A STUDY ON URBAN RESIDENTIAL DENSITY VS. TRANSPORT ENERGY CONSUMPTION

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This study aims to simulate the relationships between urban residential density, job decentralisation and transport energy consumption. In particular, it examines the linkages between road congestion and changes in modal split to public transport when new housing is added as (i) outward urban expansion (sprawl) or (ii) infill (redevelopment) within an existing urban area. In either case, new jobs are allocated spatially to minimise transport energy consumption. Whereas the sprawl scenario is supported by increased investments in freeways, the infill options are implemented in conjunction with increased transit investments.

1. INTRODUCTION

Some planners and academics, who are resident in the low density cities in North America or Australasia, often look wistfully at the currently more energy-efficient European cities, especially when confronted with the development of policies to reduce Greenhouse emissions and transport energy consumption. These views are expressed, for instance, in the study by Newman and Kenworthy (1989) as a rationale for increasing residential densities in such cities. However, in the low growth conditions which exist currently in many of these cities, a transformation to European densities may take 50 to 100 years, or more. Nevertheless, policies such as infill of existing urban sites at higher density (i.e. urban consolidation) are actively presented as major contributors to increased energy efficiency. At the same time, further outward expansion of urban areas, demonised by the word 'sprawl', is regarded as inherently wasteful. This is claimed despite the fact that many of the new jobs being created are information- or knowledge-based, and potentially integrable into residential areas, thus reducing the need to travel. Also, the amenity benefits of green and leafy suburbs are discounted in such criticisms. Clearly, some comparative analysis is required to test alternative strategies to encourage current low density cities to become more efficient in their consumption of transport energy, whilst maintaining, as far as possible, their inherent attractiveness. This paper makes an initial attempt to quantify some of the trade-offs involved, particularly between job decentralisation and urban consolidation. The results will also have general relevance for any city where more energy-efficient coordination is sought between the spatial distribution and density of housing, the spatial pattern of jobs and the supply of public and private transport networks.

With the recent world-wide efforts to develop policies for meeting Greenhouse emission targets and reducing dependence on fossil fuels, there is a renewed interest in the relationship between urban form and potential transport efficiency. In a recent study by Wegener (1995) for a medium density city in Germany, it was demonstrated that transport rather than land-use policies must bear the brunt of inducing cities to meet the emission targets in the transport sector within the next twenty years or so. Whereas new land-uses can adjust rather rapidly to new transport pricing and investment policies, the inertia to change of existing land-uses and associated infrastructure investments considerably reduces their potential contribution in the medium term to greater energy conservation. On the other hand, transport pricing and investment policies, such as road pricing and investment in more flexible public transport, can significantly increase the transport efficiency 'in use' of the existing locational pattern of urban infrastructure. This does not mean that land-use changes are to be discounted – they merely occur more slowly. Thus, our study examines their eventual potential to produce energy savings in a city which has already been created at low density.

Breheny (1995) evaluated total travel energy expenditure in urban areas of England and Wales for two scenarios:

(1) The present distribution of activities including counter-urbanisation (dispersal).

(2) The distribution which would have resulted if all counter urbanisation which occurred over the last 30 years (1961-1991) had been totally prevented (complete containment or infill).

He utilised existing analyses and data on travel generated in urban areas of England and Wales, and their mode distributions, vehicle occupancies and energy expenditures, over a range of types and sizes of towns and cities, including inner and outer London, to determine primary energy use for population changes under each scenario for the period 1961-1991. He estimated the net effect of full containment of counter urbanisation over the thirty year period, and over all urban areas involved to be an energy saving of only 2%.

In this study, a city reflecting the land-use and transport properties of a typical Australian or US city is postulated. Housing is gathered in three rings of decreasing density with distance as one moves outwards. Jobs are located in a Central Business District (CBD) and in subcentres spaced uniformly around ring roads, with radial freeways and parallel transit lines connecting the subcentres with each other and with the CBD. Then, the city is allowed to grow in different ways, in terms of alternative scenarios of infill vs. sprawl, with the former being supported by significant improvements in transit level of service and the latter by freeway and ring road widening.

