TRANSPORT EFFICIENCY IN CITIES WITH SUBCENTRES

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INTRODUCTION

With increasing concern about greenhouse gas emissions caused by urban traffic, it is timely to re-examine alternative urban forms and associated transport networks which minimise these emissions in conjunction with alternative choices of housing, employment and travel mode. Whilst it is theoretically possible to make these comparisons through repeated applications of Lowry-type models, such as described in Webster *et al.* (1988), this can be extremely tedious when a large number of alternatives are to be tested. The aim of this study is to appropriately simplify the representation of the city and to combine both simulation and optimisation procedures to provide efficient comparisons and normative guidance. It is then possible to return to the application of Lowry-type models on the actual city with a considerably reduced number of alternatives. If employment and housing zoning instruments are available, as well as investment priorities for public and private transport links, the combined approach can potentially assist in providing policy guidance to encourage the city to evolve into a more environmentally benign pattern of usage.

After transcending the conventional monocentric city model, urban economists are now addressing polycentric city structures, with the recent work of Helsey and Sullivan (1991) analysing the corresponding tradeoffs between production scale economies and transportation diseconomies. Earlier models, such as that of Hartwick (1976), already examined two alternative mixes of housing and employment: (i) a central employment core surrounded by an annulus of housing, and (ii) housing and employment evenly dispersed throughout the city. The transportation part of the Hartwick model was generalised by Anderson, Roy and Brotchie (1986) to improve the simulation of commuter job choice. In practice, the dispersed form of city is more usually represented as a central business and cultural district surrounded by higher density housing, decreasing to medium density as a ring road is approached, around which urban employment and shopping subcentres are concentrated. Beyond the ring road, the housing density gradually decreases towards the urban fringe. This paper asks the question, if a dispersed urban structure is adopted with a Central Business District and a number of subcentres on a major ring road (or railway), where should the ring road be located and how many subcentres should be encouraged and of what size such that the total pattern is transport efficient?

The first flexible geometrical approaches to analyse transport-efficient urban form were developed by Marksjö and Karlqvist (1970). Further considerations of employment dispersal and job diversity were neatly illustrated in the 'urban triangle' of Brotchie (1984), developed further in Brotchie *et al.* (1992). The triangle was reproduced analytically by Anderson et. al. (1986), using linear and circular cities with subcentres, under simplifying assumptions of uniform housing density and constant speed. The current work lifts these restrictions, allowing for different housing densities and different average travel speeds, both radially and circumferentially, in different parts of the city. The two extreme cases of random job choice and choice of a job at the nearest (fastest) centre are examined. Information on appropriate net residential densities for cities of different types are extracted from tables in Newman and Kenworthy (1989).

1. MODEL DEFINITION AND FORMULATION

1.1 Input Parameters for the City

Adjustable input parameters of the assumed city form, the households and their housing, the employment distribution and the transport system are established.

1.1.1 City form.

A circular city form is assumed with a CBD and a series of employment subcentres equally spaced around a circumferential ring road/transit line. The total population to be accommodated is P.

1.1.2 Households/housing.

The housing is located within an inner core, a middle ring and an outer ring, with subscripts 1, 2 and 3 respectively. The following quantities are defined:

Proportion of total households	q_1	q_2	q_3
Average household size	s_1	s_2	s_3
Net housing density (houses/km2)	h_1	h_2	h_3

1.1.3 Employment.

The employment is divided into two classes, knowledge-based and manual/routine. The latter group is assumed to be more likely to find a suitable job in its nearest employment centre. The following quantities are provided as input:

Worker participation rate/capita	p_1	p_2	p_3
Proportion of total workers who are knowledge-based	k_1	k_2	k_3

For the jobs themselves, location in the CBD is denoted by subscript c and in any subcentre by subscript s. The following values are specified:

Proportion of knowledge/based jobs	r_{kc}	r_{ks}
Proportion of manual/routine jobs	r_{mc}	r_{ms}

1.1.4 Transport network.

It is assumed that commuters can travel radially, directly from their place of residence, and circumferentially, either at their origin or at their destination. Future versions may identify strong radial links (either expressways or transit lines) just connecting each subcentre and the CBD, as well as allowing for congestion and modal split analysis. Trips are always assumed to take the fastest available route. In particular, this means that the circumferential component of trips to any subcentre almost always is carried out around the ring road, except for some cases of reverse commuting for residents of the inner core. The following average speed values need to be provided from observations on values for comparable existing cities, where the radial speeds must allow for a proportion of public transport trips.

