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Evaluating Urban Transport Improvements

Cost–Benefit Analysis in the Presence of Agglomeration and Income Taxation

Anthony J. Venables

Address for correspondence: Anthony J. Venables, University of Oxford, Department of Economics, Manor Road, Oxford OX1 3UQ (a.j.venables@ox.ac.uk).

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Abstract

There is a substantial empirical literature quantifying the positive relationship between city size and productivity. This paper studies the implications of that relationship for evaluations of urban transport improvements. A theoretical model is developed and used to derive a cost–benefit measure that includes the impact of transport improvements on city size and hence on the productivity of new and existing city workers. The size of such effects is illustrated in a simple computable equilibrium model. It is argued that these productivity effects, particularly when combined with distortionary taxation, are quantitatively important, substantially increasing the gains attributable to urban transport improvements.

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1.0 Introduction

Large urban centres typically have higher factor productivity than do areas with lower employment density. This paper analyses the implications of this phenomenon for the evaluation of urban transport projects. Such projects may have the effect of increasing employment in the urban centre; for example, London's Crossrail project is predicted to increase central London employment by more than 30,000 jobs. We argue that such increases in employment are associated with two market failures, both of which need to be taken into account in project evaluation, and which are quantitatively significant.

The first gap between private and social benefits arises because of the positive relationship between city size and productivity. The determinants of this relationship and the evidence for it are discussed in the next section, but its implication is that expanding city employment brings with it a (net) positive externality. Additional employment therefore raises the productivity not just of new urban workers, but also of *existing* workers now reaping the benefits of a larger urban agglomeration.

The second gap between the private and social benefits of increasing urban employment arises because of the income tax system. Higher urban productivity and associated higher wages are, in equilibrium, matched by commuting costs and rent levels that are higher in urban areas than elsewhere. This is the equilibrium condition for people to be indifferent between living in the city or outside it. However, the indifference condition holds between the full costs of commuting and the wage increment *net of tax*. The value of extra output produced by a migrant therefore exceeds the costs incurred, the difference accruing to the government. Notice that this argument is particular to travel to work, where one side of the equilibrium condition is pre-tax income and the other expenditure out of post-tax income.

The paper is structured as follows. The next section contains a brief review of the literature, in particular outlining the evidence of a positive relationship between urban employment and productivity. Section 3 sets up the simplest possible model in which the arguments above can be captured; an explicit expression for the real income effect of an urban transport improvement is derived. Section 4 reports numerical simulations of a somewhat more general model in order to assess the quantitative importance of effects. Section 5 discusses extensions.

2.0 Related Literature

The analysis turns on the existence of a positive relationship between city size and productivity, a relationship that is one of the reasons for the existence of cities. The micro-economic mechanisms underlying the relationship are reviewed in Duranton and Puga (2004), and include the benefits of thick labour markets, input–output linkages between firms, and direct knowledge spillovers. The empirical evidence for the relationship is surveyed by Rosenthal and Strange (2004). A large number of studies use cross-section data on cities (typically but not exclusively in the US) to relate productivity to city size. Findings vary according to the extent to which researchers are able to control for the quality of inputs — capital stock and the skill of the labour force — and typically yield the result that doubling city size increases labour productivity by an amount in the range 3 to 8 per cent; that is, an elasticity of productivity with respect to city size of between 0.04 and 0.11. Studies by Ciccone and Hall (1996) and Ciccone (2002) relate productivity to the spatial density of economic activity, using data for the US and for Europe respectively, and find an elasticity of productivity with respect to density of around 0.06. For the UK, Rice *et al.* (2006) estimate the elasticity of productivity with respect to access to economic mass to be 0.04.[1]

While the debate on the magnitude of these effects is far from closed, there is enough evidence to accept the existence of a positive city size/productivity relationship. The relationship suggests several ways in which a transport improvement might affect productivity. One is that improved links between firms within the city increases the effective density of the cluster. The other is that easier access to the centre causes equilibrium city employment to increase. This paper concentrates on overall urban employment growth, essentially because of the existence of robust empirical estimates of the elasticity of productivity with respect to city employment. Our analysis shows how to include these effects in appraisals of transport improvements and points to the undervaluation of benefits if they are ignored.[2]

