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AGGREGATE LAND RENTS AND AGGREGATE TRANSPORT COSTS

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ABSTRACT

This paper explores the relationship between aggregate land rents and aggregate transport costs in a city. On the negative side, we show that there is no simple relationship between the aggregate benefits from a transport improvement and the induced change in aggregate land rents. On the positive side, we demonstrate that there is nonetheless a very simple relationship between aggregate land rents and aggregate transport costs. For a city that is not geographically constrained, aggregate transport costs equal (are greater than, are less than) twice differential land rents when the elasticity of transport costs with respect to distance travelled is equal to (less than, greater than) one. Moreover, this relationship holds with remarkable generality; individuals may differ in tastes, incomes and transport cost functions, and the results are still valid.

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Aggregate Land Rents and Aggregate Transport Costs*

This paper explores the relationship between aggregate land rents and aggregate transport costs for land markets in which locations differ solely in terms of accessibility.[1]

That there exists a relationship between land rents and transport costs has been recognized at least since the time of von Thünen.[2] The precise relationship between the two is, however, not generally well-understood. For instance, until quite recently it was considered correct to estimate the benefits from a transport improvement by the induced change in aggregate land rents at those locations where travel costs are reduced. This procedure can be shown to be correct only in very special circumstances.[3] This paper presents a very general characterization of the relationship between aggregate land rents and aggregate transport costs. In some special cases, the relationship turns out to be remarkably simple: for a circular city with linear transport costs, aggregate transport costs are precisely twice aggregate land rents, independent of the distribution of tastes or income;[4] for a linear city with linear transport costs, aggregate transport costs are equal to aggregate land rents. One corollary of our general analysis is that aggregate land rents may stay the same or actually fall in response to a transport improvement which makes everyone better off.[5]

In the first section we consider a simple example. The second derives the basic theorems of the paper, while the third examines their implications for the relationship between the benefits from a transport improvement and the change in aggregate land rents induced by the improvement. And in the fourth section, we examine the extent to which the theorems of section two generalize.

$$ALR \equiv \int_0^{t^*} R(t)2\pi t dt. \tag{2}$$

Aggregate land rents are calculated as the rent per unit area of land at a distance t from the center times the number of units of land between t and $t + dt(2\pi t dt)$, integrated over all t.

Similarly, aggregate transport costs (ATC) equal

$$ATC \equiv \int_0^{t^*} f(t)2\pi t dt. \tag{3}$$

Integrating (2) by parts, and substituting (1), we obtain

$$ALR = \int_0^{t^*} - R'\pi t^2 dt + R(t^*)\pi t^{*2} = \int_0^{t^*} f'\pi t^2 dt + R(t^*)\pi t^{*2}. \tag{4}$$

The second term on the right-hand side is just the area of the city times the rent on marginal land; hence, the first term is differential land rents. Denoting differential land rents by DLR, we observe that

$$DLR \gtreqless \tfrac{1}{2} ATC \text{ when } \frac{f't}{f} \gtreqless 1 \text{ for all } t. \tag{5}$$

$\frac{f't}{f}$ is the elasticity of the transport cost function. In the special case of linear transport costs, differential land rents are precisely one-half aggregate transport costs.[9]

2. Basic Theorems

This section generalizes the example of the previous section in two ways. First, we allow for arbitrary tastes, and second we treat cities with arbitrary geographical configurations. Residents are still identical.