Average radial speeds	v_{r1}	v_{r2}	v_{r3}
Average reverse radial speeds	v_{o1}	v_{o2}	v_{o3}
Average circumferential speeds	v_{c1}	v_{c2}	v_{c3}
Average speed on ring road		v_r	

Finally, computed values include the radii r_i of each ring i, the number of knowledge and manual workers K_i and M_i respectively in each ring and the densities d_{ki} and d_{mi} of knowledge and manual workers respectively in their housing.

2. SPECIFICATION OF OBJECTIVES AND SOLUTIONS

In most urban road networks, door-to-door mean travel speeds are less than 50 km/h, with mean fuel consumption per unit distance given approximately as the sum of a constant term and a term *inversely* proportional to the mean speed (Biggs and Akcelik, 1986). Thus, a plausible objective to adopt for the combined land-use/transport planning problem is the minimisation of the average commuting time per capita. In a future more sophisticated model, the lower potential energy use per capita of public transport will be allowed for.

In order to obtain analytical solutions for the optimum, the average commuting time is minimised in terms of one key variable, the radius z of the ring road. Other input characteristics of the system, such as the number of subcentres, can be tested sequentially. For instance, the residential densities can be increased in the middle and outer rings to reflect a policy of consolidation in areas of low density housing.

As illustrated in the urban triangle of Brotchie (1984) and analytically in Anderson *et al.* (1986), job choice behaviour can be bounded from below (selecting the nearest job) and from above (travel-time indifferent or 'random' job choice), with major large cities with diverse job opportunities lying further from the lower bound than cities dominated by more uniform manufacturing jobs. The analysis will formulate each of these two cases in turn, in conjunction with shortest (fastest) path travel between home and the chosen job centre.

2.1 Job choice at nearest centre.

In this case, the desired location of the employment is obtained, such that each worker, desiring a job at his nearest centre, actually finds one there. Thus, the partitioning of the jobs between the CBD and the subcentres is initially unconstrained, being evaluated by the model such that each job selected is at the closest centre to each worker. Generally, the ring road will turn out to be located in the middle ring. However, if the solution of the optimisation problem yields z either in the inner core or the outer ring, the problem formulation needs to be revised accordingly and re-run. The average trip time for residents in each ring is now given in order.

2.1.1 Outer Ring

It is assumed that shortest (fastest) path travel involves all travel to the nearest subcentre having its circumferential component along the ring freeway, that is, ($z/v_r < r_2/v_{c3}$). In addition, all outer ring workers find their nearest job at their nearest subcentre, not at the CBD. With n subcentres, the outer region can be divided into 2n segments each subtending an angle (π/n). Denoting the area of the outer ring as A_3, the area of each segment is ($A_3/2n$). The average travel time t_{3n} for outer residents is

$$t_{3n} = \frac{2n}{A_3} \int_0^{\pi/n} d\,\theta \left[\int_{r_2}^{r_3} [(r-r_2)/v_{r3} + (r_2-z)/v_{r2} + z\theta/v_r]\, r\, dr \right. \quad (1)$$

This may be readily evaluated to yield

$$t_{3n} = 2\pi\,\{(r_3-r_2)^2\,(r_2 + 2r_3)/6v_{r3} + (r_3^2-r_2^2)\,[(r_2-z)/v_{r2} + \pi\, z/2n\, v_r]/2\}/A_3 \quad (2)$$