The study analysis is performed using the AUDIT (Appraisal of Urban Development, Infrastructure and Transport) decision support framework developed at CSIRO. Within

AUDIT, the simulation of the transport behaviour of the alternative cities is performed using the SUSTAIN model (Sustainable Urban STructure And Interaction Networks), as described in Roy, Marquez, Taylor and Ueda (1995). Trip distribution and modal split are performed via gravity/logit approaches followed by congestion assignment using Davidson speed-volume functions. This is an advance on the study on consolidation vs. job decentralisation in Roy (1992), where pre-defined speeds were used on each transport network link. Primary energy transport consumption and CO_2 emissions in commuting are based on expressions calibrated to Australian urban data, where electricity is generated from coal. Whereas for the deterministic case, where the trip distribution gravity index $\beta \rightarrow \infty$, the model locates jobs such that the commuter seeks and finds a job at his nearest employment centre, a different approach is adopted for calibrated values of β. Being written in object-oriented form, AUDIT can assemble modules from SUSTAIN to communicate with modules of the new TOPAZ model (Technique for Optimal Placement of Activities in Zones), developed by Brotchie, Sharpe, Marquez and Maheepala. This is a significant enhancement of the original TOPAZ described in Brotchie, Dickey and Sharpe (1980) and illustrated in Webster *et al.* (1988). In this way, for a given housing location scenario from SUSTAIN and a given gravity parameter β, TOPAZ can iteratively determine the job locations which minimise total transport energy costs. As locations of jobs are often subject to zoning regulation, it is reasonable from a policy viewpoint to allow the model to prescribe job centre zoning guidelines which are optimal. The minimum energy job location solution also corresponds via iteration to a network equilibrium on the congested road network. Thus, AUDIT allows an appropriate mix of optimisation and simulation modules to be chosen for any given application.

The following section describes the city which is to be studied, including the behavioural assumptions which are adopted. Then, the test results are described and compared, followed by conclusions and recommendations for further research.

2. DESCRIPTION OF STUDY

2.1 Original City and its Networks

A city is defined with 4 million inhabitants, grouped radially-symmetrically about a CBD in three housing zones, an inner core, a middle annulus and an outer annulus. The density of housing decreases in each zone as one moves outwards, with net densities corresponding to those observable in typical Australian cities as given by Newman and Kenworthy (1989). In general, these densities are somewhat greater than those in the new US cities, but considerably less than those in most European cities.

The jobs are distributed to the CBD, as well as to two rings, each containing six subcentres, with an offset of 30° between subcentre positions on the two rings. The subcentres occur at points of intersection of major links of the transport network. For the road network, these are intersections of radial freeways and ringroad freeways. For public transport, the radial links are defined as transit and the circumferential links as express buses.

As one of the key components of the study is the evaluation of transport energy consumption, its specification has required special care. For both public and private transport, the results refer to **primary** energy consumption. This includes electricity generation and transmission losses for transit and refining losses for petrol. The values used reflect average current conditions in Australia. Because of the relative large average age of the privately-owned component of the Australian car fleet, recent improvements in car fuel economy are just partially represented.

Finally, SUSTAIN is used to determine a network-equilibrated deterministic distribution of jobs, such that each worker **seeks and finds** a job at the subcentre (or CBD) reachable by him at the least generalised cost, denoted as $\bar{c}_{min}$ when averaged over the entire city. This corresponds to the gravity parameter β approaching infinity in the trip distribution model (Evans, 1973). Using this locational pattern of jobs, the travel pattern is again equilibrated for the case of 'random' or 'travel-cost-indifferent' job choice, where $\beta = 0$, yielding the upper bound $\bar{c}_{max}$. Then, referring to Brotchie's urban triangle in Anderson, Roy and Brotchie (1986) and in Brotchie, Gipps and Newton (1995) it is observed that for a major Australian city, such as Melbourne, the actual travel cost $\bar{c}_{act}$ is approximately equal to ($0.7\ \bar{c}_{min} + 0.3\ \bar{c}_{max}$). Using this value for the average trip cost $\bar{c}$, the corresponding network-equilibrated value of β is calibrated. Although energy-conserving planning policies will be expected to increase β, we make the conservative assumption that the calibrated β remains constant through the forecast period. Then, TOPAZ is applied in a job location mode to find the travel-energy minimising pattern of jobs, which at the same time represents a network equilibrium. All cases are associated with logistic modal split, using plausible trade-off parameters and percentages captive to each mode. This all then defines our 4 million city in its housing location, job location and network utilisation, acting as a base case upon which future growth is to build according to alternative scenarios of infill and sprawl.

