The full impact of transport and the built environment on greenhouse gas emissions, and the influence of urban form

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1 Introduction

1.1 Life cycle energy and emissions analysis

The impact of transport on greenhouse gas emissions is usually reported in terms of tail-pipe emissions from vehicles. However, the full impact is greater, as emissions are expended in the manufacture of motor vehicles and the construction and maintenance of transport infrastructure. Similarly, emissions from the built environment are reported in terms of the use of buildings, excluding the emissions that are expended in the construction and maintenance of buildings, and of urban infrastructure.

Emissions are produced in situ, in the city, from the operation on a daily basis of motor vehicles and building appliances, but also in far away places in the production of the 'hardware' of the transport and building systems, the concrete, bricks and steel, the motor vehicles and road materials. The emissions from the daily activities can be referred to as 'operational' emissions, while the other emissions are 'embodied' in the products used.

The totality of emissions attributable to the transport system can be characterised as its *life cycle* emissions. Life cycle energy and emissions analysis accounts for the history of emissions associated with a particular activity, and the future emissions. Failure to consider the life cycle emissions of activities can lead to distorted conclusions about the sustainability of activities. For instance, the arguments recently presented in favour of nuclear power as a part of the greenhouse abatement solution tend not to mention the substantial energy that is required to extract uranium, process it, transport it, construct and maintain the power plant, then store radioactive waste (for an extraordinary period of time), and decommission the plant. Wind and solar power solutions are not completely emissions-free, as often stated, because they involve the expenditure of energy in production, maintenance and eventually decommissioning (and at the present time that energy input is very likely to involve emissions-producing fossil fuels).

The emissions attributable to categories of household activity have been estimated for the 'average Australian household' using emission intensities derived from national input-output data applied to household expenditure, as reported in the Australian Household Expenditure Survey (Lenzen, 1998; ABS, 1995). Mobility accounted for approximately 14% of the average household emissions, and shelter accounted for around 28%.

In the research reported in this paper, life cycle energy and emissions were calculated for the transport (mobility) and housing (shelter) activities of a sample of households in Adelaide. The purpose of this analysis was to explore the implications of transport and housing emissions from this broader perspective. Hence, transport emissions are not just influenced by how far people drive, but also levels of car ownership and the size of vehicles.

1.2 The influence of urban form on transport and housing emissions

The description of urban form has a number of dimensions. It concerns the size, shape and density of cities, the characteristics of the transport and infrastructure networks, the configuration of land use patterns, the design of subdivisions, the form of buildings and the spaces between buildings.

The influence of urban form variables on the energy use or greenhouse gas emissions attributable to urban activities has been studied with respect to transport at the city-wide scale, and with respect to building heating and cooling at the individual building level. In nearly all cases the analysis has been of *operational* energy/emissions only.

In this paper, the influence of urban form on life cycle transport and housing energy and emissions is examined using energy consumption data derived from a detailed survey of 212 households in contrasting inner city and urban fringe developments. Regression analysis is used to explain the variance between the operational (travel and household appliances) and embodied (vehicles, infrastructure and dwellings) energy and emissions expenditure of the sample households, based on 28 urban form and socio-demographic variables.

In this paper the following research questions are addressed.

- Does the calculation of embodied as well as operational transport and housing energy and emissions enhance understanding of the impact of greenhouse abatement policies?
- Is the case for the compact city strengthened or weakened when the life cycle energy use and greenhouse gas emissions of urban developments are considered?
- How significant are compact city policies compared with other transport and housing related greenhouse abatement measures?

2 Methodology

2.1 Case study households

The case study households were chosen to provide substantial variation in urban form, particularly *dwelling type* (detached, courtyard, villa, semi-detached and terrace), *site area* and *orientation*. The *locations* of the two developments (3 and 38 km from the city centre) was a measure of centrality, representing the raft of variables that define inner city versus outer suburban locations – levels of access to employment and urban facilities (generally, and by none motorised modes) and levels of public transport provision.