2.1.2 Middle Ring

The simplest case occurs when all circumferential travel is via the ring road (that is, $z/v_r < r_1/v_{c2}$) and all residents commute to the subcentres (that is, $(z - r_1)/v_{o2} < r_1/v_{r1}$). This will often be valid for cities with poor transit standards and where radial freeways become congested as one enters the inner core. The travel time t_{2n} is

$$t_{2n} = \frac{2n}{A_2} \int_0^{\pi/n} d\,\theta \left[\int_z^{r_2} (r - z)/v_{r2} + \int_{r_1}^{z} (z - r)/v_{o2} + \int_{r_1}^{r_2} z\,\theta/v_r \right] r dr \quad (3)$$

where residents between r_1 and z reverse commute. After simplification, this gives

$$t_{2n} = \frac{2\pi}{A_2}\{(r_2 - z)^2\,(z + 2r_2)/6v_{r2} + (z - r_1)^2\,(z + 2r_1)/6v_{o2}$$
$$+ \pi\, z\,(r_2^2 - r_1^2)/4nv_r\} \quad (4)$$

In cities with a well-developed radial transit system, the improved average radial speeds imply that some commuters may find it faster to go to the CBD (that is, $r_1/v_{r1} < (z - r_1)/v_{o2}$). In this case, a situation such as shown in Figure 1 arises, where from radius r_2 to $\tilde{r}_{max}$ all commuters work at the subcentre, from $\tilde{r}_{max}$ to $\tilde{r}_{min}$ some go to the subcentres and others to the CBD (see shaded area), and from $\tilde{r}_{min}$ to r_1 all go to the CBD. At the same time, all circumferential travel, as before, is taken to occur on the ring road (i.e., $z/v_r < r_1/v_{c2}$). The boundary radius $\tilde{r}$ at any angle θ is given as

$$\tilde{r} = [z\,(1/v_{o2} + \theta/v_r) - r_1\,(1/v_{r1} - 1/v_{r2})]/(1/v_{r2} + 1/v_{o2}) \quad (5)$$

In this more complicated case, the average commuting time t_{2n} is given as

$$t_{2n} = \frac{2n}{A_2} \int_0^{\pi/n} d\theta \left\{ \int_z^{r_2} (r - z)/v_{r2} + \int_{\tilde{r}}^{z} (z - r)/v_{o2} \right.$$
$$\left. + \int_{r_1}^{\tilde{r}} [(r - r_1)/v_{r2} + r_1/v_{r1}] + \int_{\tilde{r}}^{r_2} z\,\theta/v_r \right\} r\, dr \quad (6)$$

Here it is being assumed that $\tilde{r}_{min} > r_1$ and $\tilde{r}_{max} < z$. As the limits $\tilde{r}$ of the integrals are themselves functions of θ, the integration of (6) is more complicated than in the previous cases. Nevertheless, certain cancellations yield the result

$$t_{2n} = \frac{2\pi}{A_2} \{ (r_2 - z)^2 (z + 2r_2)/6v_{r2} + z^3/6\, v_{o2} - r_1^3 (3/v_{r1} - 1/v_{r2})/6$$
$$+ \pi z\, r_2^2/4nv_r - [\tilde{r}_{max}^2 + \tilde{r}_{min}^2] [\tilde{r}_{max} + \tilde{r}_{min}] (1/v_{r2} + 1/v_{o2})/24 \} \qquad (7)$$

Other combinations are possible for fastest path travel, depending on factors such as the expected level of congestion (if any) on the ring road.

2.1.3 Inner Core

The simplest case occurs for a more private transport oriented city, where some residents from the inner core find it faster to reverse commute to their nearest subcentre and always use the high capacity ring road for the circumferential component of their travel. The radius r^* at which travel to the CBD or the nearest subcentre takes equal time is expressed as

$$r^* = [z\, (1/v_{o2} + \theta/v_r) + r_1 (1/v_{o1} - 1/v_{o2})]/(1/v_{r1} + 1/v_{o1}) \qquad (8)$$

This reaches its maximum value r^*_{max} at $\theta = \pi/n$ and its minimum value r^*_{min} at $\theta = 0$. The radius $y = z\, v_{c1}/v_r$ at which circumferential travel starts potentially to take place in the inner core is taken as $< r^*_{min}$ and it is also assumed that $r^*_{max} < r_1$. The average inner travel time is given as

$$t_{1n} = \frac{2n}{A_1} \int_0^{\pi/n} d\theta \; \{ \int_{r^*}^{r_1} [r_1 - r)/v_{o1} + (z - r_1)/v_{o2} + z\,\theta/v_r] + \int_0^{r^*} r/v_{r1} \}\; r\, dr \qquad (9)$$