2.2 Growth Scenarios and Analysis

Alternative scenarios for the forecast growth of the defined 4 million city to 5 million are to be examined. Whilst such a degree of growth is very large for a 'Western' city, it allows the influence of alternative land use policies to be identified. As such, the analysis may have more immediate implications for the rapidly growing cities of Eastern Asia. The alternative growth scenarios are now described in detail.

2.2.1 Infill Growth Scenarios

Although, in practice, growth will occur as a mixture between outward sprawl and infill of existing areas, this study defines the infill scenarios as pure infill without sprawl. In other words, the entire extra one million population is taken to be accommodated within the boundaries defined by our base city of 4 million. This approach yields a firmer basis for comparison with the sprawl scenarios. In the first scenario, infill is made in the middle ring such that it reaches almost the same density as the inner core, with a small residue spilling over into the outer ring. The second infill scenario is more conventional, with infill occurring in the outer ring to raise its density almost to that originally existing in the middle ring, with a small residue then spilling back into the middle ring.

The two infill scenarios are accompanied by a significant upgrading of the radial transit network. An increase of service frequency reduces waiting times, where waiting times are taken to have double the disutility of in-vehicle times. The increase of service frequency, taken together with an increase of vehicle speeds, are taken to increase average transit speeds by 20%.

2.2.2 Sprawl Scenarios

With medium density development being encouraged on the periphery of some Australian cities, such as Sydney, two different types of sprawl are considered. The more conventional case allocates the entire one million population growth to sprawl outwards at the same low density as the existing outer ring. Then, a second case takes this same growth to sprawl outwards at the medium density of the existing middle ring.

For each of the above two sprawl scenarios, two different subcentre scenarios are defined. In the first, no new employment subcentres are created, with the new jobs being optimally allocated to the CBD and the existing two rings of subcentres. For the second case, a third ring of six subcentres moves out in sympathy with the new outward development, with the number of jobs allocated to the CBD and the three subcentre rings again optimally allocated via TOPAZ to minimise primary energy consumption. This configuration, as well as the corresponding transport network and zonal specification, is illustrated in Figure 1.

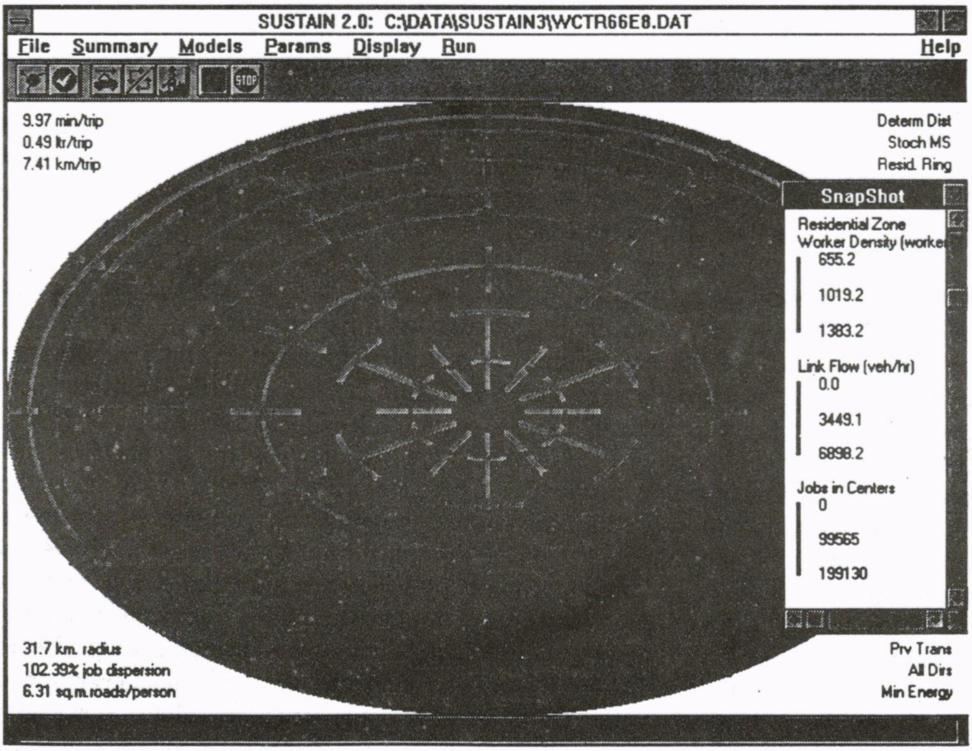

Figure 1. Configuration of city with medium density sprawl and extra ring

The sprawl scenarios are associated with transport investment priorities which favour roads. All major radial and ringroad freeways are widened by one lane in each direction, leading to a mix of 6 lane (that is, 3 lanes in each direction) and 8 lane routes. In the scenarios where sprawl is **not** accompanied by new employment subcentres, public transport average speeds are increased by 5%. In addition, for the case of sprawl at medium density, the radial transit lines are extended to the new outer boundaries of the city.