The analysis of this paper is based on a simple version of the standard model urban economics model (as developed by Alonso, 1964; or for a recent statement see Fujita and Thisse, 2002). In this model a productivity differential between workers in the city and outsiders is supported as an equilibrium because city workers also pay commuting costs and, at the margin, these are such that individuals are indifferent between city and

[1] While most studies are done at the aggregate city level, some focus on particular sectors (for example, Nakumura, 1985; Henderson, 2003), distinguishing between urbanisation effects (city size as a whole) and localisation effects (the effect of the scale of operation of a particular sector in the city). Generally, the latter are more pronounced, and vary across sectors.

[2] For a survey of transport evaluation see Small (1999). The arguments in this paper depend on market failures, not simply the derived market benefits that are captured by standard techniques (Mohring, 1993).

non-city locations. The city expands up to the point at which a worker is indifferent between locating at the edge of the city and commuting to the central business district (CBD), or living (and working) in a non-city location. Although transport costs secure indifference at the margin, the city as a whole generates an economic surplus from its productivity advantage. The surplus arises as workers who live closer to the city centre pay lower commuting costs. However, this surplus is all captured by rent/house prices so that, in equilibrium, the entire surplus accrues to owners of the immobile factor, land.[3]

We note that many more sophisticated variants of this model have been developed in the literature, including those with polycentric urban structures, heterogeneous labour, and multiple activities (see Abdel-Rahman and Anas, 2004, for a survey). For clarity, our analysis is based on the simplest core model. We also abstract from congestion externalities. These are additional effects that have been the subject of a large body of transport economics research, including some in an explicitly urban setting (for example Sullivan, 1983a, b; Safirova, 2002).

3.0 Real Income Effects of an Urban Transport Improvement

The basic model is as follows. All city employment takes place in the CBD. Output per worker depends on the total number of jobs in the CBD according to the function $x(N)$, where N is total employment in the city. We assume that x is an increasing and concave function of N, because of some agglomeration externality that creates overall increasing returns to city employment.[4] For simplicity we do not model the exact mechanism that generates these increasing returns; a number of possible micro-foundations of such a relationship are set out in Duranton and Puga (2004). We assume that firms are perfectly competitive and use no inputs other than labour,[5] so $x(N)$ is the wage paid to workers in a city of size N. Each worker's net of tax income is therefore $x(N) - t(x(N))$ where the function $t(.)$ describes the income tax system. Workers occupy housing outside the CBD, and z denotes distance from the CBD. Commuting costs from location z to the CBD are given by the function $c(z)$.

[3] This assumes a perfectly elastic supply of labour to the city. If this does not hold then wages will be bid up, and the surplus divided between owners of land and labour.

[4] These urban increasing returns can be defined net of congestion diseconomies.

[5] So firms occupy zero area in the city, an assumption that we relax in Section 4.

Given these production and commuting technologies, the equilibrium is found as follows. The real income of a representative worker is post-tax income net of commuting costs $c(z)$ and housing rent $\rho(z)$.[6] Free mobility of workers within the city means that rents adjust so that workers get the same real income wherever they live, that is,

$$u(N) = x(N) - t(x(N)) - c(z) - \rho(z), \qquad \text{for all } z \in [0, \hat{z}], \tag{1}$$

where $u(N)$ denotes the common real income level of all workers in a city of size N, and $\hat{z}$ is the city edge. We also assume free mobility of workers between the city and other locations outside the city. Real income in these other locations is constant at $\bar{u} = \bar{x} - t(\bar{x})$, where commuting costs and rent are set equal to zero.[7] At the edge of city rent is zero, so $\hat{z}$ is implicitly defined by

$$u(N) = x(N) - t(x(N)) - c(\hat{z}) = \bar{x} - t(\bar{x}). \tag{2}$$

We have to link the number of workers in the city to its physical size. If $n(z)$ workers live at distance z from the centre, then the relationship between N and $\hat{z}$ is given by