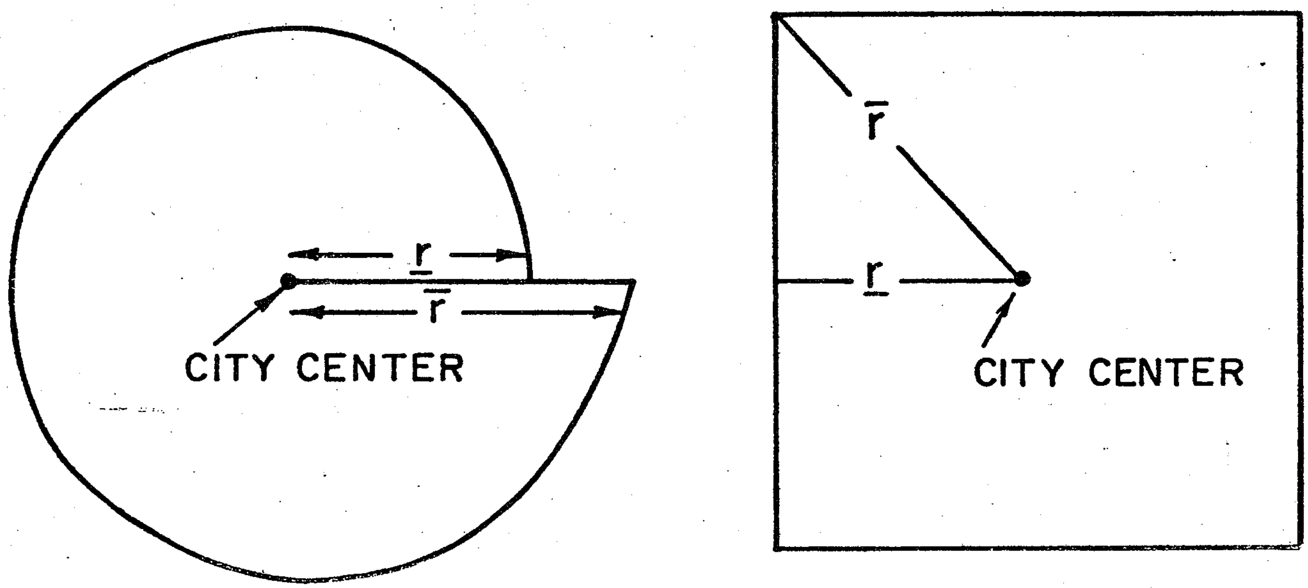


Figure 1: Two Cities with Different Geographical Configurations but the Same *Shape*

We now apply the Theorem and its Corollaries to a number of special cases.

(a) If there are no natural obstacles and if cities do not border on one another, the city is <u>circular</u>, in which case $\Phi = \pi t^2$ and $\frac{\Phi' t}{\Phi} = 2$. Thus, from Corollary 1,

$$\text{ATC} \gtreqqless \frac{2}{\gamma}\,\text{DLR} \quad \text{as} \quad \frac{f't}{f} \lesseqqgtr \gamma \quad \text{for all } t.$$

If, for instance, there are fixed costs and constant marginal costs associated with travel, then ATC > 2DLR since $\frac{f't}{f} < 1$. And in a circular city with linear transport costs, aggregate transport costs are precisely twice differential land rents.

(b) In a <u>linear city</u> of width $\bar{w}$, $\Phi = \bar{w}t$ and $\frac{\Phi' t}{\Phi} = 1$, and

$$\text{ATC} \gtreqqless \frac{1}{\gamma}\,\text{DLR} \quad \text{as} \quad \frac{f't}{f} \lesseqqgtr \gamma \quad \text{for all } t.$$

With linear transport costs, differential land rents equal aggregate transport costs.

(c) In an <u>hexagonal city</u>,

$$\Phi = \begin{cases} \pi t^2 & \text{for } t \leq \frac{\sqrt{3}}{2} t^* \\ 6\left[\frac{\sqrt{3}}{2} t^* \sqrt{t^2 - \frac{3t^{*2}}{4}} + \left(\frac{\pi}{6} - \cos^{-1}\left(\frac{\sqrt{3}t^*}{2t}\right)\right) t^2\right] & \text{for } t^* \geq t \geq \frac{\sqrt{3}}{2} t^*, \end{cases}$$

where t^* is the outer radius of the hexagon. For such a city, $\frac{\Phi' t}{\Phi} \leq 2$ for all t with strict inequality for some t, so that

$$\text{ATC} < \frac{2}{\gamma}\,\text{DLR} \quad \text{if} \quad \frac{f't}{f} \geqq \gamma \quad \text{for all } t.$$