After considerable simplification, this reduces to

$$t_{1n} = \frac{2\pi}{A_1} \{ r_1^3/6v_{o1} + r_1^2 (z - r_1)/2v_{o2} + \pi\, z\, r_1^2/4nv_r$$
$$- \{ r^*_{max}{}^2 + r^*_{min}{}^2] [r^*_{max} + r^*_{min}] (1/v_{r1} + 1/v_{o1})/24 \} \qquad (10)$$

In the city with strong radial public transport (see (5) to (7) above), the previous conditions indicate that all inner core residents will commute to the CBD. In this case, the average travel time is simply

$$t_{1n} = \frac{2n}{A_1} \int_0^{\pi/n} d\theta \int_0^{r_1} (r/v_{r1})\; r\, dr \qquad (11)$$

which can be evaluated immediately to give

$$t_{1n} = \frac{2\pi}{A_1} \{r_1^3/3v_{r1}\} \qquad (12)$$

The average trip time t_n for the whole city is finally evaluated as

$$t_n = [\sum_{j=1}^{3} (K_j + M_j)\, t_{jn}]/[K + M] \qquad (13)$$

which is the quantity which is to be minimised in terms of the optimal ring radius z by setting $\partial t_n/\partial z = 0$. Defining the resulting quadratic equation in the conventional form $az^2 + bz + c = 0$, the relevant terms for the more private transport oriented city can be computed. With a and b universally positive and c negative for this system, it yields one real positive root, as required. Also, because $\partial^2 t_n/\partial z^2$ is universally positive, this root represents the unique ring radius z which minimises the average commuting time.

Upon separating out the trips of those workers who have faster trips to the CBD from those in which the workers have faster trips to their nearest subcentre, it is possible to determine the most transport efficient distribution of employment in the CBD vs the subcentres, both for the knowledge and manual workers. This proportion will clearly vary with the relative mix of private vs public transport in the city, whereby cities with fast, efficient, radial public transport lines will have a relatively stronger CBD than cities with poor radial public transport.

2.2 Job choice random

In cities where jobs are very diverse or where the employer pays (or subsidises) the commuting costs of his employees, workers are much less likely to choose the nearest job than in other cases. Ideally, a consideration of this complex problem would involve a very disaggregated spatial subdivision of both the workers as well as categories of their compatible jobs to identify strong locational mismatches. In the following, just two categories are considered, as before. The analysis now follows, recognising that a worker here chooses a job at the CBD vs one at any of the subcentres entirely in proportion to the relative number of jobs at these locations. The assumption of radial symmetry implies that one merely doubles the result of integration between 0 and π of the angle θ subtended between any subcentre and the elemental area ($r\, dr\, d\theta$) of workers. The analysis, which is illustrated for the knowledge workers, is processed similarly for the manual workers.

2.2.1 Outer Ring

Assuming that no trips to subcentres occur out through the CBD (feasible for a strong ring road) and using the defined job ratio and density terms, the average trip time t_{3rk} is

$$t_{3rk} = \frac{2d_{k3}}{K_3} \int_0^{\pi} d\theta \; \{r_{ks} [\int_{r_2}^{r_3} \{(r - r_2)/v_{r3} + (r_2 - z)/v_{r2} + z\theta/v_r\} \; r \, dr]$$

$$+ r_{kc} [\int_{r_2}^{r_3} \{(r - r_2)/v_{r3} + (r_2 - r_1)/v_{r2} + r_1/v_{r1}\} \; r \, dr]\} \qquad (14)$$

This readily comes out as

$$t_{3rk} = \frac{2\pi d_{k3}}{K_3} \{[(r_3 - r_2)^2 (2r_3 + r_2)/6 \, v_{r3} + (r_3^2 - r_2^2) \, r_2/2v_{r2}]$$

$$+ r_{ks} [(r_3^2 - r_2^2) \, z \, (\pi/2v_r - 1/v_{r2})/2] + r_{kc} [(r_3^2 - r_2^2) \, r_1 \, (1/v_{r1} - 1/v_{r2})/2]\} \quad (15)$$