$$N = \int_0^{\hat{z}} n(z)dz. \tag{3}$$

This relationship can be integrated if a particular functional form is assumed for population density, $n(z)$. We assume that $n(z) = kz^{\theta}$, where the parameter k is a scaling constant, and parameter θ captures the geography of the city. Integrating,

$$N = \int_0^{\hat{z}} kz^{\theta}dz = \hat{z}^{(1+\theta)}k/(1+\theta),$$
$$\text{implying} \quad \hat{z} = [N(1+\theta)/k]^{1/(1+\theta)}. \tag{4}$$

It is also convenient to use a specific functional form for commuting costs, and we assume that $c(z) = cz^{\lambda}$. The parameters c and λ characterise the transport technology, so $\lambda = 1$ means that transport costs are linear in distance travelled. The transport costs of a worker at the edge of the city are therefore

$$c(\hat{z}) = c\hat{z}^{\lambda} = c[N(1+\theta)/k]^{\lambda/(1+\theta)}, \tag{5}$$

[6] Commuting costs can be monetary or direct utility costs; however, we assume that commuting does not reduce work time. $\rho(z)$ is total rent paid by a worker at location z, not rent per unit land.

[7] This is a normalisation, meaning that city commuting costs and rent are the incremental amounts paid by urban workers.

where the second equation uses (4). Equations (2) and (5) are a pair of simultaneous equations in $\hat{z}$ and N. We can eliminate $\hat{z}$ to give the equilibrium condition that determines N,

$$x(N) - t(x(N)) - cN^{\gamma-1} = \bar{x} - t(\bar{x}). \tag{6}$$

This is the key equation, giving equilibrium city size as a function of production technology, the tax system, commuting costs, and the parameter γ, defined as $\gamma \equiv (1+\theta+\lambda)/(1+\theta) > 1$ (units are chosen such that $k = 1+\theta$). This parameter summarises the diminishing returns to city size arising through commuting costs. Larger γ means more diminishing returns, either because transport costs increase sharply with distance (larger γ) or population increases slowly with distance (small θ). For example, if the city is linear and lot sizes are the same at all distances then population is proportionate to the length of the city, $\theta = 0$ and $\gamma = 1+\lambda$. In a circular city with uniform lot sizes $\theta = 1$, so increasing city radius brings in increasingly many workers and reduces the value of $\gamma = 1+\lambda/2$.

Now consider the effect of an urban transport improvement, modelled as a reduction in transport costs per unit distance of amount $dc < 0$. The effect on city population is, from (6),

$$\left[x'(1-t') - (\gamma-1)cN^{\gamma-2}\right]dN = N^{\gamma-1}dc. \tag{7}$$

The term in square brackets is negative (at a stable equilibrium), so $dN/dc < 0$. As expected, a reduction in commuting costs increases city size.

We are interested in the effect on real income, which is given by

$$U = Nx(N) - TC + (\bar{N} - N)\bar{x}. \tag{8}$$

The first term on the right-hand side is the total output of the city, and the second is total commuting costs, TC. The final term is output in the rest of economy, where $\bar{N}$ denotes the total employment in the economy as a whole. Total commuting costs can be found by integrating over the costs of workers at all distances from the CBD,

$$\begin{aligned} TC &= \int_0^{\hat{z}} kz^{\theta}cz^{\lambda}dz = \frac{ck\hat{z}^{(1+\theta+\lambda)}}{1+\theta+\lambda} \\ &= \frac{ck}{1+\theta+\lambda}\left[\frac{N(1+\theta)}{k}\right]^{(1+\theta+\lambda/1+\theta)} = N^{\gamma}c/\gamma, \end{aligned} \tag{9}$$

where evaluation of the integral uses (5), the definition of γ, and the normalisation $k = 1+\theta$.