2.2.3 Details of Analysis

Each of the two infill scenarios and four sprawl scenarios is associated with three distinct analytical frameworks, defined as follows.

Analytical framework 1. In each case, a **fully normative** approach is adopted by SUSTAIN, whereby workers both **seek and find** a job at the subcentre (or CBD) reachable by them from home at the least generalised cost on an equilibrated transport network (that is, for $\beta \rightarrow \infty$). This yields distinct non-overlapping residential catchments for each employment centre, with travel just overlapping on the ringroads and the major radial roads occurring mid-way between subcentres. This framework yields the minimum possible energy consumption in commuting achievable under the given pattern of housing and transport networks, together with the corresponding optimal pattern of employment. As such, it represents a lower bound toward which the city would adjust under transport policies such as road pricing, dramatic increases in the cost of petrol or the widespread use of information systems encouraging spatial matching of workers in their housing to emerging jobs.

Analytical Framework 2. This case is based on use in trip distribution via SUSTAIN of the **behavioural** gravity parameter β calibrated on the original 4 million city and the $\beta \rightarrow \infty$ **normative** locational pattern of jobs obtained from framework 1 above. In other words, workers are assumed to trade off job benefits and generalised costs of travel in the same way as 'observed' in the original city. This is again solved iteratively to obtain equilibrium simultaneously on the transport network.

Analytical Framework 3. Finally, in this case, SUSTAIN and TOPAZ are coordinated under AUDIT such that, using the β calibrated upon the original city, jobs are allocated optimally to all employment centres to minimise transport energy consumption in commuting. At the same time, as shown in Figure 2, a simultaneous transport network equilibrium is achieved iteratively together with the locational distribution of jobs. The reduction of transport energy consumption from the previous framework indicates the potential of job zoning policy instruments to produce savings. TOPAZ uses the method of simulated annealing to solve the non-convex programming problem of obtaining the optimal pattern of jobs (and potentially, housing) which minimises transport energy consumption. Thus, in making our comparisons between the performance of the infill scenarios vs the sprawl scenarios, we have a consistent basis for comparison if each scenario is associated with its own corresponding optimal job location pattern. Note that, for $\beta \rightarrow \infty$ in Framework 1, SUSTAIN obtains directly the same minimum energy result as would have been obtained via the TOPAZ iterative optimisation procedure. However, for a calibrated β, TOPAZ is able to obtain the most efficient job location pattern in Framework 3, compared with our 'educated guess' in Framework 2.