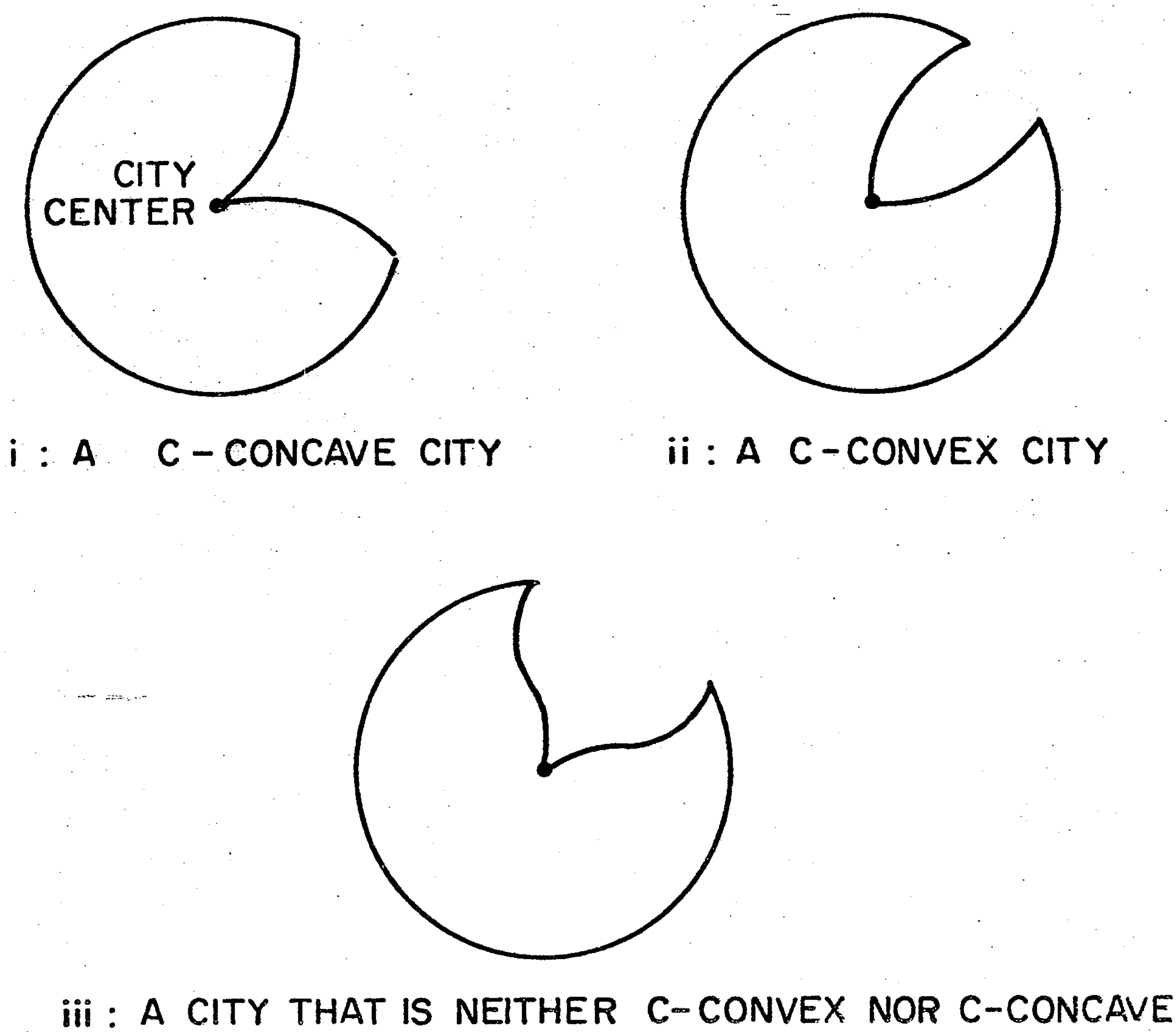


Figure 2: Alternative City Shapes

a circular city with radial transport costs linearly proportional to distance and costless circumferential transportation, in which city residents have identical Cobb-Douglas utility functions and in which the opportunity rent on land is zero.[12] We assume too that the transport improvement results in an equi-proportional reduction in travel costs at all locations.