Differentiating (8) and (9), the effect of a transport improvement is

$$\frac{dU}{dc} = \left[Nx' + (x(N) - \bar{x}) - cN^{\gamma-1}\right]\frac{dN}{dc} - \frac{N^{\gamma}}{\gamma}. \tag{10}$$

The first two terms are the change in production. The first comes from increasing productivity of existing city workers (if $x' > 0$) and the second from expanding city employment, in which productivity is higher by amount $(x(N) - \bar{x})$. Offsetting this, new city workers have to pay edge of city commuting costs, $cN^{\gamma-1}$. The final term is the direct cost saving of the transport improvement (the derivative of total commuting costs). Equilibrium condition (6) relates the productivity gap to commuting costs, and using this gives,

$$\frac{dU}{dc} = -\frac{N^{\gamma}}{\gamma} + \frac{dN}{dc}\left[Nx' + t(x) - t(\bar{x})\right]. \tag{11}$$

The first term is the direct effect of the transport improvement on total commuting costs. Remaining terms give the value of the change in the number of workers, creating benefit through two distinct mechanisms. The first, Nx', is the agglomeration externality, so increasing urban employment raises the productivity of existing workers if $x' > 0$. The second is a tax distortion, which can be expressed as the difference between wages inside and outside the city times the marginal tax rate, $(x - \bar{x})t'(x)$. The intuition is that there is a tax wedge between the extra income earned by moving to the city, and extra commuting costs that are paid out of after tax income. Notice that this tax argument does not apply to leisure travel (where the choice is between consuming travel or consuming other goods, both paid from after tax income) or commercial traffic (where costs and benefits are both pre-income tax).

Equations (7) and (11) can be combined to give the real income change from the transport improvement as

$$\frac{dU}{dc} = -\frac{N^{\gamma}}{\gamma}\left[1 + \frac{\gamma\left[Nx' + t(x) - t(\bar{x})\right]}{c(\gamma - 1)N^{\gamma-1} - (1 - t')Nx'}\right], \tag{12}$$

although it is often more informative to look at (7) and (11) separately.

This analysis is illustrated in the four panels of Figure 1, the vertical axis of which measures costs and benefits per worker. The horizontal axis measures the number of urban workers who, for the purpose of these figures, each occupy one unit of land in a linear city with linear commuting costs, $\theta = 0$, $\lambda = 1$, $\gamma = 2$; the horizontal axis is therefore also distance from the CBD, point 0. In each figure the upward sloping rays through the origin are the costs of commuting to the CBD from each of these locations.

In Figures 1a and 1b there is no taxation or productivity effect, so $t' = 0$ and $x' = 0$. The productivity (and wage) gap between city workers and outsiders is constant at $(x - \bar{x})$, illustrated by the horizontal line. The size of the city is determined at point N, where the wage gap is equal to the commuting costs of the most distant city worker. At point N no further workers want to be employed in the city. Workers located closer to the CBD face lower commuting costs but higher rents, as given by the distance between the horizontal line $(x - \bar{x})$ and the commuting cost curve. Clearly there is a rent gradient, with rents falling from the centre to the edge of the city.

A transport improvement has the effect of shifting the commuting cost schedule downwards, as illustrated in Figure 1b. Areas in the figure correspond to terms in equations (10) and (11) as follows:

Area $\alpha = N^{\gamma}/\gamma$	Direct cost saving.
Area $\beta + \eta = (x - \bar{x})dN$	Extra output from new city workers.
Area $\eta = cN^{\gamma-1}dN$	Commuting cost of new city workers.

