnon [2]. These authors ignored land use within the CBD. Solow and Vickrey [19] provided the first treatment of congestion within the CBD and Livesey [12] the first treatment of congestion both within the CBD and in the residential ring, in a monocentric city. Empirical studies have had to assume that the location of activities does not respond to congestion and congestion pricing (see, for example, Meyer, Kain, and Wohl [14] and Keeler and Small [11]).

them to reduce their labor supply to the CBD. This, in turn, would cause employers (who, in the standard model, are assumed not to be able to move out of the CBD) to initially offer higher wages. The comparative statics tells us that the transportation cost increase (due to tolls) would initially cause the city to shrink and residential densities to rise, while the income increase (induced by tolls) could expand the city and flatten residential densities. The combined effect of these two influences is ambiguous.

Tolls would also affect the level of land rents in the urban economy which, in turn, would influence the consumer’s income from land shares. The change in overall income from wages and rents is itself ambiguous in sign.[4] In summary, once the labor market is considered, congestion tolls could either contract or expand the residential part of the monocentric city, and either flatten or steepen the rent and density functions.

Consider now that employers could respond to tolls on commuters by moving out of the CBD and thus locating jobs closer to the commuters’ residences. Similarly, retailers could respond to congestion tolls by locating stores and shopping centers nearer customers. Firms value access to customers and to workers, and households to their jobs and to retailers. A change in the cost of travel causes a reevaluation of each of these types of access, setting off a process of circular feedback between firms and households.

In our model, this circular feedback unfolds as follows. The equilibrium spatial distribution of jobs is relatively more centralized around the city’s *geometric center* than is the spatial distribution of residences. Imposing congestion tolls has the following two effects. On the one hand, if one could keep the spatial distribution of residences unchanged, tolls increase the commuting and shopping travel costs of consumers and would raise central rents and wages. This would induce firms to decentralize, substitute land for labor in production, and increase productivity. Tolls would thus cause firms to become more dispersed among the consumers. On the other hand, if one could keep the spatial distribution of firms (and jobs) unchanged, consumers would respond to tolls by locating more centrally, since this helps economize on gross-of-tolls costs of commuting and shopping travel. This would, in turn, confer higher accessibility advantages to centrally located firms. To the extent that the distribution of residences becomes more centralized, the tendency of firms to become more decentralized would be offset. In the simulations presented in this paper, the centralizing influence of tolls on residential land use does dominate over the decentralizing influence of tolls on business land use. The combined

[4] Pines and Sadka [17] provided a comparative statics analysis of a city in which rental income redistribution takes place.

effect, therefore, is that the imposition of tolls causes the spatial distribution of jobs and residences to become more centralized. This result holds true in the short run, when the allocation of land to roads is inefficient, as well as in the long run when the allocation of land to roads is first-best efficient.

We also find that, for a dispersed city, the gain from efficiently allocating land to roads and from tolls is about 3.0% of average consumer income, but only 20% of this is from tolls with the remaining 80% coming from road planning. Meanwhile, in the absence of agglomeration economies which can cause distinct subcenters, much higher efficiency gains come when jobs, in an initially monocentric city, disperse. This suggests that it might be better to focus on relaxing unreasonable land use restrictions on employment (if such exist), rather than on tolling traffic.

The paper is organized as follows. In Section 2 we present the structure of the model and we discuss the properties of the *dispersed general equilibrium* in which rents, wages, and the retail price are endogenously determined. In Section 3 some properties of this dispersed equilibrium are examined, parameters are selected, and a base simulation is presented. In Section 4, we examine the effects of tolls on employment and residential land use dispersion and do a stylized efficiency analysis of congestion tolls. Section 5 concludes.

2. THE MODEL

We utilize a general equilibrium model similar to that of Anas and Kim [1] which treats the linkages between firms and households. There are no predetermined employment centers. Jobs and residences are locationally unconstrained and their spatial distributions are interdependent through the labor and shopping markets. Consumers value locational variety in shopping and their taste for variety is specified as in Dixit and Stiglitz [5], so that they want to shop everywhere, although the number of trips made to retailers at a particular location attenuates with the full cost of the trip. The taste for locational variety is equivalent to assuming that goods produced and sold at different locations are viewed as product variants by virtue of their location. This also means that as the city expands, product variety is improved. Hence, consumers prefer a spread out city to a compact one, because the former offers more variety.

Given the spatial distribution of firms, households respond to more costly transport by moving closer to their jobs and/or by locating more centrally with respect to the distribution of retailers. At the same time, given the spatial distribution of residences, firms respond to more costly transport by locating closer to workers and/or customers. This interdependence among the economy's agents results in a dispersed land use equilibrium in which accessibility to the *geometric center* guides the city's selforganization. At equilibrium, jobs and residences occur everywhere within the urban area. Land rent and residential and job densities peak at the geometric center and decline towards the edges of the space but, under stylized parameters, the spatial distribution of jobs is more centralized than the spatial distribution of residences.

Our model is related to the models of Beckmann [3], Borukhov and Hochman [4], and Solow and Vickrey [19], which treat spatial equilibrium without a predetermined center. These three models are partial equilibrium. The first two papers treat an economy of households who make social visits to one another. Income is exogenous. Congestion is not treated. Solow and Vickrey do treat congestion within a linear CBD in which there are only firms interacting with one another. In these models, the intensity of interaction between two agents does not attenuate with the distance between them. Also, each agent is *forced* to interact with each of the others.

Other authors have focused, as we do in this paper, on the interaction between firms and households. In Papageorgiou and Thisse [16] (a partial equilibrium model which ignores congestion and labor markets) each household visits each of the firms in a linear space. They assumed that the intensity of interaction attenuated with distance in an exogenously specified manner. Fujita and Ogawa [7] and Fujita [6] developed quasi-general equilibrium models. In the former, households are assigned to job and home locations and spatial wage as well as rent functions are determined, but shopping trips are ignored. In Fujita [6], jobs are ignored but consumers value product variety and travel to each firm to shop. Congestion is not treated in either model and there is no substitution of land for labor in production and of land for goods and leisure in consumption.

Another group of papers is Sullivan [22], Usowski [23], and Sivitanidou and Wheaton [18]. These either do not treat congestion (Sullivan's is the exception) or are not focused on its effects, but they are of interest because they treat, as we do, the interaction of urban land and labor markets in a nonmonocentric context. Each paper deals with just *two* predetermined centers: the CBD and a Suburban Business District (SBD). Sullivan's model is fully closed general equilibrium, Usowski's is quasi-general equilibrium, and Sivitanidou and Wheaton's is partial equilibrium.