It is characteristic of the Cobb-Douglas utility function that the ratio of each individual's expenditure on land to his expenditure on the private good is constant. It follows, since individuals have identical tastes, that aggregate expenditure on the private good is a constant proportion of aggregate land rents. We also know from Theorem 1 that for such a city, when the opportunity rent on land in non-urban use is zero, aggregate transport costs equal twice aggregate land rents. Thus, aggregate expenditure on the private good is a constant proportion of aggregate land rents. Aggregate income from production, we assume, is unaffected by the transport improvement. Putting these results together, we have that aggregate land rents, aggregate transport costs, and aggregate expenditure on other goods are unaffected by the transport improvement. Thus, reduction in unit transport costs leads to more land consumption and the same aggregate expenditure on transport costs and land rents.[13]

Since aggregate land rents may, in general, rise, remain the same, or fall in response to a transport improvement, the induced change in aggregate land rents by itself is, except under conditions very unlikely to be satisfied, an incorrect measure of benefits from the transport improvement. The change in aggregate land rents from a transport improvement is, however, relevant

Let $\tilde{f}(t)$ be the equilibrium transport cost function, which gives for each t the transport expenditures of the individual who locates at t in equilibrium. (11') shows that what is relevant to the determination of ATC/DLR is the elasticity of each individual's transport cost function at his equilibrium location $\left(\frac{f_1(t;t)t}{f(t;t)}\right)$ and <u>not</u> the elasticity of the equilibrium transport cost function $\left(\frac{\tilde{f}'(t)t}{\tilde{f}(t)}\right)$.

To clarify the point, imagine the following scenario. The city is circular and each individual's transport cost function is linear in distance, with costs per mile depending on income. Tastes are such that, in equilibrium, the rich live closer to downtown. And the distribution of income is such that the transport expenditures incurred by the equilibrium resident at each location are equal.[14] Thus, $\frac{f_1(t;t)t}{f(t;t)} = 1$ while $\frac{\tilde{f}'(t)t}{\tilde{f}(t)} = 0$. Application of (11') indicates that in this city, ATC = 2DLR since each individual's transport costs are linear in distance even though equilibrium transport costs are invariant with location. More generally, in a circular city, as long as all individuals have linear transport costs, even though they may differ in tastes, incomes, and transport costs, it is still true that aggregate transport costs are precisely twice differential land rents.

4.2 Time and money costs of travel, etc.

It is easy to show that the results of section 2 generalize to the case where trip frequency is variable, where $f(t)$ is interpreted as costs per trip.[15] They also generalize straightforwardly to the situation where

A possible objection to our analysis thus far is that we have ignored housing and its durability. The analysis does in fact generalize to cities with housing. In the long run, land and structure rent may be separated and the presence of structures on the land does not affect our propositions. In the short run, land and structure rent are not separable; we refer to their sum as housing rent. In this case, the analysis must be reformulated in terms of the relationship between differential housing rents and aggregate transport costs, and our earlier theorems are applicable.[16]

4.3 Generalization to higher dimensions

Thus far we have assumed that urban residents are unanimous in their ranking of locations in terms of accessibility, so that location may be parameterized by a single variable, some index of accessibility. However, individuals may judge differently the relative accessibility of two locations. For instance, one may be indifferent between two commuting trips, one of which costs \$1.00 and takes 15 minutes, while the other costs \$.50 and takes 20 minutes. Another individual who values his time less may be indifferent between the trip which costs \$1.00 and takes 15 minutes, and another which costs \$.50 and takes 30 minutes. In such cases, one needs two variables to characterize a location.