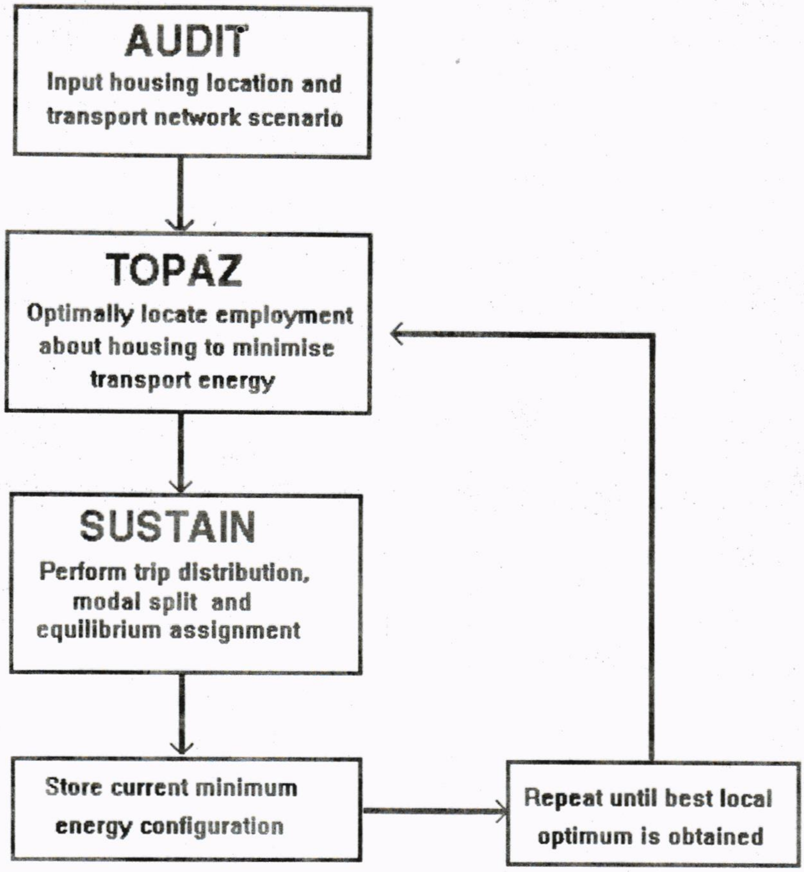

Figure 2. Structure of analytical framework 3.

3. RESULTS OF TESTS

The test results for the original city and the two infill scenarios are given in Table 1, with Tables 2 and 3 illustrating the sprawl scenarios. As the key results are the per capita energy use for each scenario, this is discussed first, followed by consideration of all the factors which have influenced these values.

For the calibrated gravity parameter β, the best primary energy result of 34.78 m joules/trip is for the first infill scenario. On the other hand, the best corresponding sprawl result of 40.87 m joules/trip, an increase of 17.5%, is for the case of medium density sprawl supported by an extra ring of job subcentres. The results for CO_2 emissions closely parallel those for primary energy consumption. This difference is clearly significant, even under the caveats that (i) neither 100% infill nor 100% sprawl is likely to occur in practice and (ii) such a major infill process will take many, many years to complete, and thus not be a major factor in the medium term for achieving the Greenhouse targets for the transport sector. At the same time, as the gravity parameter β moves towards infinity, the energy consumption of 17.88 m joules/trip of the best infill case becomes only 2.4% better than the corresponding result of 18.30 m joules/trip for the best sprawl result. In other words, a lower density city with a CBD and three rings of job subcentres is almost as energy-efficient as a medium density city with a CBD and two rings of job subcentres, so long as most workers seek and find their jobs locally. Certainly, many of the newly evolving service and knowledge-based jobs can locate readily in subcentres within residential areas. Also, if road pricing or fossil fuel price increases are imposed to help achieve the 2005 targets, as proposed by Wegener (1995), the gravity parameter β may increase radically, with workers seeking jobs much closer to home and employers locating closer to their potential work force. Thus, whilst the savings due to infill are significant they (i) will take very many years to accrue and (ii) will be reduced relatively as transport pricing policies are introduced in the medium term to cut energy consumption.

	Original City			**Infill into Middle Ring**			**Infill into Outer Ring**		
Job Location	deter-ministic	calibra-ted	optimum	deter-ministic	calibrated	optimum	deter-ministic	calibrated	optimum
Existing Population	4 million	4 million	4 million	4 million	4 million	4 million	4 million	4 million	4 million
New Population				1 million	1 million	1 million	1 million	1 million	1 million
Total Zones	84	84	84	84	84	84	84	84	84
Total Job Centres	13	13	13	13	13	13	13	13	13
Land Area (sq.km)	2591.56	2591.56	2591.56	2591.56	2591.56	2591.56	2591.56	2591.56	2591.56
City Radius (km)	28.72	28.72	28.72	28.72	28.72	28.72	28.72	28.72	28.72
Ave Energy (MJoules/trip)	17.78	36.34	35.32	17.88	34.95	34.78	17.96	35.93	35.90
Ave CO2 Emission (kg/trip)	1.20	2.44	2.37	1.20	2.35	2.34	1.21	2.41	2.41
Ave Trip Time (min/trip)	10.11	15.98	15.70	10.73	16.54	16.45	11.95	17.13	17.16
Ave Trip Distance (km/trip)	7.32	14.58	14.28	7.53	14.65	14.57	7.74	15.04	15.03
Usage of Public Transport (%)	33.54	29.88	30.38	33.86	31.35	31.41	34.74	31.18	31.18
Job Dispersion Index (%)	91.23	91.23	72.25	89.98	89.98	89.32	90.73	90.73	90.76
Jobs in Centres									
CBD	111065	111065	814876	111065	111065	115788	111065	111065	125742
Inner Ring Road	119003	119003	3633	140849	140849	145055	130229	130229	124866
Outer Ring Road	235813	235813	233881	307300	307300	302307	317920	317920	320837