2.1 *The Setting*

Figure 1 shows the urban space. We cut an area of φ radians out of a circular city and divide it into annular wedges (zones). Zone 6 is the geometric center and has a one-mile diameter, while all others are of one-mile widths. This scheme preserves the simplicity of travel in a single direction, while capturing the feature that in real cities the supply of land

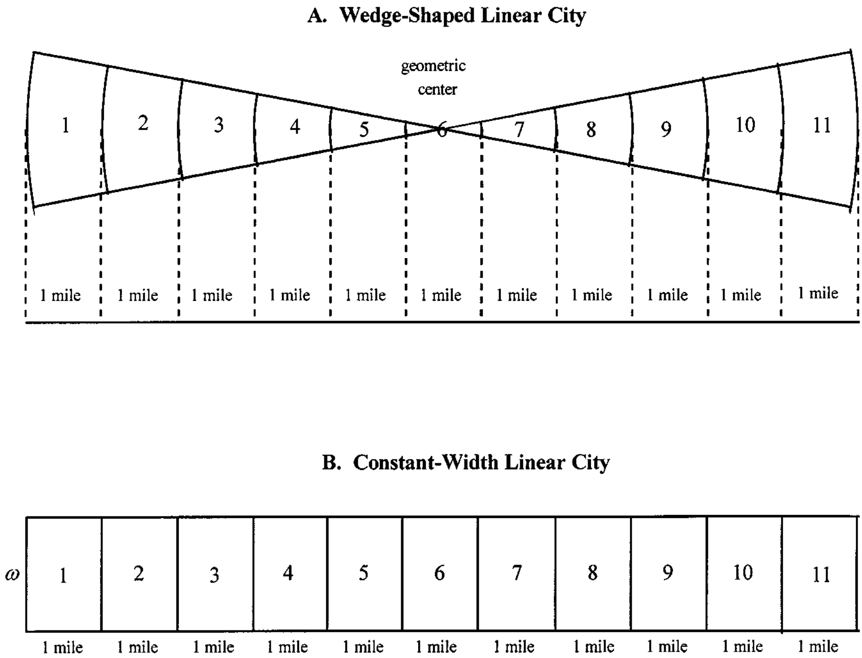

FIGURE 1.

increases with distance from the geometric center.[5] The area of the central zone is $(1/2)\varphi\pi$, while the area of a zone i miles from the center ($i \geq 0.5$) is $A_i = \varphi\pi(R_i^2 - R_{i-1}^2)$, where R_{i-1} and R_i are the zone's inner and outer radii. The number of zones is I, which will be endogenous, and the edge zones could be fractional.

2.2 *Firms*

When production is dispersed among all zones, the markets for land, labor, and the locally produced good will clear in each zone, establishing an equilibrium rent (r_i), wage (w_i), and commodity price (p_i) in each zone i. Firms producing at the same zone are identical and competitive in the output and input (land and labor) markets. However, from the consumers' point of view, goods produced in different zones are differentiated by virtue of their location. The firm's technology is Cobb−Douglas and constant returns to scale, with labor and land the only two inputs. Hence,

[5] Because in our model consumers choose to visit all locations, circumferential travel would occur if our city were two-dimensional. We deal with a linear city in order to avoid this complication.

the number of firms in a zone is indeterminate. Let X_i be the aggregate output produced in zone i and let M_i and Q_i be the aggregate labor and land inputs utilized in the zone. Then, $X_i = BM_i^{\delta}Q_i^{\mu}$ with $\delta + \mu = 1$. The aggregate conditional input demand functions are $M_i^* = \delta p_i X_i w_i^{-1}$ and $Q_i^* = \mu p_i X_i r_i^{-1}$. Free entry in each zone insures that profit maximizing firms make zero economic profit. Recall that the cost function is $C(w_i, r_i, X_i) = (B\delta^{\delta}\mu^{\mu})^{-1} w_i^{\delta} r_i^{\mu} X_i$. Hence, the condition that price equals average (= marginal) cost gives

$$p_i = \left[B\delta^{\delta}(1-\delta)^{1-\delta}\right]^{-1} w_i^{\delta} r_i^{1-\delta}. \tag{1}$$

2.3 *Consumers*

A consumer resides in some zone i and works in some zone j. We refer to the zone-pair (i, j) as the consumer's "job-residence pair" or "commuting arrangement." The consumer residing at i travels from i to every zone where production occurs to shop the unique good produced there. We assume that separate trips are made to each production zone, purchasing a unit quantity per trip.[6] The consumer's utility function is

$$U_{ij} = \alpha \ln\left(\sum_{k=1}^{I} Z_{ijk}^{\eta}\right)^{1/\eta} + \beta \ln q_{ij} + \gamma \ln L_{ij} + u_{ij}, \tag{2}$$

where $\alpha, \beta, \gamma > 0$, $\alpha + \beta + \gamma = 1$, $0 < \eta < 1$. q_{ij} is the lot size at i, L_{ij} are the leisure hours, and Z_{ijk} is the number of shopping trips the consumer makes to zone k. u_{ij} are idiosyncratic taste constants which vary among the consumers for each (i, j). We will assume, as was the case in Anas and Kim [1], that the idiosyncratic tastes are identically and independently distributed (i.i.d.) for each (i, j), i.e., are spatially uncorrelated.

Note that the shopping subutility function is of the Dixit–Stiglitz [5] form, with constant elasticity of substitution $1/(1-\eta)$, and embodies an *extreme* taste for variety. The marginal utility from the first trip to a new shopping zone is infinite. Hence, the consumer will choose to shop at each zone where shopping is possible, regardless of the price and travel cost of making such a trip, but the number of trips made to a zone will decrease with price and travel cost. Meanwhile, because the overall utility is of the Cobb–Douglas form, α is the disposable income share spent on all shopping.[7]

[6] This assumption rules out "trip chaining" which has not been studied in an urban model.

[7] A difference between the current model and Anas and Kim's treatment is that, in the latter, the number of zones was fixed and the shopping subutility was defined to be Cobb–Douglas in form.