The inner city development contained a predominance of two storey terraced and semi-detached dwellings on generally smaller sites. The fringe location comprised predominantly detached dwellings on larger sites (refer Figure 4, p8). The level of accessibility to a wide range of services was much higher for the inner urban sample. The two developments are indicative of two different directions in which the development of Australian cities is proceeding – towards compaction and expansion.

2.2 Household energy and socio-demographic survey

Information was collected on each household relating to the physical characteristics of the dwelling, the site and the case study neighbourhood. This formed the basis for constructing *urban structure*, *built form* and *consumption* explanatory variables. Information collected on the *socio-economic* and *demographic* circumstances of household members was also used to construct explanatory variables.

Detailed information on dwelling and site design and dimensions, household vehicles, road construction and dimensions, plus information on appliance energy consumption, was used to calculate household energy use and greenhouse gas emissions for each of the life cycle transport components:

- energy/emissions produced by the household's motorised travel - "Travel",
- energy/emissions embodied in the household's vehicles - "Vehicles",
- energy/emissions embodied in the development 's roads and footpaths - "Roads",

…and the life cycle housing components:

- energy/emissions produced in operating household appliances - "Household Appliances" and
- energy/emissions embodied in the household dwelling and site - "Dwellings".

These formed the response variables for the statistical analysis.

The socio-demographic and much of the energy consumption information was obtained through a household survey comprising two main parts, a questionnaire directed to respondents during the first of two house visits, and a two-day trip diary which was kept by the respondents and their families and checked through with the interviewer at the second visit.

Detailed information on dwelling design and dimensions, and site features (garaging, paved areas, fencing etc.) was derived from subdivision and house plans, aerial photos, the household questionnaire and site visits.

2.3 Life Cycle Energy and Emissions Calculations

Greenhouse gas emissions were calculated in tonnes of carbon dioxide equivalent per household per annum (CO_2-e *per household p.a.).* Energy expenditure can be measured as primary energy or delivered energy. Delivered energy is the quantity of energy consumed directly by the end user. The primary energy measure accounts for the energy consumed at the point of use plus the energy used in the production processes. Greenhouse gas emission factors are based on the primary energy consumption.

Fossil-fuel generated electricity, which is the predominant energy medium used in buildings, has a high emission factor because for every unit of electrical energy delivered to a building, approximately two additional units of energy have been used in electricity generation. Similarly, the emissions from petrol consumed in the internal combustion engines of motor vehicles do not represent the totality of emissions because energy has been expended and emissions released in the processes of oil exploration, oil well operation, bulk transportation, fractionation and refining, and finally in delivery to the end user. Nevertheless, the primary energy and emissions factors for petroleum-derived fuels are much lower than those for electricity.

The influence of urban form on energy use is most accurately assessed by using the delivered energy measure (*in gigajoules per household p.a.)* to control for the effects of different fuel mixes[1].

No single model was available to calculate life cycle operational and embodied energy/emissions attributable to the whole of the housing or transport systems. The elements that constitute these two systems are not usually investigated in the same studies, and housing and transport are rarely considered together. It was necessary to utilise several

[1] As this article focuses on the urban form influence, the reported results relate primarily to delivered energy rather than greenhouse gas emissions.

existing models to calculate the energy use and emissions that could be attributed to each component.

The model used to calculate the energy and emissions embodied in dwellings was an Embodied Energy/Emissions Analysis Spreadsheet developed specifically for this purpose using Australian economic input-output data (Pullen, 1995).

The model used to calculate the energy and emissions embodied in motor vehicles was a similar spreadsheet using Hybrid Embodied Energy Analysis of the manufacture and assembly of an Australian car, also supported by the data from the Australian economic input-output tables (Parikh, Watson & Charters, 1996).