Table 1. AUDIT results for original city and infill cases

Note that, for the range of β from its calibrated value towards $\beta \rightarrow \infty$, the low density sprawl only incurs an extra energy penalty of 2.3% to 3.2% over the medium density sprawl scenario. Thus, unless new development threatens prime agricultural land, there is not a strong energy argument for imposing strong medium density zoning regulations in new areas, especially if this detracts from the amenity value of these areas. Attractive

mixed density developments will occur **through market forces** as average household size continues to decrease, and if increases in car travel costs are introduced to save energy.

	Low Density Sprawl			Low Density Sprawl with Extra Ring		
Job Location	deterministic	calibrated	optimum	deterministic	calibrated	optimum
Existing Population	4000000	4000000	4000000	4000000	4000000	4000000
New Population	1000000	1000000	1000000	1000000	1000000	1000000
Total Zones	108	108	108	108	108	108
Total Job Centres	13	13	13	19	19	19
Land Area (sq.km)	3456.92	3457.14	3457.14	3457.15	3457.37	3457.37
City Radius (km)	33.17	33.17	33.17	33.17	33.17	33.17
Ave Energy (MJoules/trip)	22.54	43.59	43.03	18.93	43.34	41.82
Ave CO2 Emi. (kg/trip)	1.51	2.93	2.89	1.27	2.91	2.81
Ave Trip Time (min/trip)	11.93	18.63	19.52	10.10	17.13	17.03
Ave Trip Dist. (km/trip)	9.20	17.41	17.26	7.56	16.63	16.27
Public Trans. Usage (%)	29.43	26.58	25.82	32.11	26.03	27.05
JobDisp. Index (%)	82.58	82.58	86.57	95.50	95.50	80.66
Job Centres						
CBD	111065	111065	271763	111065	111065	904326
Inner Ring Road	119017	119017	23991	118981	118981	4624
Outer Ring Road	329103	329103	397345	130041	130041	89625
Sprawl Ring Road				199085	199085	221671

Table 2. AUDIT results for low density sprawl cases

The role of optimal job location. In all the cases where the $\beta \rightarrow \infty$ job location pattern was replaced by an optimal pattern determined by TOPAZ, energy savings of up to 4.1% were obtained. In the analysis, TOPAZ increased the size of the CBD and the sizes of the outer rings of job centres at the expense of the inner rings of subcentres. This **implies efficient reverse commuting by car from the middle residential ring to the outer ringroad, as well as more use of public transport to the CBD**. This is a very interesting result from the standpoint of compatible urban form and transport interaction.

Modal split. One of the main reasons for the improved energy efficiency of the infill case with calibrated β is the somewhat greater use of public transport, with sprawl modal split of typically about 27% increasing to over 31% for infill. In addition, as expected, trip distances were also somewhat smaller for the infill cases. As the current energy efficiency of the private Australian car fleet is quite poor, we performed some additional tests where this efficiency was increased by 30%, accompanied by an increase of the base car occupancy level of 1.3 to 1.5. Whereas for calibrated β, these factors reduced the energy advantage of infill over sprawl from 17.5% to 14.1%, the advantage decreases to a negligible 0.9% as the gravity parameter $\beta \rightarrow \infty$.

	Medium Density Sprawl			**Medium Density Sprawl with Extra Ring**		
Job Location	deterministic	calibrated	optimum	deterministic	calibrated	optimum
Existing Population	4000000	4000000	4000000	4000000	4000000	4000000
New Population	1000000	1000000	1000000	1000000	1000000	1000000
Total Zones	108	108	108	108	108	108
Total Job Centres	13	13	13	19	19	19
Land Area (sq.km)	3151.16	3150.87	3150.87	3151.36	3151.36	3151.36
City Radius (km)	31.67	31.67	31.67	31.67	31.67	31.67
Ave Energy (MJoules/trip)	22.01	43.39	42.05	18.30	42.62	40.87
Ave CO2 Emi. (kg/trip)	1.48	2.92	2.83	1.23	2.86	2.75
Ave Trip Time (min/trip)	11.89	18.60	18.49	9.97	17.21	16.93
Ave Trip Dist. (km/trip)	9.05	17.25	17.11	7.41	16.57	16.12
Public Trans. Usage (%)	30.22	25.92	28.45	33.74	27.81	28.6
JobDisp. Index (%)	83.26	83.26	63.34	102.40	102.40	75.04
Job Centres						
CBD	111065	111065	990959	111065	111065	844064
Inner Ring Road	119017	119017	8559	118981	118981	30798
Outer Ring Road	329207	329207	293016	130024	130024	205776
Sprawl Ring Road				199130	199130	89394