There are N consumers, each with annual time endowments H. Let ν be the number of work days in a year. Also, let t_{ij} be the money cost of one-way travel from i to j and let g_{ij} be the one-way travel time from i to j. The budget constraint is

$$\sum_{k=1}^{I} Z_{ijk}\left(p_k + 2t_{ik}\right) + r_i q_{ij} + 2\upsilon t_{ij} = w_j\left(H - T_{ij} - L_{ij}\right) + D \quad (3)$$

where $T_{ij} = 2\upsilon g_{ij} + \sum_{k=1}^{I} 2g_{ik} Z_{ijk}$ and $D = (1/N)\sum_{i=1}^{I} A_i r_i$. T_{ij} is the total annual travel time of the consumer with commuting arrangement (i, j) and consists of commuting and shopping travel times. $H - T_{ij} - L_{ij} \geq 0$ are the labor hours supplied annually by the consumer.[8] D is the rent dividend paid to each consumer reflecting his share of land. Rearranging (3) we write it as

$$\sum_{k=1}^{I} Z_{ijk}\,\rho_{ijk} + r_i q_{ij} + w_j L_{ij} = \Omega_{ij} \quad (3')$$

where $\Omega_{ij} \equiv w_j H + D - 2\upsilon(t_{ij} + w_j g_{ij})$ is the consumer's full economic income net of the money cost and time-value of commuting, and $\rho_{ijk} \equiv p_k + 2t_{ik} + 2w_j g_{ik}$ is full price of a shopping trip to zone k, inclusive of the round-trip money cost and time value.

Given a commuting arrangement (i, j), the consumer maximizes (2) subject to (3′) with respect to $\mathbf{Z} \equiv [Z_{ij1}, Z_{ij2}, \ldots, Z_{ijI}]$, q_{ij} and L_{ij}. Letting $\theta \equiv \eta/(\eta - 1) < 0$, the Marshallian demands are:

$$Z_{ijk} = \frac{\rho_{ijk}^{\theta}}{\sum_{s=1}^{I} \rho_{ijs}^{\theta}}\,\alpha\,\Omega_{ij}\,\rho_{ijk}^{-1}, \quad (4)$$

$$q_{ij} = \beta\Omega_{ij} r_i^{-1}, \quad (5)$$

$$L_{ij} = \gamma\Omega_{ij} w_j^{-1}. \quad (6)$$

Substituting (4)–(6) into (2), the indirect utility function is $U_{ij}^{*} = V_{ij} + u_{ij}$, where

$$V_{ij} \equiv \ln \Omega_{ij} - \frac{\alpha}{\theta} \ln\left(\sum_{k=1}^{I} \rho_{ijk}^{\theta}\right) - \beta \ln r_i - \gamma \ln w_j. \quad (7)$$

[8] This inequality is satisfied for each consumer in all of our simulations. Hence, all consumers work and there is no consumer who derives income from land ownership only.

Given this optimization for *each* (i, j), the consumer must now compare commuting arrangements and choose the most preferred, taking into account his idiosyncratic tastes. Since these are distributed among the consumers for each (i, j), choices are described probabilistically in the form of a discrete choice model

$$\Psi_{ij} = \text{Prob}\left[V_{ij} + u_{ij} > V_{sm} + u_{sm}, \forall (s, m) \neq (i, j)\right], \tag{8}$$

where Ψ_{ij} is the probability that a randomly selected consumer most-prefers commuting arrangement (i, j). Assuming that the i.i.d. u_{ij}'s are Gumbel distributed with $\text{E}[u_{ij}] = 0$, variance σ^2 and dispersion parameter $\lambda = \pi/(\sigma\sqrt{6})$, the choice probabilities are multinominal logit:[9]

$$\Psi_{ij} = \frac{\exp(\lambda V_{ij})}{\sum_{s=1}^{I} \sum_{m=1}^{I} \exp(\lambda V_{sm})}; \quad \sum_{i=1}^{I} \sum_{j=1}^{I} \Psi_{ij} = 1. \tag{9}$$

The role of the dispersion parameter (λ) is critical. At one extreme, as $\lambda \to \infty$, taste idiosyncrasies vanish and all consumers choose identically. In this case, the Ψ_{ij} which corresponds to the highest V_{ij} goes to one and all others go to zero (or a number of (i, j) are tied as most-preferred and are chosen equiprobably). At the other extreme, as $\lambda \to 0$, idiosyncrasies swamp the systematic part of utility (given by the V_{ij}'s) and consumers choose randomly so that each $\Psi_{ij} = 1/I^2$.

To measure overall welfare, we make use of the expected value of the maximized utilities. Under the foregoing assumptions, it is[10]

$$\text{E}\left[\max_{ij}\left(V_{ij} + u_{ij}\right)\right] = \frac{1}{\lambda} \ln \sum_{s=1}^{I} \sum_{m=1}^{I} \exp(\lambda V_{sm}). \tag{10}$$

A bit of algebra allows us to rewrite (10) as[11]

$$\text{E}\left[\max_{ij}\left(V_{ij} + u_{ij}\right)\right] = \sum_{s=1}^{I} \sum_{m=1}^{I} \Psi_{sm} V_{sm} + \left[-\frac{1}{\lambda} \sum_{s=1}^{I} \sum_{m=1}^{I} \Psi_{sm} \ln \Psi_{sm}\right]. \tag{10'}$$

[9] For the derivation of the multinomial logit model see, for example, McFadden [13].

[10] It is important that $\max_{ij}(V_{ij} + u_{ij})$ is itself Gumbel distributed with dispersion parameter λ. Hence, changes in the nonidiosyncratic utilities will shift the mean of the expected value of the maximized utilities given by (10), without altering the variance of the maximized utilities. This property makes welfare comparisons based on (10) straightforward.

[11] Take the natural log of both sides of (9) for each (i, j). Divide each resulting expression by λ. Multiply the (i, j)th equation by its corresponding choice probability. Sum the resulting expressions over (i, j) and solve for the right side of (10).

The first set of summations on the right is the mean of the nonidiosyncratic utilities. The bracket on the right (which is positive) measures the amount by which the expected maximum utility exceeds the mean nonidiosyncratic utility. The second set of summations vanishes as $\lambda \to \infty$ and goes to infinity as $\lambda \to 0$. The last fact means that the expected value of maximized utilities increases with the variance of idiosyncratic tastes. Clearly, that happens because more varied tastes afford higher levels of *maximized* utilities. Note from (10) that, *ceteris paribus*, adding more commuting arrangements (i.e., enlarging the diameter of the city) improves expected welfare as a higher variety of job-residence pairs means that idiosyncratic tastes are better matched on average.