Figure 1a
Urban Equilibrium

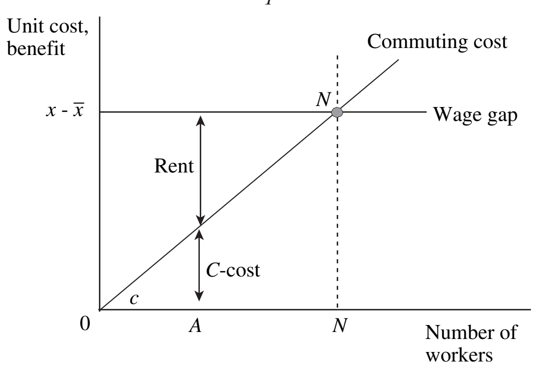
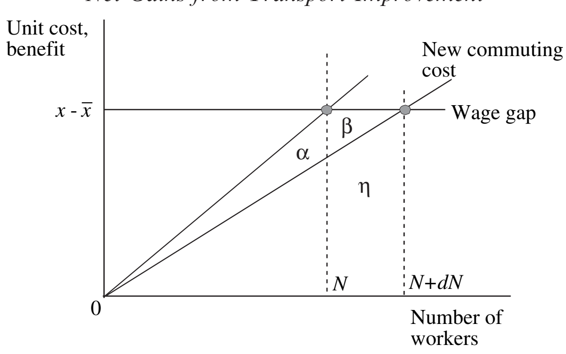


Figure 1b
Net Gains from Transport Improvement



To a first-order approximation benefit $\beta + \eta$ and cost η net out as, in the absence of taxes, the benefits of moving to the city equal the marginal cost (equation (6)), so the only benefit is the direct cost saving. For a non-marginal change there is also the second order gain, β, giving real income change $\alpha + \beta$. In our framework $\alpha + \beta$ is the value of the improvement that would be obtained from a standard cost–benefit analysis.

Figure 1c adds an endogenous productivity effect to the picture. Agglomeration benefits mean that a larger city has higher productivity, so that instead of a constant wage gap $(x - \bar{x})$ there is now the increasing relationship $x(N) - \bar{x}$. The induced productivity response has two consequences. First, the change in city size from the transport improvement is larger, and second, the higher productivity of existing city workers raises real income by area δ:

$$\text{Area } \delta = Nx'dN \qquad \text{Induced productivity gain.}$$

The real income gain is now $\alpha + \beta + \delta$.

Figure 1c

Net Gains from Transport Improvement with Endogenous Productivity

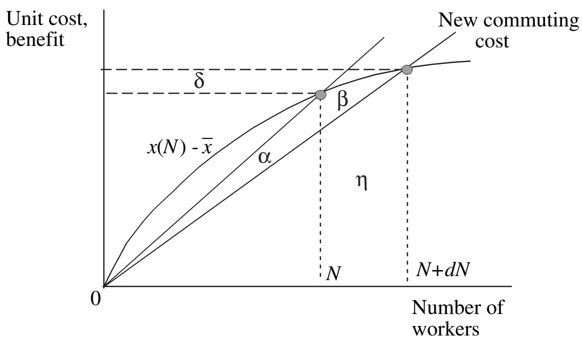


Figure 1d

Net Gains from Transport Improvement with Endogenous Productivity and Tax Wedge (t)

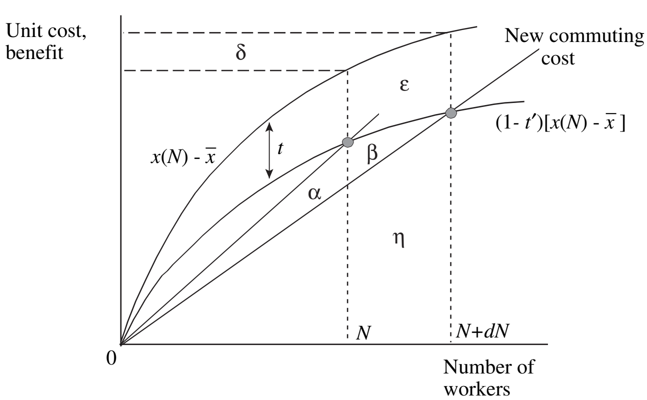


Figure 1d completes the illustration, adding a tax wedge. The productivity gain from the city is the curve $x(N) - \bar{x}$, but workers' decisions are taken on the basis of the curve $(1 - t')[x(N) - \bar{x}]$. Consequently, the output increment produced by marginal city workers now exceeds their commuting costs. Commuters only receive the net of tax share of the extra output they produce, but pay the whole of commuting costs. The difference, area ε, accrues to government as tax revenue, so,

$$\text{Area } \varepsilon = [t(x) - t(\bar{x})]dN \approx t'(x)[x(N) - \bar{x}]dN \qquad \text{Tax revenue.}$$

Notice also that the appropriate tax rate is that paid on the increment to earnings of new city workers, so is the marginal rate $t'(x)$, not the average rate. The real income gain is now $\alpha + \beta + \delta + \varepsilon$. Comparing Figures 1a and 1d we see that productivity and tax effects generate additional benefits $\delta + \varepsilon$, and also increase the size of the increase in employment created by a given size transport improvement.