Table 3. AUDIT results for medium density sprawl cases

Trip distance. Whilst the average trip distance for calibrated β was about 10.6% less in the best infill case than in the best sprawl case, for the case of $\beta \rightarrow \infty$, where everyone works locally, the best overall result of 7.41 kms. was obtained for the case of **medium density sprawl with extra ring**. This is a purely **geometric** result, based on the reduced average spacing of subcentres when the extra ring is added. By more decentralisation of compatible jobs, the need to travel is reduced.

Index of job dispersion. From the definition in Brotchie's urban triangle (Brotchie et al., 1995), the index of job dispersion, given as a per cent, is $100\ \bar{r}/R$, where R is the radial centre of gravity of the housing and $\bar{r}$ the radial centre of gravity of the jobs. Thus, the index is zero for a monocentric city, 100 for a city where there is a job next to each house and infinity if all housing were concentrated in the CBD. Note that, this is a **relative** measure, not an absolute measure of 'job sprawl'. For the optimal cases, the relative job dispersion for the infill cities of about 90% was higher than the average value of 75% for the sprawl cities. This reflects the much larger size of the CBD in the sprawl cities, inducing more use of public transport than would otherwise be the case.

4. CONCLUSIONS AND RECOMMENDATIONS

For values of the gravity impedance parameter β which are currently typical for large Australian cities, strong infill scenarios can produce energy savings in commuting of over 17% compared with the best sprawl scenarios, so long as the infill policies are accompanied by significant improvements to level of service in public transport. Any incipient extra congestion caused by loading an increased number of generated commuters onto the same area of road network is neutralised by a significant modal shift to the improved public transport system. On the other hand, the degree of infill required to reflect the scenarios tested would take many years to occur, especially in cities where much of the housing stock has been constructed during the last 40 years and is in generally good condition. Thus, whilst infill policies will play some role in meeting the 2005 Greenhouse targets, the major task must be undertaken using TDM (Transport Demand Management) and associated pricing policies (Wegener, 1995), and information schemes to encourage matched jobs to disperse to subcentres in residential areas, yielding strong increases in the value of the gravity parameter β. However, the energy advantage of infill shrinks to merely 2% to 3% as β rises towards infinity, reflecting choice of job in the nearest subcentre. Thus, the timely application of transport policies, necessary to meet the 2005 targets, will cause the energy savings of the slower-working consolidation policies to become very small. If the subcentres contain ancillary services, as well as transit stops and other public transport nodes (e.g. stops for circumferential express buses), market forces will automatically increase housing densities in the surrounding areas, yielding natural equilibrium levels of infill without the need for intrusive land-use controls.

Whereas the quantifiable energy benefits of infill policies have been identified above, amenity factors were not considered. For instance, many Australians continue to value green and leafy suburbs and villages beyond the urban fringe. So long as appropriate jobs move into such areas and transport pricing policies are introduced, accompanied by encouragement of para-transit modes (e.g. demand-responsive mini-buses) in these low density areas, consumer surplus levels can be maintained and transport energy consumption reduced. Impediments to infill should certainly be removed, and directly encouraged in cases where sprawl threatens prime agricultural land. When infill occurs at relatively modest levels, it will help increase the architectural diversity of our suburbs, whilst not threatening their 'leafy' character. At the same time, spacious suburban housing lots allow barbecues and small swimming pools to be established, encouraging in-situ weekend activities with family and friends. This reduces the need to 'escape' the city for energy-intensive weekend recreational travel.