The case of finite λ has empirical validity. In observing actual travel patterns, it is easy to see that many possible commuting arrangements are used (see, for example, Hamilton [9], which gave rise to the "wasteful commuting" literature). Such a pattern is readily explained by assuming idiosyncratic tastes, but cannot be explained using the uniform-tastes assumption of the standard model of urban economics.

2.4 *Transport*

Roads are provided using land only. Let $S_i \leq A_i$ be the land in zone i put in roads and let F_i be the two-way flow of commuting plus shopping trips crossing zone i per day. The expected commutes from i to j are ${}^wF_{ij} \equiv N\Psi_{ij}$ and the expected shopping trips per day from i to j are ${}^sF_{ij} \equiv (N/v)\sum_{s=1}^{I} \Psi_{is}Z_{isj}$ where i is a zone of residence, j is a shopping zone, and $s = 1, 2, \ldots, I$ are all work zones. Total trips from i to j are then $F_{ij} \equiv {}^wF_{ij} + {}^sF_{ij}$. To obtain zonal traffic flows, we must distinguish between edge zones ($i = 1$ and $i = I$) and internal zones $1 < i < I - 1$. For edges zones ($i = 1$ and $i = I$), $F_i \equiv F_{ii} + \sum_{j \neq i} (F_{ij} + F_{ji})$. For internal zones $(1 < i < I - 1)$, $F_i \equiv F_{ii} + \sum_{j \neq i} (F_{ij} + F_{ji}) + 2\sum_{j=1}^{i-1} \sum_{k=1}^{I-i} (F_{i-j,i+k} + F_{i+k,i-j})$. Note that traffic originating or terminating in i is assumed to cross only half of i and gets the weight one, while traffic crossing the entire zone i gets the weight two.

The time for a traveler to cross zone i is determined by the congestion function:

$$g_i = d\left[1 + b\left(\frac{F_i}{S_i}\right)^c\right];\ d, b > 0,\ c \geq 1. \tag{11}$$

Intrazonal travel times are $g_{ii} = (1/2)g_i$, while $g_{ii} = (1/2)(g_i + g_j) + \sum_{s=i+1}^{j-1} g_s$ are the interzonal times. The money cost of travel consists of a congestion toll which is the difference between the marginal and average time-costs of the traffic traversing zone i. The total time-cost of traffic traversing i is $G_i = F_i g_i$. Hence, the marginal time-cost is $d + db(1 + c)(F_i/S_i)^c$ and the congestion toll (in units of time) is $\tau_i = dbc(F_i/S_i)^c$. The monetary toll is $t_i = \tau_i \overline{w}_i$ where $\overline{w}_i$ is the weighted average wage rate of all the travelers (F_i) crossing zone i. In calculating $\overline{w}_i$, we recognize that wages of travelers in F_i differ according to their places of work.

Because the total time-cost of traffic, $G_i = F_i g_i$, is homogeneous of degree one in F_i and S_i, the first-best rule requires $\upsilon F_i t_i = S_i r_i$ in each zone i: that toll revenue just cover the rental cost of the land in roads. Plugging in $t_i = \overline{w}_i \tau_i$ and solving this for S_i we obtain the amount of land put in roads in zone i as

$$S_i = F_i \left(dbc\upsilon \overline{w}_i r_j^{-1} \right)^{1/(c+1)}. \tag{12}$$

We will also consider inefficient, short-run allocations. Suppose that $\mathbf{S} \equiv [S_1, S_2, \ldots, S_I]$, with each $S_i \le A_i$, is any short-run road allocation profile. Such an inefficient road profile can be financed either by a head tax or by a congestion toll. If financed by a toll, calculated as discussed above, the excess or shortfall in toll revenue should be redistributed among the consumers so that $D \equiv (1/N)[\sum_{i=1}^{I} A_i r_i + \sum_{i=1}^{I} (\upsilon t_i F_i - r_i S_i)]$. If roads are financed inefficiently by a head tax, then $t_i = 0$ for each i and $h = (1/N) \sum_{i=1}^{I} r_i S_i$ is the level of the head tax. Then, $D = (1/N) \sum_{i=1}^{I} A_i r_i - h$.

2.5 *General Equilibrium and Solution Procedure*

We now need to combine the consumption, production, and transport sectors to simultaneously clear the markets for land, labor and the locally produced commodity in each zone. We use an (*) to denote the previously defined functions for $Z_{ijk}, q_{ij}, L_{ij}, \Psi_{ij}, T_{ij}, M_i$ and Q_i. Then, in each i, the land, labor and X-good markets clear by

$$N \sum_{j=1}^{I} \Psi_{ij}^* q_{ij}^* + Q_i^* + S_i - A_i = 0, \tag{13}$$

where S_i is either the efficient long-run allocation S_i^*—given by the right side of (12)—or any inefficient short-run allocation, and

$$N \sum_{s=1}^{I} \Psi_{si}^* [H - T_{isi}^* - L_{si}^*] - M_i^* = 0, \tag{14}$$

$$N \sum_{n=1}^{I} \sum_{s=1}^{I} \Psi_{nsi}^* Z_{nsi}^* - X_i^* = 0. \tag{15}$$

To these excess demand equations, add the zero-profit conditions given by (1). Equations, (1), (13)–(15) are to be solved for the vectors **p**, **r**, **w**, and **X**. Note, however, that there are a couple of straightforward simplifications. *First*, (1) can be substituted into (13)–(15) to eliminate **p**. *Second*, **X** from Eq. (15) can be substituted into Q_i^*, M_i^* in (13)–(14). Then, the modified (13) and (14) are solved simultaneously for **r*** and **w***. Since (13) and (14) are implicit functions of **r** and **w**, an iterative procedure must be employed to get the equilibrium **r*** and **w***. Given **r*** and **w***, (15) is evaluated and the equilibrium **X*** is computed. While performing these iterative calculations of rents and wages, the rent dividend, the congested travel times, travel costs and traffic flows, and the allocation of land to roads (if efficient) are calculated according to the relationships derived earlier, each time that **r** and **w** are updated.