4.0 A Computable Equilibrium Model

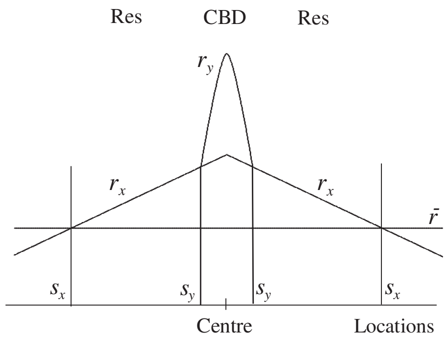
We now move from the linear approximations of equations (10) to (12) to numerically implementing a more general model. Numerical methods allow us to look at non-marginal changes, as well as capturing a somewhat more general geography and production structure.

The economy has 20,000 spatial cells and a transport network defined by four lines that intersect at a single point. In equilibrium, this point will form the centre of the CBD to which workers commute. Employment takes up space, so that the CBD occupies an endogenously determined number of cells around this intersection, and cells further out are residential, until the (endogenous) city edge is reached. Production technology is such that productivity is increasing in total employment, weighted by an inverse measure of distance (appendix). This means that productivity is highest at the centre of the CBD and declines towards its edge.

Figure 2a illustrates the initial equilibrium. The horizontal axis gives locations on one of the four transport lines, and the vertical gives rents per unit land.[8] The CBD occupies cells within s_y of the centre, and rents in this area are given by r_y. Because of proximity effects in the production function, rents peak at the centre of the CBD. Residential rents are given by

[8]The city initially has radial symmetry, and this is a slice along one of the four lines.

Figure 2a
Rent Gradients



r_x; we initially assume that commuting costs are linear in distance, so these rents decline linearly to the city edge s_x, where they equal outside rents $\bar{r}$. The area of the residential district is determined by city population, and the area of the CBD determined by the number of people working there — both endogenous variables. Equilibrium values to be calculated are city population and employment, productivity, wages, and commercial and residential rents.

Although the model is not calibrated to real data, parameters have been chosen to be of realistic orders of magnitude. Thus:

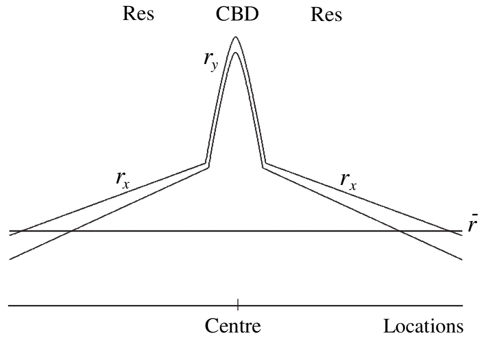
City/non-city productivity gap: 20 per cent
Commuting cost share of city income: 7 per cent
Residential rent share of city income: 18 per cent
Commercial rent share of city income: 7 per cent
Residential rent share of non-city income: 15 per cent
Commercial rent share of non-city income: 3 per cent.

The key parameter is the elasticity of productivity with respect to city employment, and we report results with this ranging in value from 0 (a benchmark case) to 0.077.

4.1 Effect of a transport improvement

The experiment we undertake is to reduce commuting costs by 20 per cent on one of the four lines in the city. Figure 2b illustrates effects. Residential rent gradients on this line are flattened, as the relative advantage of cells closer to the CBD is reduced. The city edge then expands as more locations can access the CBD sufficiently cheaply. Increased CBD employment has a positive productivity effect, and this is transmitted into CBD land rents, giving the upwards shift illustrated. The increase also shifts residential

Figure 2b
Rent Gradients Following a Transport Improvement



rent levels upwards. While the change in slope of the residential rent gradient occurs only along the line that experiences the transport improvement, the upwards shift affects all lines. Thus, increased CBD productivity causes a further expansion in city size as the return to commuting along all lines increases.