2.2.2 Middle Ring

Here the simplest case is illustrated, where no subcentre trips proceed out through the CBD and where circumferential travel always occurs on the ring road. This yields

$$t_{2rk} = \frac{2d_{k2}}{K_2} \int_0^{\pi} d\theta \; \{r_{ks} [\{ \int_z^{r_2} (r-z)/v_{r2} + \int_{r_1}^{z} (z - r)/v_{o2} +$$

$$\int_{r_2}^{r_1} z\theta/v_r\} \; r \, dr] + r_{kc} [\int_{r_1}^{r_2} \{(r - r_1)/v_{r2} + r_1/v_{r1}\} \; r \, dr]\} \qquad (16)$$

This is evaluated to give

$$t_{2rk} = \frac{2\pi d_{k2}}{K_2} \{r_{ks} [(r_2 - z)^2 (2r + z)/6v_{r2} + (z - r_1)^2 (2r_1 + z)/6v_{o2}$$

$$+ z \, \pi \, (r_2^2 - r_1^2)/4v_r] + r_{kc} [(r_2 - r_1)^2 (2r_2 + r_1)/6v_{r2} + (r_2^2 - r_1^2)/2v_{r1}]\} \qquad (17)$$

2.2.3 Inner Core

It is again assumed that no subcentre trips proceed outwards through the CBD. However, at a certain point, reverse commuters travel circumferentially at the origin rather than on the ring road. This radius y is given as $y = z \, v_{c1}/v_r$ and is assumed to be $< r_1$. The average trip time t_{1rk} is derived as

$$t_{1rk} = \frac{2d_{k1}}{K_1} \int_o^{\pi} d\theta \, \{r_{ks} \, [\{ \int_o^{r_1} [(r_1 - r)/v_{o1} - (z - r_1)/v_{o2}] +$$

$$\int_y^{r_1} z \, \theta/v_r + \int_o^{y} r\theta/v_{c1}\} \, r \, dr] + r_{kc} \, [\int_o^{r_1} (r_1/v_{r1}) \, r \, dr]\} \qquad (18)$$

Using the expression for y, the above expression can be obtained as

$$t_{1rk} = \frac{2\pi d_{k1}}{K_1} \{r_{ks} \, [r_1^3/6v_{o1} + (z - r_1) \, r_1^2/2v_{o2} + \pi \, z \, (3r_1^2 - y^2)/12 \, v_r]$$

$$+ r_{kc} \, [r_1^3/3v_{r1}]\} \qquad (19)$$

The most important observation to be made about the above average time expressions, in comparison for those for commuters choosing the nearest job, is that the average time is independent of the number n of subcentres. This property was also observed in the simpler models described in Anderson *et al.* (1986). In minimising the average commuter time t_{rk} over the city for knowledge workers with random job choice, a quadratic expression again results, where the solution is not necessarily real. In these cases, the optimal ring road may collapse into the CBD. However, when the average speed v_r on the ring road is high and when the job density d_{k1} of the inner core is only say about double of that further out, a real optimal ring road radius z will exist.

3. SOME TYPICAL SIMULATIONS

The model as formulated allows a very wide variety of simulations to be carried out. In this paper, a sample of these simulations together with the associated optimisation is presented for a city with population 2.5 million. Two classes of cities are considered, drawing from the typology in Newman and Kenworthy (1989). Firstly, an 'Australian' city is analysed, with a medium to high density inner core surrounded by a medium density middle ring and a low density outer ring. Secondly, a large city typical of the western part of the USA is treated, with the inner core as for the Australian city, but both middle and outer rings at low density. Each of these land use forms is combined with one of two transport system alternatives, a private transport dominated solution and a more balanced system with strong radial public transport links.

3.1 Comparisons of Results

The comparisons can be made with respect to the land-use density options, job choice behaviour and properties of the transport network.

3.1.1 Land-use density options (Aust. vs US).

As shown in Figure 4, average travel time for choice of the nearest job only increases by 10 to 15% for the US versus the Australian land use. However, as job choice becomes less dependent on perceived travel time (i.e., random), the US city trips take up to 30% longer than for the Australian case, primarily due to the long circumferential distances in the extensive low density areas. On the other hand, with the ring road generally located further out for the US case, more jobs are most accessible to the CBD and its optimal size increases (Figure 3). In practice, the lower density of the US city may typically allow less congested travel, decreasing the unit trip times (and associated private transport energy use) somewhat towards those of the Australian city.