Because (13)–(15), together with the transportation sector, comprise a fully closed general equilibrium, Walras' Law holds and one price in $(\mathbf{p}, \mathbf{r}, \mathbf{w})$ is arbitrary. We will adopt the convention that the arbitrary (numeraire) price is the land rent of the central zone. The above discussion assumed that the number of zones I is predetermined. As explained, because of the taste for locational variety, adding more zones causes the equilibrium welfare to increase without bound: consumers prefer to spread over a larger and larger city making fewer and fewer trips to various shopping locations, rather than being concentrated in a relatively small city and making more trips to a smaller set of shopping destinations. A similar result was obtained by Fujita [6]–see his equation (4.25) on page 104—who shows that adding firms (i.e., new products) to a city where consumers value product variety increases the *equilibrium* level of utility without bound. To endogenize the length of the urban area at equilibrium, we assume that the land rent at the edge zones is anchored at some exogenous value (r_a).[12] Then, if the equilibrium edge rent is higher (lower) than r_a, the city length will expand (contract) in both directions until the edge rent equals r_a, because developers will convert to urban (non-urban) use any land near the edge until returns from such conversions are exhausted. Since zone sizes are discrete, we allow edge zones to be fractional, if necessary, so that the edge rent is as close as possible to r_a. The only parameter that needs adjusting for different zone lengths is d, in (11), the free-flow time of traversing a full length zone.

2.6 *Some Properties of Dispersed Equilibrium*

Note that Eq. (1)—the zero profit condition—is $p_i = (\text{constant})\, w_i^{\delta} r_i^{1-\delta}$ and relates the wage, rent, and product price correspondences. Pretend for

[12] We may think of r_a as the land rent of an outside economy. But note that economic linkages with the outside world are ignored.

a moment that p, w, and r are each continuous differentiable functions of χ, distance from the geometric center. Then, differentiating (1) with respect to χ, we get

$$\varepsilon_p(\chi) = \delta\varepsilon_w(\chi) + (1-\delta)\varepsilon_r(\chi) \tag{16}$$

where ε_p, ε_w and ε_r are the elasticities of the p, w, and r functions with respect to distance, χ. Equation (16) says that the distance-elasticity of the commodity price function is a weighted average of the distance elasticities of the rent and wage functions. Rearranging, we have $\varepsilon_r(\chi) = [1/(1-\delta)]\varepsilon_p(\chi) - [\delta/(1-\delta)]\varepsilon_w(\chi)$. Spatial equilibrium requires that $\varepsilon_r(\chi) < 0$ (otherwise the city would be infinitely long and land use densities would increase with distance from the geometric center). This, in turn, requires that $\varepsilon_w(\chi) > (1/\delta)\varepsilon_p(\chi)$. If $\varepsilon_w(\chi) > 0$, then $\varepsilon_p(\chi)$ can be either decreasing, invariant, or increasing with distance, and still result in $\varepsilon_r(\chi) < 0$. On the other hand, if $\varepsilon_w(\chi) \leq 0$, then $\varepsilon_p(\chi) \leq 0$ is necessary to have $\varepsilon_r(\chi) < 0$.

The economic cause of a possibly positive wage gradient is as follows. Suppose that the rent function declines steeply with distance from the geometric center. Then, producers substitute land for labor as their distance from the center increases. As more land is substituted for labor, the marginal product of labor can rise sufficiently with distance to cause competitive firms to pay higher wages. One of the factors which causes land rent to fall sharply and the wage to increase with distance from the geometric center is the fact that—in the wedge-shaped linear city—land supply increases linearly with distance from the center (see Fig. 1). Hence, it is not surprising that, in simulating the wedge-shaped linear city, we find a sharply falling equilibrium rent function and a wage function which rises with distance. By contrast, in simulating the constant-width city under the same parameter values, rent falls mildly with distance and the wage rate falls even more mildly. At equilibrium, it is possible for a consumer to commute past a high-wage location and accept a lower wage at a more distant location because the consumer attaches a positive idiosyncratic preference to that particular commuting arrangement.

3. CONGESTION AND DISPERSED EQUILIBRIUM

Table 1 shows parameters selected for the base simulation. We model a 5° wedge-shaped linear city of one-mile long zones (see Fig. 1). For comparison, we have also simulated a constant-width linear city with the same number of one-mile long zones and same total land area as the wedge-shaped city. Letting ω be the width, the area of the constant-width city is set so that $\omega I = \sum_{i=1}^{I} A_i$ where A_i is the area of the wedge-shaped

TABLE 1

Parameters for Base Simulation

Production					
	$B = 0.25$	$\delta = 0.65$	$\mu = 0.35$		
Consumers					
	$N = 50{,}000$	households (one commuter per household)			
	$H = 6{,}000$	hours per year (24 hours per day)			
	$v = 250$	work days per year			
	$\alpha = 0.45$	$\beta = 0.15$	$\gamma = 0.40$	$\eta = 0.60$	$\lambda = 5.0$
Transport					
	$d = 0.0222$	hours per mile (45 miles per hour)			
	$b = 500$	$c = 4.0$			
Setting					
	$\varphi = 5°$ ($\pi/72$ radians)				
	Zone length = 1 mile = 5280 feet				
	Rent in center (numeraire) = \$144.38/square foot				

ith zone. We suppose that the number of households in the 5° slice is 50,000 which (assuming one worker and three persons per household) would imply a population of 1.8 million commuters and 5.4 million people in a fully circular city. Our assumption is that free-flow (uncongested) travel time is 45 miles per hour. The congestion function, (11), resembles the Bureau of Public Roads form, with travel time a fourth power of the traffic-to-land ratio ($c = 4$). Cost-shares of labor and land in production are set at 65% and 35%, respectively. Preferences are set so that 45% of full economic (but not monetary) income goes to shopping, 15% to land, and 40% to leisure.

Using the 12 independent parameters in Table 1 (recall $\delta + \mu = 1$ and $\alpha + \beta + \gamma = 1$), we produce a fairly reasonable urban form in which roads are tolled and land is allocated optimally. The city is set at 11 miles long. So, there are $11^2 = 121$ commuting arrangements and 11^3 or 1331 shopping-commuting arrangements.