The magnitude of the real income effects are given in Table 1. The first row is a benchmark case, and the second and third look at tax and productivity effects separately. Remaining rows combine tax and productivity effects, looking at successively higher elasticities of productivity with respect to CBD employment. In the benchmark case the change in commuting costs (the direct cost saving offset by an increase in numbers commuting) is 0.35 per cent of initial city income and there is a substantial

Table 1
Real income gains (% base income) from transport improvement ($\gamma = 2$)

	1: Commuting cost reduction	*2: Urban employment change %*	*3: Value of productivity increase*	*4: Increase in tax revenue*	*5: Full effect*
$x' = 0$, $t' = 0$	0.351	5.91	0	0	0.44
$x' = 0$, $t' = 0.33$	0.332	5.8	0	0.308	0.738
$x' = 0.045$, $t' = 0.00$	0.347	7.9	0.354	0	0.909
$x' = 0.022$, $t' = 0.33$	0.329	6.65	0.145	0.389	0.987
$x' = 0.045$, $t' = 0.33$	0.327	7.45	0.337	0.481	1.277
$x' = 0.077$, $t' = 0.33$	0.324	9.15	0.709	0.662	1.881

increase in CBD employment of nearly 6 per cent. The overall gain is 0.44 per cent of base city income, exceeding the direct effect because of the presence of a non-marginal 'triangle', like β in Figure 1b.[9]

The presence of 33 per cent marginal tax wedge (row 2) increases the total gain by nearly three-quarters. The productivity gap between city and non-city workers is 20 per cent, so increasing urban employment by 5.8 per cent gives an increase in tax revenue which amounts to 0.308 per cent of initial city income. In the third row the elasticity of productivity with respect to CBD employment is set at 0.045, and tax rates are assumed to be zero. The additional gain then comes from employment growth raising productivity, and its effect is to make the overall gain more than twice the size of the change in commuting costs alone. The remaining three rows have both the tax wedge ($t' = 0.33$) and a productivity response, set at increasingly high rates ($x' = 0.022$, 0.045, 0.077). The higher the elasticity of productivity with respect to employment the greater the increase in city employment and the greater the overall economic gain. When the elasticity reaches 0.077 the overall gain amounts to 1.88 per cent of initial city income, approximately 5 times the value of the change in commuting costs, and 4 times larger than the base case welfare gain (0.44 per cent of income, row 1).

How do these values vary with parameters of the model? The simulations reported in Table 1 were conducted with commuting costs linear in distance, and residential units spread at constant density along each of the travel lines — essentially like the linear city case ($\gamma = 2$) of Section 3. The effect of these assumptions is to give quite large increases in commuting and in CBD employment following the transport improvement. This quantity response is smaller if the parameter γ is larger, so commuting creates stronger diminishing returns to city size. As discussed in Section 3, γ captures several underlying parameters. Thus, γ is higher if commuting costs are a convex function of distance, $\lambda > 1$. Alternatively, γ is larger if residential population density falls off sharply with distance from the centre, for example, if the parameter θ is negative. Table 2 reports results where $\gamma = 3$, consistent with commuting costs increasing with the square of distance $\lambda = 2$, or equivalently with population density falling off with distance, $\theta = -1/2$.

This change more than halves the change in city employment, bringing it down to around 3 per cent. In the central case in which the tax rate is 0.33 and the elasticity of productivity is 0.045 the overall gain amounts to 0.53 per cent of base income, as compared to 1.28 per cent in Table 1. However,

[9] In all cases the difference between values in column 5 and the sum of values in columns 1, 3 and 4 is due to these second order interaction effects.