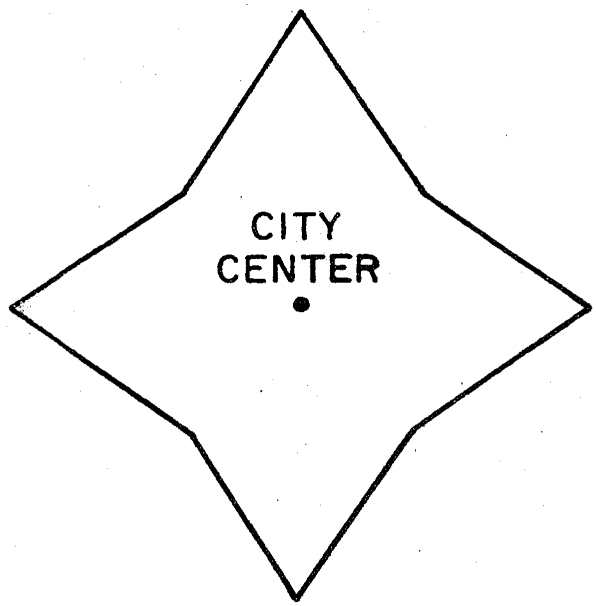
This can be seen from Figure 3, which shows an equal accessibility contour for two different individuals. If one were to index locations according to individual 1's travel costs, f^1, one could not write down individual 2's transport cost function, since for different locations with the same value of f^1 his transport costs would be different. Similarly, if one were to index locations according to individual 2's travel costs, one could not characterize individual 1's transport costs. One can however characterize both individuals' transport cost functions using two coordinates to describe location.

In section 2 the analysis was considerably simplified by employing the concept of the shape of the city. This allowed us to transform any city with a complex geographical configuration into another city, equivalent for the purpose of analysis but with a simple shape. Furthermore, the shape of the city was defined in such a way that rent was the same everywhere along the boundary, as a result of which there was no ambiguity in defining differential land rents. Unfortunately, this technique of simplification is not possible when residents rank locations differently in terms of accessibility. One must work instead with the actual geographical configuration of the city. In this case, land rents may not be the same everywhere along the (physical) boundaries of the city, and differential land rents may in consequence be hard to define.

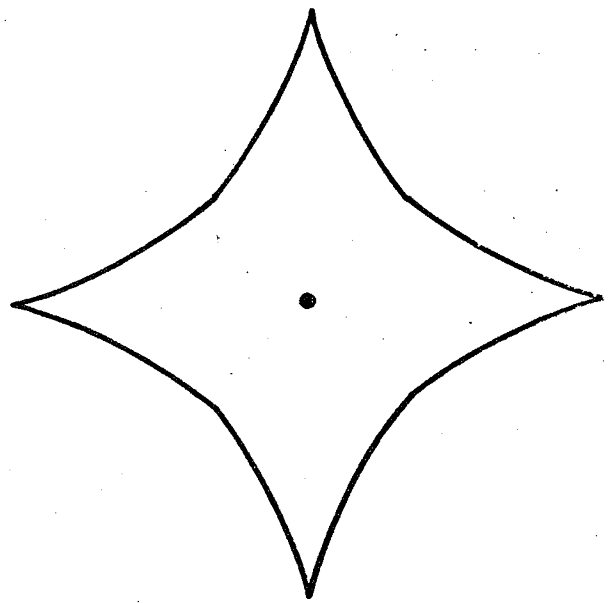
We shall treat two cases in turn, first that where land rents are everywhere the same along the boundaries of the city, and then that where they are not.

4.3.1 Land rent the same everywhere along the boundaries of the city

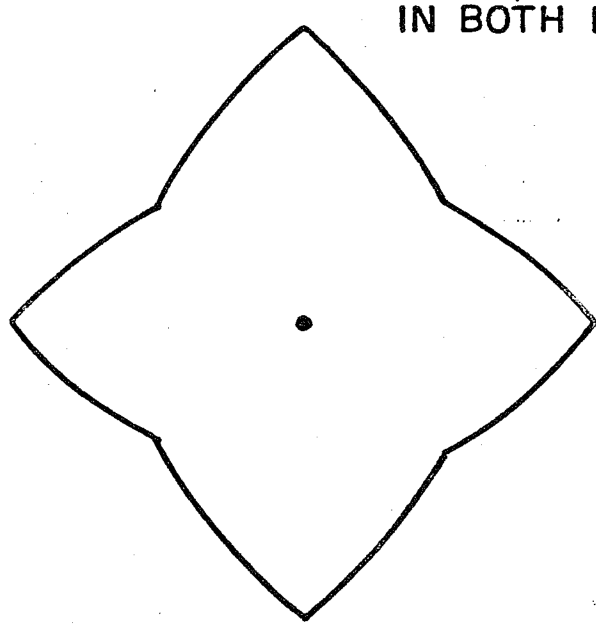
We shall parameterize locations using Cartesian coordinates, x and y, with (0,0) being the city center (or the central business district in the case of a multinucleated city). Let $f(x',y';x,y)$ denote the transport costs of the individual who lives at (x,y) in equilibrium of travelling to (x',y'), and let $f_x(x,y;x,y) \equiv \left(\frac{\partial f(x',y';x,y)}{\partial x'}\right)_{(x,y)}$ with