Only 9.86% of equilibrium welfare, as measured by the second term on the right side of (10′), is due to taste idiosyncrasies. Figures 2(a) and 2(b) show the equilibrium rent and wage profiles. Note that, when $c = 4.0$, land rent falls 14-fold from center to edge, while product prices fall to about half. Wages increase by 40%. The result that the rent function is much steeper than the wage and commodity price functions reflects two facts. One is that land is immobile. This means that while land near the geometric center is in relatively much greater demand by consumers, producers, and road planners, its supply there (as in each zone) is perfectly inelastic. The second fact is that the supply of land increases with distance from the geometric center. These two facts combine to cause a sharply

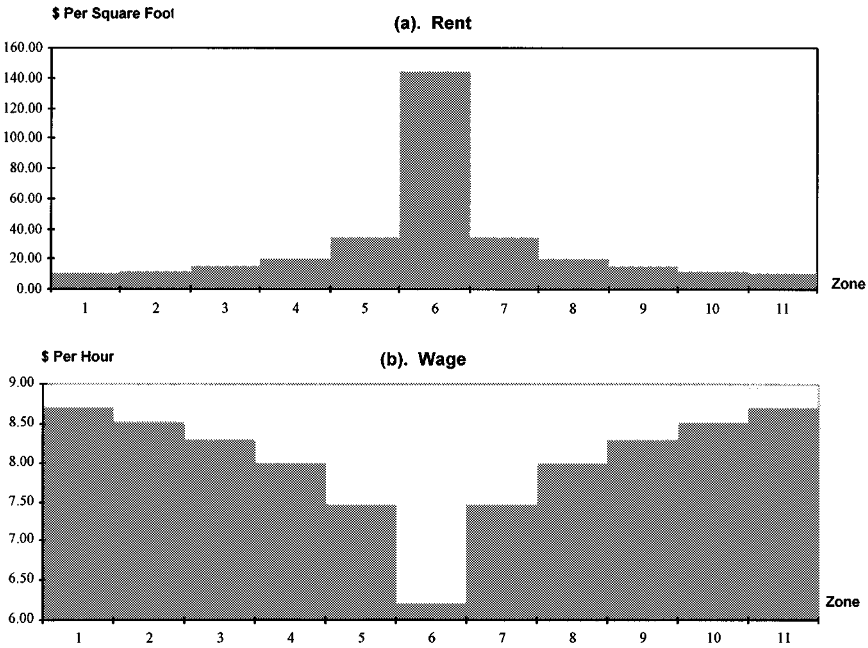

FIG. 2. The profile of rent and wage.

falling rent function.[13] By contrast, the supply of labor and product to each zone is elastic. Labor is in relatively greater demand near the center (because land there is so expensive and producers substitute labor for land), but workers can supply more labor to the center. Shopping is in relatively greater demand in the center (because the center is the most accessible point), but firms can meet that demand by producing more in the center. These effects cause the wage and price functions to be relatively flat.

Figure 3 shows the split of land among roads, production, and housing. Over the entire city, 49.24% of the land is used by households, 44.42% by firms, and the remaining 6.34% is taken up by roads. 62% of the land is required for roads in the central zone, but this percentage falls to about 1.4% in the edge zones.

A household's monetary income consists of wages earned which vary by the household's workplace plus dividends from land. On the average, a household's income is $42,463, but only 44.5% of this comes from wages,

[13] As already mentioned, in the constant-width city, the rent function is flatter under the same parameter values.

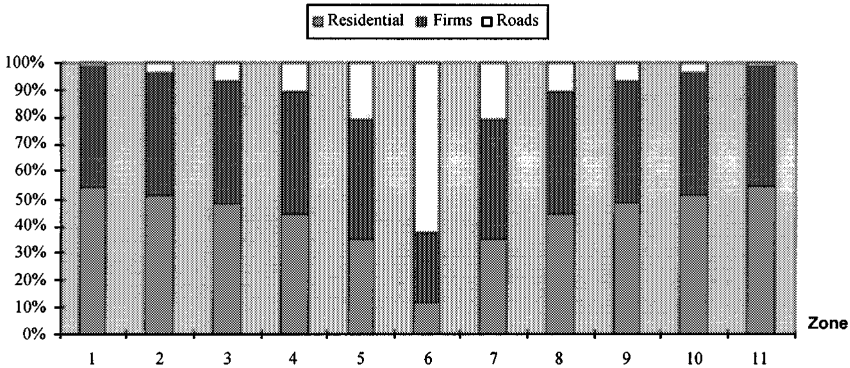

FIG. 3. Allocation of land to the residences, firms, and roads.

the rest being income from land rents.[14] 68.5% of *monetary* income is spent on shopping, 24.8% on land, and 6.7% on tolls. The average worker supplies 9.32 hours of labor and enjoys 13.93 hours of leisure, traveling about 45 minutes per day for work and shopping travel. Household lot size increases with distance from the center. It is about 62−77 square feet in zone 6 and rises to about 849−1094 square feet in the edge zones, varying within the same zone according to the workplace of households residing there. Figure 4 shows the gross residential and employment densities. Gross residential density falls from about 44,770 households per square mile in the center to 14,924 in the edge zones. Gross employment density falls from 153,941 in the center to 11,372 in the edge zones. The number of residents per zone increases from 977 in the center to 6512 at the edge and the number of jobs per zone increases from 3358 to 4962. Output, labor hours, and land used in production all increase with distance from the center. The land to labor hours ratio increases nearly 20 times, mirroring the steep drop in the rent to wage ratio.

Congested travel speed is 11.5 miles per hour in the center, but rises to 23.2 miles per hour in zones 5 and 7 and to 33.4 miles per hour in the edge zones. Tolls are levied at a rate of about $8.1 per hour of delay caused to others. This rate ($\overline{w}_i$) varies only slightly by zone. The toll paid per mile falls from $2.09 in the center to 25 cents in the edge zones. Crossing one mile takes 5.2 minutes in the center and 1.8 minutes at the edge.

[14] Our model overstates the role of land ownership, since it is a fully closed general equilibrium model: there is no absentee land ownership whatsoever and all rents paid (whether on roads, factories or housing) revert to households. Trade and labor migration among cities are ignored.

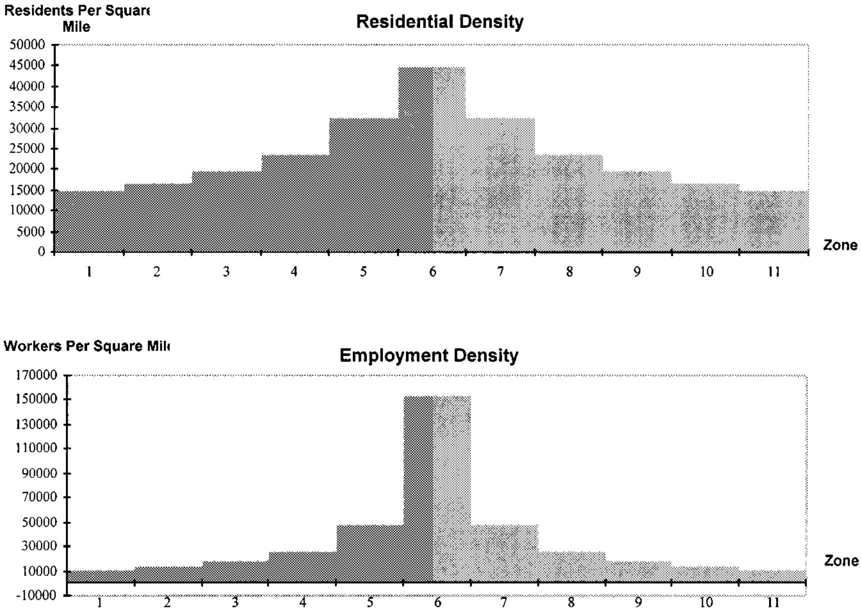

FIG. 4. The profiles of employment and residential density.