Spreadsheets were also developed to calculate the energy/emissions embodied in on-site structures and paving, and the road/footpath infrastructure.

The calculation of embodied energy and emissions expenditures requires the application of energy coefficients and emission factors to the processed data. In the embodied energy spreadsheet models these coefficients were the energy in mega-joules per unit weight (in kilograms) of the material or item. The calculation of these coefficients for the dozens of different materials and items is at the core of embodied energy analysis.

The calculation of *operational* energy/emissions involved the use of conversion factors for delivered energy applicable to each of the main fuels, which can be applied directly to fuel consumption data. There are also greenhouse gas emission factors that can be applied to each fuel. The spreadsheets which were formulated to convert raw operational data to comparable energy and emissions figures involved a series of conversions to account for passenger loadings, fuel consumption, fuel mixes and emission factors.

2.4 Statistical analysis

It was possible to gain insights into the patterns of energy and emissions expenditure by simple descriptive statistical analysis of the data. Average and the frequency distributions of the energy and emissions response variables were considered.

Forward stepwise regression analysis was used to determine which of the explanatory variables were statistically significant, and to determine what proportion of the total observed variance in energy/emissions expenditure was explained by the significant variables.

28 potential explanatory variables were constructed, six of which were direct expressions of urban form (urban structure or built form) – *location, site area*, *dwelling type*, *number of shared walls, number of storeys, orientation.* A further five variables were representations of consumption levels – *persons per dwelling, dwelling size*, *conditioned floor area*, *number of bedrooms* and *number of vehicles*.

Fourteen socio-economic and demographic variables were constructed. Eight of these were sufficiently significant to be entered in all or most of the regression equations. Between them they covered a range of possible explanations for transport or housing energy consumption relating to the income, age, work practices and the family composition of each household.

3 Results

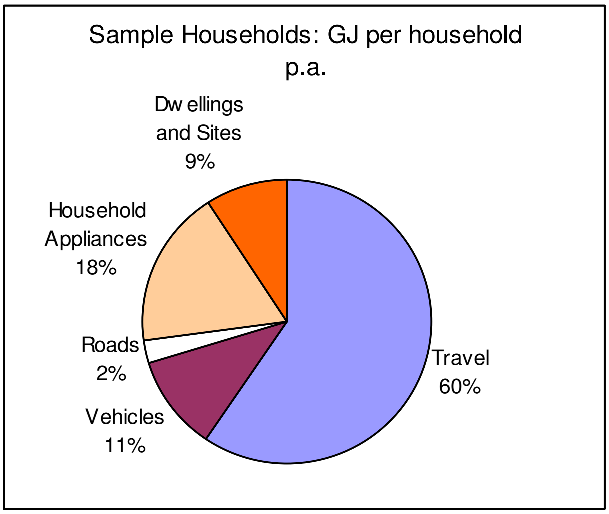
3.1 Life cycle energy and emissions per household

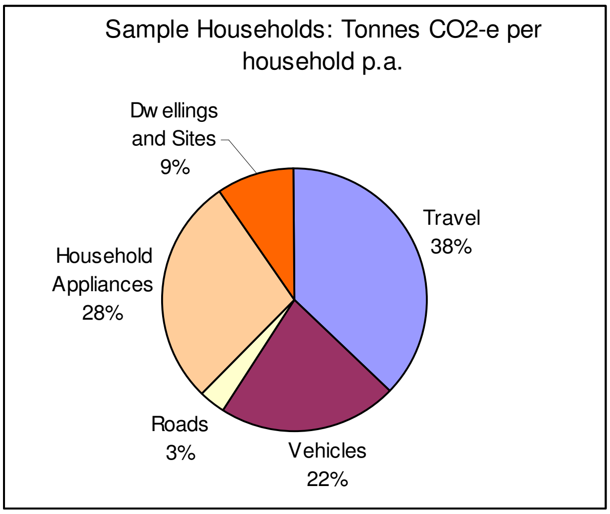
The emissions from the 212 household sample were 12.1 tonnes CO2-e per household per annum for transport and 7.4 tonnes for housing, giving a combined total of 19.5 tonnes.