3.1.2 Job choice options

Comparisons are made of results for nearest vs random job choice and for different numbers of employment subcentres. From Figure 4, it is seen that trip times are almost doubled between the nearest and random job choice cases. Note that, large increases in travel costs would inevitably move the solution towards the nearest job choice situation. Alternatively, if commuters put a high disutility on their commuting time, they will tend to move house or change job of their own accord to have shorter trips. In addition, if potential employers are supplied with improved spatial labour market information, they may locate their firms closer to the relevant parts of the labour market. Thus, in the longer term, it should be possible to move closer to the lower bound on average travel time.

In comparing results from Figure 2 for various numbers of employment subcentres, it is seen that decreases in average travel time of over 30% can occur when the number of subcentres is increased from say 3 to 8. These gains are relatively larger than those obtainable by increasing housing density (e.g., US → Australian city). Note also, that any increase of the number of subcentres beyond 8 or 10 produces relatively modest gains. If we have some assessment of agglomeration economies in cities with fewer subcentres (Helsey and Sullivan, 1991), the transport energy savings of more subcentres can be set against the potential productivity losses.

3.3.3 Transport network options

Trip time savings of about 10% are available when there is efficient radial public transport. This does not include the effects of the resulting lower congestion on the radial road network. In addition, from an energy point of view, each person km on a well-patronised public transport system will use less per capita energy than a person km with private transport. This difference is lessened with the use of car pooling and small fuel-efficient vehicles. However, the outer ring road freeway, supplemented by circumferential public transport, may well be the best solution for travel which is primarily circumferential.

4. CONCLUSIONS

City forms with idealised geometry, but with other land use and transport characteristics representative of actual cities, do appear to provide insights on establishing parameters for more transport energy efficient urban structures. The case is strong if the primary interest is in obtaining a rough guide as to relative benefits of alternative policies. These policies include (i) housing density and zoning regulations, (ii) employment location incentives for different sectors and (iii) public vs private transport investment priorities.

Clearly, the realism of the model simulations can be improved if relevant area congestion functions can be specified, especially for radial travel, in conjunction with iterative solution for the expected trip patterns. As already shown, the solutions can be obtained more simply under the assumption of radial symmetry, where for the nearest job choice case, one need only consider travel within a (π/n) sector on either side of a typical subcentre. In theory, it should be possible to develop a continuous traffic assignment model for such a typical sector.

The spatial coordination of job availability in relation to worker residences seems the area where greatest gains can be made if combined with a policy of employment subcentre development (Figures 2 and 4). If it were possible to finally assess the greenhouse emissions of the alternative arrangements, the advantages of more public transport investment would become relatively more important. If a modal split feature were added, one could determine the relative effects on public transport viability of policies to increase residential densities in the middle and outer rings. A key item of interest is the determination of whether the expected extra road traffic congestion induced by such increased residential densities would be mitigated by the induced switch to a more viable and thus more attractive public transport system.

When the model can be enhanced as above, it may well provide a stimulus for directed application of the well-tested equilibrium and optimisation models described in Webster *et al.* (1988), most of which are calibrated to actual cities, and include feedback effects of changes in accessibility on land prices.

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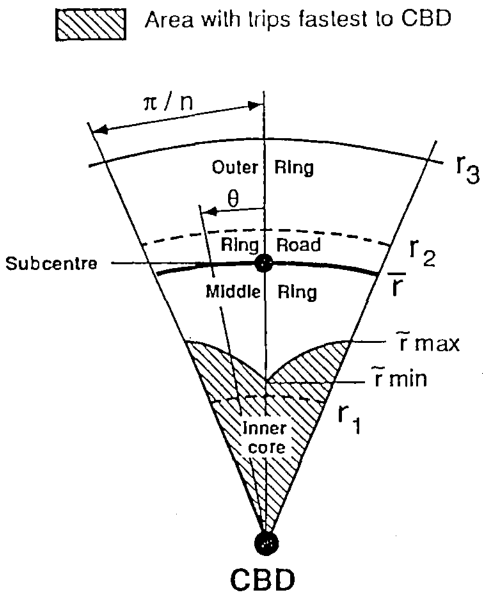