Table 2
Real income gains (% base income) from transport improvement ($\gamma = 3$)

	1: Commuting cost reduction	2: Urban employment change %	3: Value of productivity increase	4: Increase in tax revenue	5: Full effect
$x' = 0$, $t' = 0$	0.18	2.91	0	0	0.214
$x' = 0.0$, $t' = 0.33$	0.172	2.91	0	0.122	0.324
$x' = 0.045$, $t' = 0.00$	0.177	3.33	0.148	0	0.395
$x' = 0.045$, $t' = 0.33$	0.17	3.33	0.148	0.172	0.53

the change also reduces the value of the direct change in commuting costs — more commuters are close to the centre so receive relatively little gain from the commuting cost reduction. Thus the ratio of the full effect (column 5) with tax and productivity effects present ($t' = 0.33$, $x' = 0.045$) to that with them absent is $0.53/0.214 \approx 2.5$. The analogous number in Table 2 is $1.277/0.44 \approx 2.9$. Thus, while dampening the employment effect reduces the overall gain from the project, the 'multiplier' effect due to tax and productivity change remains comparable, and very large.

5.0 Conclusions and Qualifications

The results of this paper suggest that there are significant gains from urban transport improvements, over and above those that would be contained in a standard cost–benefit appraisal. Productivity in the city may be increased by additional urban employment, this externality raising the productivity of existing as well as incoming workers. In addition, the combination of income taxation and an urban/non-urban productivity differential is a source of gain, even if productivity levels are constant. Moving workers to higher productivity jobs raises real income and raises tax revenue; extra commuting costs are incurred, but the presence of a tax wedge in the equilibrium condition between the wage gap and the marginal commuting cost means that the increase in output exceeds the increase in commuting costs. The calculations undertaken in the paper, using econometric estimates of the relationship between city size and productivity, suggest that these effects are large — typically yielding total gains several times larger than those that would be derived from a standard cost–benefit analysis.

These large effects must be qualified by several remarks. The first is that, in the model, journeys are made only for commuting. Standard cost–benefit analysis applies to leisure journeys, so if both types of journeys are made total benefits are an appropriately weighted sum of the effects. Second, the paper has not analysed the interaction between the transport improvement and negative congestion externalities. Such externalities may be present in the model — the dependence of output per worker on employment, $x(N)$, incorporates congestion externalities — but the relationship is assumed not to be shifted by transport improvements. This is a modelling simplification which can be the subject of future research.

Third, our modelling assumes that productivity outside the city remains unchanged. Thus, while expanding city employment raises productivity, reducing employment outside the city does not reduce outside productivity. Obviously, if activities outside the city experience a reduction in productivity following a decline in employment levels, then overall gains are reduced. The message is that transport investments have additional benefit in cities where the employment–productivity relationship is strongest. The reality here is likely to be complex. The employment–productivity relationship works not only by drawing more people into the city as a whole, but also by enabling more of the city's initial inhabitants to work in the CBD. Transport improvements also increase the effective density of activity — in London terms, making docklands closer to the City. The productivity relationship varies across sectors, and is generally strongest in those sectors that are clustered in large cities. All this means that, as usual, implementation of policy requires careful identification of where the market failures — tax wedges and agglomeration externalities — are largest.

Despite these qualifications, the message of this paper is clear. The same forces that cause cities to exist — agglomeration benefits — provide additional effects that should be included in urban transport appraisal. Estimating their exact size remains the subject of future work, but to ignore them is surely to miss one of the benefits of urban transport improvements.

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Appendix

Simulation: Gauss code available on request from the author. Output per worker at location $s, x(s)$ is

$$x(s) = a + b\left[\sum_z \frac{y(z)}{d(s,z)}\right]^{\mu},$$

where $y(z)$ is employment at location z and $d(s,z)$ is the distance between s and z. The term in square brackets is a measure of the economic mass of the CBD. The parameter μ measures the impact of this mass on average productivity, so agglomeration effects are present if $\mu > 0$. Simulations set, $a = 1$, $b = 0.1$, $\mu = 0.2$, 0.3, 0.4. The elasticity of output per worker with respect to CBD employment reported in the text is computed numerically for each value of μ. Residential density is set at 1/5 of CBD density. Other parameters as described in text.