The above analysis has concentrated on commuting trips, some of which will disappear in the future as tele-commuting takes hold. On the other hand, as more and more families have both partners employed, work-based shopping or shopping on the way home from work is increasing relative to home-based shopping, thereby strengthening the overall role of the work journey. Another trip category which has been omitted is business trips. Whilst the creation of large, diverse employment subcentres, as covered in this study, may induce a large proportion of business trips within each subcentre, trips between subcentres will still be very frequent. As work time is generally valued more highly than leisure time, the fastest mode available is generally used for business trips. Usually, this is car or taxi, even in relatively congested cities such as Tokyo which are also well served by transit. Thus, the large public transport investments associated with infill policies may have little impact in attracting business trips, which will still require a viable road network. However, business travel by car or taxi during peak periods will benefit indirectly from the reduced congestion resulting from some commuters switching to an improved public transport system. On the other hand, if the new jobs being created, many of which are arising in knowledge-based activities, move into outer suburban locations as a source of their potential workforce, associated savings in commuting time will be accompanied by efficient business trips on the relatively uncongested outer roads. In any case, a future analysis of this topic should include the energy consumed in business travel, as well as the economic costs of the associated travel time.

Ueda and Roy have included a random bidding housing model in SUSTAIN, as described in Roy, Marquez, Taylor and Ueda (1995). This model allows land price and housing density to be determined endogenously. As the model needs some further calibration, it has not been included in this study. In future work, it could be applied to project market-based patterns of housing of varying density, optionally accompanied by alternative zoning or pricing scenarios. Higher housing densities in areas surrounding important transport interchange, job and service centres (e.g. our subcentres) would be identifiable, enriching our current scenario of the three rings of decreasing density as one moves outwards. In fact, areas adjacent to the subcentres would become a market-based focus for infill or consolidation, freeing the more peripheral areas to retain their leafy character. Although it seems unlikely that such an enhanced analysis would change the relativities in the results of the scenarios tested here, it could pick up the changing locational housing options available to different socio-economic groups, enabling the evaluation of the different scenarios to be augmented by the inclusion of locational equity indicators.

New urban extensions, freed from any derogatory description as sprawl, can take a variety of innovative forms and densities, including integration of clean information- and knowledge-based enterprises into residential and recreational environments and use of environmentally-sensitive planning to create urban forests and to maintain vegetation and natural drainage systems, as exemplified in the Woodlands development on the outskirts of Houston, Texas. Such integrated developments, in conjunction with higher energy price futures, would become increasingly self-contained, with local provision of employment, educational facilities, natural amenities, social services, retailing and demand-responsive transport reducing travel energy use.

A fundamental role in the improved energy performance of the infill scenarios vs. sprawl relates to the lower per capita energy consumption of transit/buses compared with the use of cars, as well as our increased transit investment in the infill cases to raise average transit speeds by 20%. Increases of car fuel efficiency in urban conditions to 5 litres per 100 km, as foreshadowed in some countries (Wegener, 1995), as well as programs to encourage ride-sharing, will reduce or eventually even eliminate this disparity. Personalised Rapid Transit (PRT) networks would produce further energy savings. In devising sustainable and financially reliable urban public transport systems, one would then use a flexible approach, inducing use of conventional transit or LRT in congestion-sensitive corridors, and the use of fuel-efficient cars or PRT or demand-responsive mini-buses in the rest of the system. At the same time, virtual neutralisation of the relative energy advantage of transit vs. cars would stimulate a comprehensive financial analysis on the appropriate mix of radial freeway/ringroad vs. transit/express busway investments.

The main message emerging from this study is that, whilst urban consolidation or infill policies can have an identifiable effect on reducing transport energy consumption, they are very slow-working, and can adversely influence the amenity value of existing residential areas if carried too far. Of course, in cases where further outward expansion of a city is forced by scarcity to use prime agricultural land, infill policies may be strengthened. In any case, the role of such land-use policies should not be over-emphasised at the expense of more potent, fast-working TDM and transport pricing policies. After all, the market itself will automatically raise land prices and increase residential densities when the cost of travel is increased.

Whilst most cities on the Eastern Asian mainland suffer more from the effects of high residential densities than low densities, it is nevertheless hoped that the above study provides some general insights on the relationship between urban residential density, transport availability and energy consumption. In particular, the above analysis based on optimal job location for alternative housing development scenarios may be relevant for Asian cities, where job location guidelines may be easier to implement than detailed controls on residential location. At the same time, some broad controls on density of new residential developments may allow experimentation with alternative spatial patterns of high and low density housing, with model frameworks, such as AUDIT, yielding estimates of transport energy use.

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