i: LINEAR TRANSPORT COSTS (α=1)



ii: DECREASING COST TO TRAVEL IN BOTH DIRECTIONS (α<1)



iii: INCREASING COST TO TRAVEL IN BOTH DIRECTIONS (α>1)

Figure 4: Possible Geographical Configurations for Cities when Individuals Rank the Accessibility of Locations Differently: Grid Road Systems

The a_i's differ by group, as do the b_i's and the $\frac{a_i}{b_i}$'s. Thus, each group ranks locations in terms of accessibility differently from every other group. This could occur if, for instance, travel in one direction were slower than in the other, and if the shadow value of time varied by group while money expenditures did not. For each group at each location $\nabla f^i \cdot t = f^i$. From the definition of f, it follows that $\nabla f \cdot t = f$, and from (16) that $DLR = \frac{1}{2} ATC$. Thus, even in this rather complex and quite realistic city, there is a simple relation between DLR and ATC.

4.3.2 Land rent not the same everywhere along the boundaries of the city

When land rent is not the same everywhere along the boundary, the question arises as to what is the appropriate opportunity rent on land in non-urban use to employ in computing differential land rents. We shall pose the question somewhat differently. Is there a reasonable definition of differential land rents that results in the Theorems of the paper holding where i) land rent is not the same everywhere along the physical boundary of the city, and ii) city residents do not rank locations equally in terms of accessibility? Rather strikingly, the answer is in the affirmative. If we define the opportunity rent on land at a location (r,θ), measured in polar coordinates, to be land rent at the boundary of the city in the direction θ, then (16) remains valid.[20] The proof is in the Appendix.

5. Concluding Remarks

This paper had two central objectives:

Appendix[22]

To prove: that $DLR \gtreqless \frac{1}{2}$ ATC if $\nabla f \cdot t \gtreqless f$

The proof is facilitated by using polar coordinates, in which r denotes the crow-line distance from the city center and θ the angle from the city center in radians. To simplify the analysis we assume that there are no "holes" in the city, viz at all locations in the city, a straight line joining the location to the city center passes across only residential land. The proof can be extended to cities with holes.

Aggregate land rents are

$$ALR = \int_0^{2\pi} \left[\int_0^{\overline{r}(\theta)} R(r,\theta) r dr \right] d\theta, \tag{Ai}$$

where $R(r,\theta)$ is land rent at (r,θ), and $\overline{r}(\theta)$ is the distance to the boundary in the direction θ.

Differentiation of the term in square brackets in (Ai) by parts gives

$$ALR = \int_0^{2\pi} \left[\left(R(r,\theta)\frac{r^2}{2} \right)_0^{\overline{r}(\theta)} - \int_0^{\overline{r}(\theta)} R_r(r,\theta)\frac{r^2}{2} dr \right] d\theta$$

$$= \int_0^{2\pi} R(\overline{r}(\theta),\theta) \frac{\overline{r}(\theta)^2}{2} d\theta - \int_0^{2\pi} \int_0^{\overline{r}(\theta)} R_r(r,\theta)\frac{r^2}{2} dr d\theta, \tag{Aii}$$

where $R_r(r,\theta) = \frac{\partial R(r,\theta)}{\partial r}$.