Figure 1

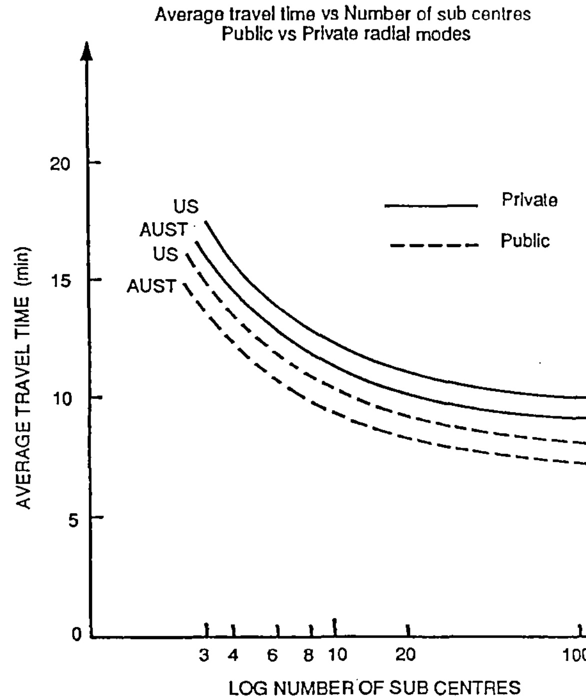

Figure 2

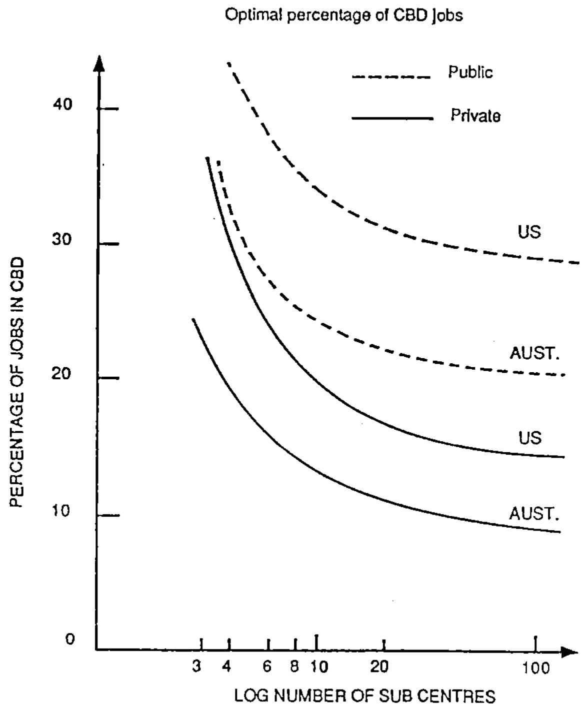

Figure 3

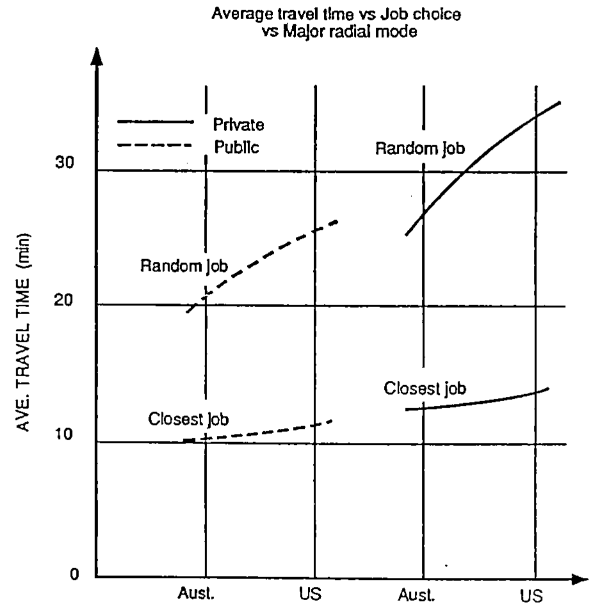

Figure 4