Consideration of tail pipe emissions only would have accounted for 7.25 tonnes of transport emissions, while a further 4.84 tonnes embodied in the household vehicles and the household's share of local and regional road infrastructure (ie. 40% of the life cycle total) would not have been counted. 1.84 tonnes could be attributed to emissions embodied in dwellings and on-site paving and structures, compared with 5.54 tonnes emitted per annum through the use of household appliances.

The embodied emissions accounted for 34% of the total, indicating that they represent a significant component of the full greenhouse impact of the transport and housing systems. The proportions of delivered energy and emissions are shown in Figure 1.

Figure 1: Delivered Energy and Greenhouse Gas Emissions from Sample Households





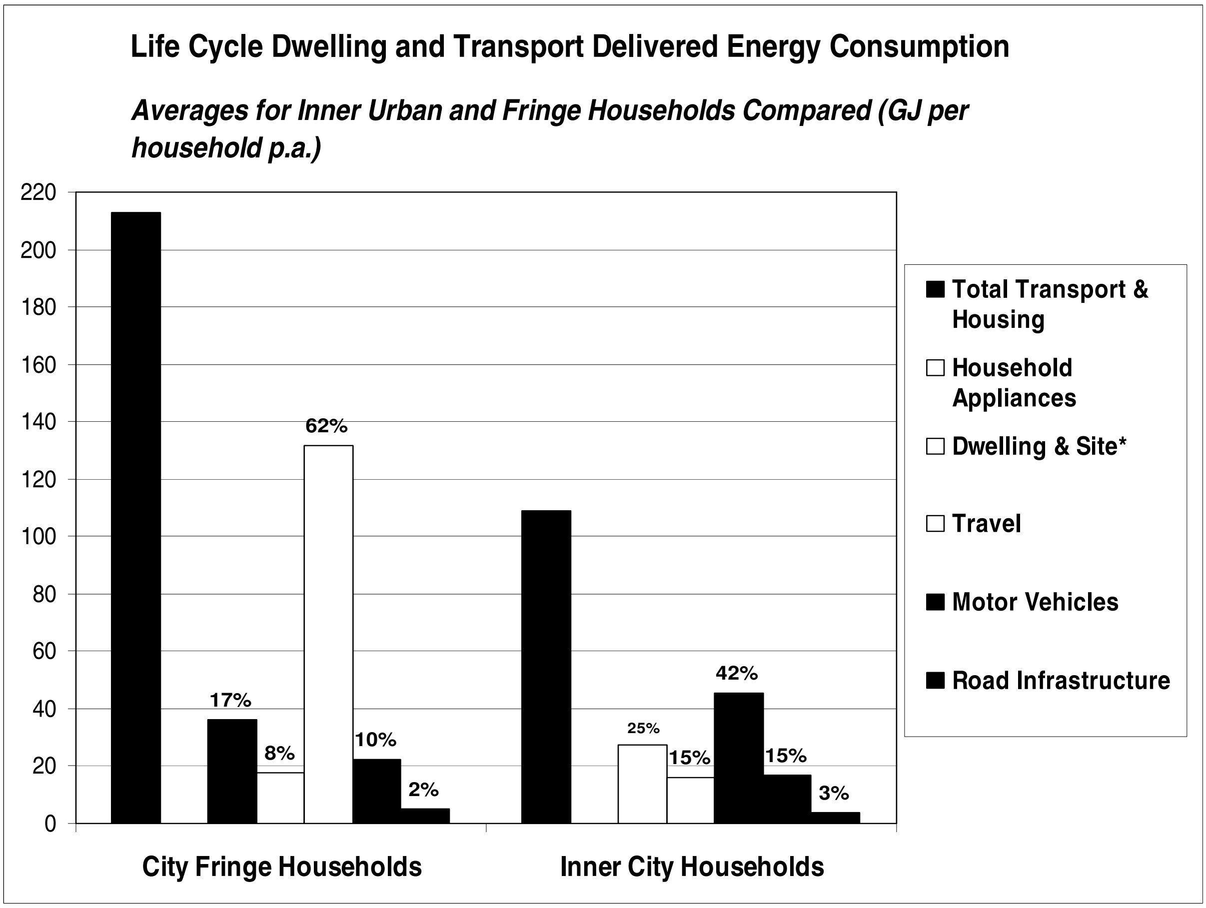
The delivered energy, rather than the emissions, profile most closely reflects the influence of end-use factors, such as urban form, family composition or socio-economic circumstances. The emissions profile reflects the additional effect of the fuel mix on the end use. The proportion of delivered energy attributable to travel is much higher than the proportion of emissions (due to the lesser emissions impact of petroleum than electricity, which still relies substantially on coal). Similarly the mix of energy sources involved in vehicle manufacture results in a higher the proportion of vehicles emissions compared with the delivered energy for vehicles. The fuel mix also produces a significant variation between the proportions of delivered energy and the emissions attributable to household appliances.