Consider next the commuting arrangements. Recall (and observe from Fig. 2) that equilibrium wage increases with distance, rising by 40% from center to edge.[15] As a consequence, given any residence zone i, the commuters residing in that zone and working in zone j increases with the wage offered at j. For example, only 7.1% of the center's residents also work in the central zone. 19.3% commute out to the edge zones. For the edge zone ($i = 1$), 11.7% of the residents in $i = 1$ work in $i = 1$, 6.6% work in the center, and 8.6% work in zone 11 (the other end of the city) because of the higher wage offered there and their idiosyncratic preference for the commuting-arrangement $(1, 11)$.

The price of the commodity (p) falls by 50% from center to edge. This is a reflection of the sharply falling land costs and mildly rising wage costs incurred by the firms. For any commuting arrangement (i, j), the full price of a shopping trip, ρ_{ijk}, also falls with the shopping destination's distance

[15] The wage function in the constant-width city falls mildly with distance and land for labor substitution is moderate. In such a city, the value of the marginal product of labor (= wage) does not to rise with distance, because product price falls with distance.

from the center. Given (i, j), the consumer's shopping trips to k increase with k's distance from the center.[16]

4. CONGESTION TOLLS AND THEIR IMPACT ON LAND USE

We now turn to the second goal of the paper which, as explained in the introduction, is to examine how the imposition of congestion tolls impacts the dispersion of jobs and residences at equilibrium. We will examine this under the assumptions that land is inefficiently and efficiently allocated to roads.

We begin with the assumption that land is initially inefficiently allocated to roads. As a stylized example of such an inefficient allocation, suppose that the amount of land allocated to roads is equal in each zone, but the total across the 11 zones equals the sum of the efficient land allocation of the base case. This corresponds to a constant-width road which contains too much land in roads at the periphery of the urban area and too little near the center. We treat two pricing schemes for such a short run allocation of land to roads. A ‘‘short-run unpriced’’ equilibrium is one in which the constant-width road is financed via a head tax (see Section 2.4). A ‘‘short-run priced’’ equilibrium is one where congestion tolls are levied to finance the constant-width road. This causes a surplus or deficit from road operations which is shared equally by the residents. If the city's length changes because of the pricing, the road width does not.

We refer to the first-best efficient road allocation (see Section 2.4), as the ‘‘long-run priced’’ equilibrium. We also consider the case where the land allocation is efficient, but a head tax (rather than congestion tolls) is used to finance the road. We refer to this case as a ‘‘long-run unpriced ’’ equilibrium.

Table 2 shows the effect of imposing congestion tolls on the spatial profiles of employment and population (or residential) density. Table 3 shows the effect of the tolls on the spatial profiles of rent and wage. The left halves of these tables show these results for the short-run situation when land allocation to roads is uniform, while the right halves show them for the long-run situation when the allocation of land to roads is first-best efficient. In both cases, congestion tolls cause the concentration of employment and population to increase near the center and to decrease in the outlying two or three zones.

[16] We also simulated the dispersed city assuming that shopping travel costs nothing and creates no congestion. That would be the case if everyone teleshopped. This causes the city to expand from 11 miles to more than 20. Transport savings are capitalized into higher rents and wages and incomes go up. Similar results are obtained if we assumed that all workers telecommute.

TABLE 2

Effect of Tolls on Job and Residential Densities in the Dispersed City

	Short-run		Long-run	
	Uniform allocation of land to roads		First-best allocation of land to roads	
Zone	Job density[1]	Population density[2]	Job density[1]	Population density[2]
1	12,813 (−1.5%)	16,077 (−0.8%)	11,579 (−1.8%)	15,087 (−1.0%)
2	14,136 (−1.2%)	17,067 (−0.6%)	14,122 (−0.9%)	16,896 (−0.2%)
3	18,253 (−0.4%)	19,850 (+0.1%)	18,186 (−0.1%)	19,487 (+0.4%)
4	26,079 (+0.5%)	24,328 (+0.9%)	25,896 (+0.5%)	23,659 (+0.8%)
5	47,600 (+1.6%)	33,283 (+1.5%)	47,127 (+1.4%)	32,089 (+0.9%)
6	146,662 (+4.5%)	40,775 (+1.0%)	148,898 (+3.4%)	44,633 (+0.3%)

[1] Workers per square mile employed in the zone before tolls are imposed (roads funded by head tax) and percentage change when tolls are imposed (in parentheses).

[2] Residents per square mile residing in the zone before tolls are imposed (roads funded by head tax) and percentage change when tolls are imposed (in parentheses).

TABLE 3

Effect of Tolls on Rents and Wages in the Dispersed City

	Short-run		Long-run	
	Uniform allocation of land to roads		First-best allocation of land to roads	
Zone	Rents[1]	Wages[2]	Rents[1]	Wages[2]
1	10.37 (0.0%)	7.85 (−0.4%)	10.37 (0.0%)	8.66 (+0.3%)
2	11.25 (+0.1%)	7.77 (−0.3%)	12.28 (+0.9%)	8.48 (+0.5%)
3	13.75 (+0.8%)	7.57 (−0.3%)	15.16 (+1.5%)	8.25 (+0.6%)
4	18.32 (+1.4%)	7.29 (−0.2%)	20.34 (+1.8%)	7.93 (+0.8%)
5	30.72 (+1.8%)	6.80 (+0.2%)	34.36 (+2.1%)	7.39 (+1.1%)
6	149.29 (+2.6%)	5.48 (+1.3%)	140.72 (+2.6%)	6.09 (+1.8%)

[1] Rent per square foot of land in the zone before tolls are imposed (roads funded by head tax) and percentage change when tolls are imposed (in parentheses).