When land rent is the same everywhere along the boundary, $\overline{R}$, the first term on the right-hand side of (Aii) is this rent times the area of the city. When land rent is not the same everywhere along the boundary, and if we define the opportunity rent of land at (r,θ) to be the land rent at the boundary of the city in the direction θ, then the first term on the right-hand side of (Aii) is the aggregate opportunity rent on land an individual's transport cost function in Cartesian coordinates,

$$f(x',y';x,y) = f(r'\cos\theta',r'\sin\theta';\ r\cos\theta,\ r\sin\theta).$$ Also,

$$f_r(x,y;x,y) \equiv \left(\frac{\partial f(r'\cos\theta',r'\sin\theta';\ r\cos\theta,\ r\sin\theta)}{\partial r'}\right)_{(r,\theta)}$$

$$= f_x(x,y;x,y)\cos\theta + f_y(x,y;x,y)\sin\theta, \qquad \text{(Aviii)}$$

where $f_x(x,y;x,y) \equiv \left(\frac{\partial f(x',y';x,y)}{\partial x'}\right)_{(x,y)}$ and f_y is defined accordingly.

Using $x = r\cos\theta$ and $y = r\sin\theta$ again, one may rewrite (Aviii) as

$$f_r = \frac{1}{r}(f_x(x,y;x,y)x + f_y(x,y;x,y)y), \text{ or}$$

$$f_r r = f_x x + f_y y. \qquad \text{(Aix)}$$

Now, $f(x,y;x,y) = \hat{f}(r,\theta;r,\theta)$, and $f_r(x,y;x,y) = \hat{f}_r(r,\theta;r,\theta)$. Thus, $f_r r = \hat{f}_r r$. Too, $f_x x + f_y y \equiv \nabla f \cdot t$ where $\nabla f = (f_x \quad f_y)$ and $t = [x \quad y]$. Combining these results, (Aix), and (Avii) gives

$$DLR \gtreqless \frac{1}{2} ATC \text{ if } \nabla f \cdot t \gtreqless f \text{ for all } t, \qquad \text{(Ax)}$$

which is the result presented in the text.

Where land rent is not the same everywhere along the boundary of the city with other reasonable definitions of differential land rents, (16) does not obtain. For instance, if the opportunity rent on land in non-urban use is defined as the minimum rent on land at the boundary of the city, $\tilde{R}$, then, where $\overline{DLR}$ denotes differential land rents according to this alternative definition,

FOOTNOTES

* This paper draws on Arnott's Ph.D. thesis [1]. He would like to thank the Canada Council for financial support during the period the thesis was being written. Stiglitz would like to thank the National Science Foundation for financial support. The comments of Ronald Grieson and two anonymous referees were helpful.

1. Thus, we abstract from differences in the site-intrinsic or Ricardian characteristics of land.

2. In the von Thünen model differences in agricultural land rents are related to the costs of transporting goods to the central market.

3. The argument underlying this procedure is based on partial equilibrium analysis. If transport costs to all locations but one small location were to remain unchanged, then the benefits from the transport improvement would be correctly measured by the induced change in land rents at that location. But as in most instances in spatial economics, partial equilibrium analysis is inappropriate, and general equilibrium analysis should be applied. The incorrectness of this procedure was persuasively argued in an important paper by Mohring [7] fifteen years ago; one still, however, comes across analyses that use some variant of it ([4,5] for instance). The conditions under which the above partial equilibrium argument is appropriate can be seen by considering a resident's indirect utility function. In a spatial economy, a resident's utility is a function of the land rent where he locates, R, his income <u>net</u> of transport costs, I, and other prices, p, so that $V = V(R,I,p)$, <u>where</u> V is the indirect utility function. Where other prices are unaffected by the transport improvement, $dV = V_1dR + V_2dI$. From the properties of the indirect utility function, $V_1 = -TV_2$, where T is the resident's lot size. Thus, $dV = V_2(-TdR + dI)$, from which it follows that the benefits to this resident from the transport improvement, dI, equal the change in his land rents, TdR, only when $dV = 0$. Thus, only when the transport improvement leaves unchanged the utility of residents at locations to which travel costs have been reduced (which will occur when the city is completely open, for instance) is the partial equilibrium analysis appropriate. This line of argument is developed further in Polinsky and Shavell [8].

4. Mohring [7] calculated the relationship between aggregate transport costs and aggregate land rents in a circular city with linear transport costs for the rather special case where all individuals have identical and fixed lot sizes. His method of analysis, summarized below in footnote 9, does not, however, generalize to other cases.