[2] Wage per hour paid for jobs in the zone before tolls are imposed (roads funded by head tax) and percentage change when tolls are imposed (in parentheses).

This can be explained by recalling the two opposing effects of tolls on land uses. The first effect would cause firms to want to move out of the center where tolls cause rents and wages to increase the most, and to relocate closer to customers and laborers where land for labor substitution confers productivity gains. *Ceteris paribus*, such decentralizing moves by firms would partially mitigate the adverse effects of tolls on labor supply and on shopping access by customers. This effect, however, is dependent on keeping unchanged the spatial distribution of residences.

The second effect of tolls would cause residents of the dispersed city to move closer to the center (as they also do in all monocentric models) in order to mitigate the burden of tolls by reducing travel distances for commuting as well as for shopping. Then, if this second centralizing effect on residences is stronger than the first decentralizing effect on jobs, the overall effect is that both jobs and residences become more centralized after the imposition of tolls. In fact, the centralizing effect on residences is very powerful for centrally located producers because a slight concentration of residents toward the center greatly increases the accessibility of centrally located producers to customers and workers.

It can be seen from Table 2 that tolls cause residential densities in the central zone to increase by about 1% in the short run, while job densities in the central zone increase by 4.5%. In the long run, residential densities in the central zone increase by 0.3% while job densities increase by 3.4%. Meanwhile, Table 3 shows that tolls cause rents and wages to increase in the central zones relative to the peripheral zones.

We also examine efficiency gains from congestion tolls. The upper half of Table 4 shows the results for the four dispersed city cases. Efficiency gains (in welfare units) from congestion pricing are small. For example, introducing congestion pricing under the short-run road allocation increases the welfare level by only +0.042%, and under the long-run road allocation, welfare is increased by only +0.028%. Making the road allocation efficient increases welfare by +0.130% under congestion pricing or by +0.143% under the head tax. Thus, the efficiency gain from better road planning is 3.1–5.1 times as big as the gain from replacing the head tax with tolls. To make these numbers more tangible, we calculated a compensating variation between the short-run unpriced and the long-run priced allocations. Taxing each consumer for $1,130 per year (or 3.0% of income) would eliminate the gains from road planning and tolls.

It is useful to check these efficiency gains against a monocentric equilibrium under the same parameter values (see lower half of Table 4). We do this by assuming that all 50,000 jobs are located in the geometric center of a 7 zone city. Hence, all commuting and shopping trips terminate in the central zone (zone 4). An equilibrium wage and product price are endogenously determined for the central zone only. Land use in all other zones is divided between residences and roads. Since there are no agglomeration economies, a big welfare loss is caused by monocentricity. The dispersed city's welfare is about 26% higher. In the monocentric city, rent and wage incomes are lower and congestion tolls (or head taxes) are higher. Shopping travel is curtailed since variety is reduced. Output is greatly reduced because when production is centralized, this causes labor for land substitution, reducing the productivity of labor. In the monocentric case, the change in welfare from the short-run unpriced allocation to the long-run

TABLE 4

Per Capita and Aggregate Effects of Congestion Tolls in the Short-Run and Long-Run (a: head tax, b: tolls, *city length is rounded)

		Length			Roads	Time allocations (Hours/day)					
	Welfare	(miles) *	Rents ($/year)	Wages ($/year)	Taxes ($/year)	Work travel	Shop travel	Total travel	Labor	Leisure	Output (millions)
Dispersed											
Short-Run											
Unpriced	9.52320	10.8	$20,564	$16,719	$2591[a]	0.47	0.67	1.14	9.38	13.49	18.05
Priced	9.52721	10.8	$20,210	$15,981	$2571[b]	0.35	0.46	0.81	9.21	13.97	17.65
Long-Run											
Unpriced	9.53683	11.0	$23,266	$19,108	$2790[a]	0.40	0.58	0.98	9.48	13.55	18.38
Priced	9.53950	11.0	$23,560	$18,903	$2847[b]	0.32	0.43	0.75	9.32	13.93	18.01
Monocentric											
Short-Run											
Unpriced	7.55011	6.8	$17.224	$13,051	$3433[a]	0.47	0.16	0.63	9.81	13.56	4.20
Priced	7.55030	6.8	$17,430	$13,027	$3446[b]	0.46	0.15	0.61	9.64	13.75	4.14
Long-Run											
Unpriced	7.56523	7.0	$18,143	$14,210	$3122[a]	0.50	0.17	0.67	9.79	13.54	4.29
Priced	7.56535	7.0	$17,991	$13,873	$3068[b]	0.49	0.17	0.66	9.60	13.75	4.23

priced allocation is 0.2% (compared with 0.17% in the dispersed case) and the compensating variation computed for this case is $750 per consumer or 2.5% of average income. This result can be compared to that of Arnott and MacKinnon [2] who calculated gains from tolls of 0.068% of income and to that of Sullivan [21] who calculated gains of 1.91% of income. Both treated a monocentric setting, ignoring labor markets and shopping.

5. CONCLUSIONS

In the absence of agglomeration economies which can cause employment to concentrate in distinct subcenters, but in the presence of traffic congestion, dispersed urban forms are more productive, offer more variety, higher welfare, and less congestion than monocentric forms. We found that the imposition of congestion tolls in such a dispersed city caused both employment and residential density to increase near the center despite the fact that tolls motivate firms to decentralize in order to substitute land for labor and increase productivity. The reason for this result is that tolls also induce residents to centralize in order to reduce the burden of tolls on commuting and shopping travel cost.

An indirect policy implication of our results is that planners could very possibly achieve better outcomes by relaxing locational constraints on jobs and residences—especially zoning restrictions on the location of businesses, *where such restrictions do exist*—rather than by attempting to price congestion. One may argue that putting more jobs in or near residential areas could increase local traffic congestion. But our analysis finds that the congestion in and near the center is greatly reduced by job dispersion while it increases only slightly in previously developed edge zones. Restrictions such as large lot suburban zoning may achieve other efficiencies. But these regulations may lead to excessive travel and congestion by causing jobs to remain too centralized.

It is important to emphasize that we have ignored strong agglomeration economies which can cause subcenters, assuming—as the recent observations of Gordon and Richardson [8] imply—that such agglomeration will continue to weaken. But, if strong agglomeration economies are present, then concentration of jobs in one or more centers could improve welfare (see Anas and Kim [1]).

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