5. The same result, for a somewhat different type of urban model, has been derived by Getz [6].

along the radial road is costless, and transport costs are equal to circumferential distance from the radial road. The transport cost shape of this city is shown below to be

$$\Omega(f) = 4\,(\bar{r}f - \frac{f^2}{\pi}),\; f \leq \frac{\pi\bar{r}}{2}, \tag{i}$$

where $\bar{r}$ is the radius of the city. Since $f\Omega' < \Omega$ for all f, then from Theorem 1', DLR > ATC.

(i) is derived as follows: Divide the city into four symmetric quadrants, each with the radial road as its base. Consider one of these. Travel costs to all locations subtended by an angle θ of less than or equal to $f/\bar{r}$ radians should be included in $\Omega(f)$. This area equals $f\bar{r}/2$. For $\pi/2 \geq \theta \geq f/\bar{r}$, transport costs exceed f for $r > \frac{f}{\theta}$. Thus, we should integrate r only from 0 to f/θ for $\frac{\pi}{2} \geq \theta \geq \frac{f}{\bar{r}}$. The value of this area is $\frac{f\bar{r}}{2} - \frac{f^2}{\pi}$. Hence, $\Omega(f) = 4(\bar{r}f - \frac{f^2}{\pi})$.

12. To circumvent the conceptual problems associated with the boundary resident consuming an infinite amount of land because of its zero rent, we may assume instead that the opportunity rent on land is positive but arbitrarily small.

13. A transport tax has the same effects as a negative transport improvement, when the disposition of revenue is ignored. Thus, in this economy, the incidence of a transport cost tax is entirely on consumers. Aggregate land rents remain the same; some landowners near the city center benefit, but their gains are precisely offset by losses to landowners further out.

14. For this to be possible, residential settlement must start at some distance from the city center.

15. Let $f(t)$ be the cost per trip at t, and $n(t)$ be the trip frequency chosen by the person at t (who maximizes $U(C,T,n)$ s.t. $Y = C + R(t)T + nf(t)$). The first-order condition of the resident's maximization problem with respect to t is $-nf' = R'T$, and the counterpart to (11) is

$$\frac{ATC}{DLR} \doteq \frac{\int_0^{t^*} \frac{n(t)}{T(t)} [f(t)\Phi'(t)]dt}{\int_0^{t^*} \frac{n(t)}{T(t)} [f'(t)\Phi(t)]dt}.$$

17. The mathematics employed in the Appendix is somewhat more complex than that employed in the rest of the paper. The Appendix can be skipped without loss of continuity.

18. With this transport cost function, $\nabla f \cdot t \gtreqless f$ as $\alpha \gtreqless 1$ which implies from (16) that $DLR \gtreqless \frac{1}{2} ATC$ as $\alpha \gtreqless 1$.

19. Suppose the equal-accessibility contours in Figure 3 are C^1 and C^2. From the definition of C^1, an individual in group 1 is willing to bid $\bar{R}$ (the opportunity rent on land in non-urban use) per unit area for any location on C^1. Furthermore, this individual is willing to bid less than $\bar{R}$ per unit area for any location outside C^1 since it is less accessible than any location on C^1. Now consider the location Z in Figure 3. An individual from class 2 is willing to bid $\bar{R}$ per unit area for land there, since Z is on C^2. An individual from class 1 is not willing to bid as much as $\bar{R}$ per unit area for land there since Z is outside C^1. Thus, the land at Z goes to an individual in class 2 and is on the boundary of the city since the maximum residential bid-rent there is $\bar{R}$.

20. The definition can be modified to treat cities with holes in them.

21. There are a number of interesting extensions to the analysis. First, the theorems should extend to cities with industrial, commercial, etc. as well as residential urban land. Second, it would be useful to investigate how the relationship between aggregate transport costs and differential land rents is affected when locations differ not only in their accessibility, but also in their Ricardian characteristics such as soil fertility and quality of the microclimate. Third, one would like to know whether the actual ratio of differential land rents to aggregate transport costs is close to that indicated by the theorems presented in the paper.

22. We would like to thank Jim Mirrlees for assistance in deriving this generalization.

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