3.2 Variability in energy/emissions expenditure between households

For the sample as a whole, the emissions attributable to transport exceeded the housing-related emissions. However, the results for the full sample were heavily influenced by the fringe households, where travel energy was a very large component. The proportions between transport and housing energy/emissions were distinctly different for the households in each development, as shown in Figure 2.

Total life cycle delivered energy consumption per household in the urban fringe development was 213 J per household per annum, compared with 109 GJ in the inner urban development. Energy used for motor travel accounted for 62% of the household total for the urban fringe development compared with 42% for the inner urban development. Energy consumption per household in the fringe development was higher for all of the life cycle components - travel, vehicles, roads, appliances and dwellings.

Figure 2: Delivered energy for inner city and fringe household sub-samples

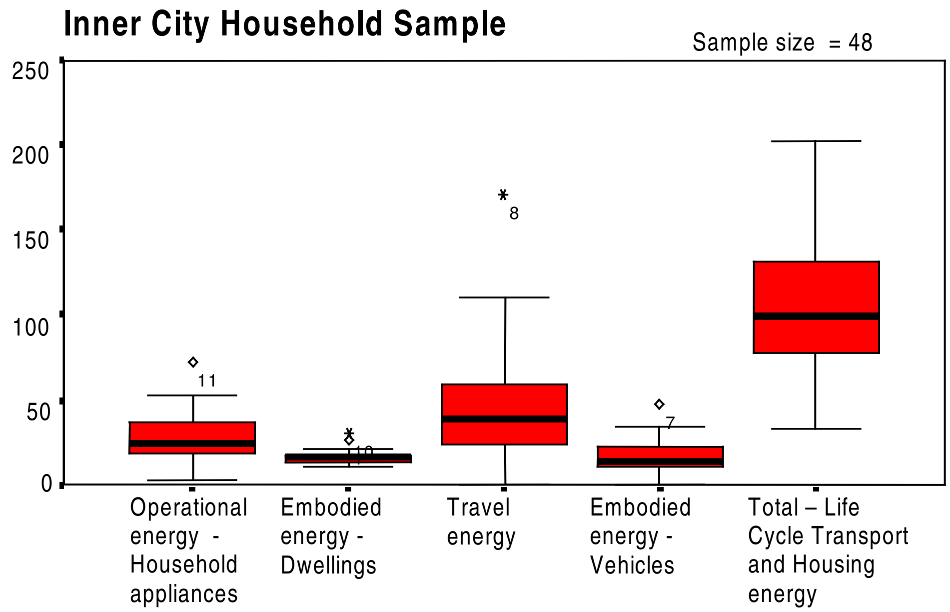


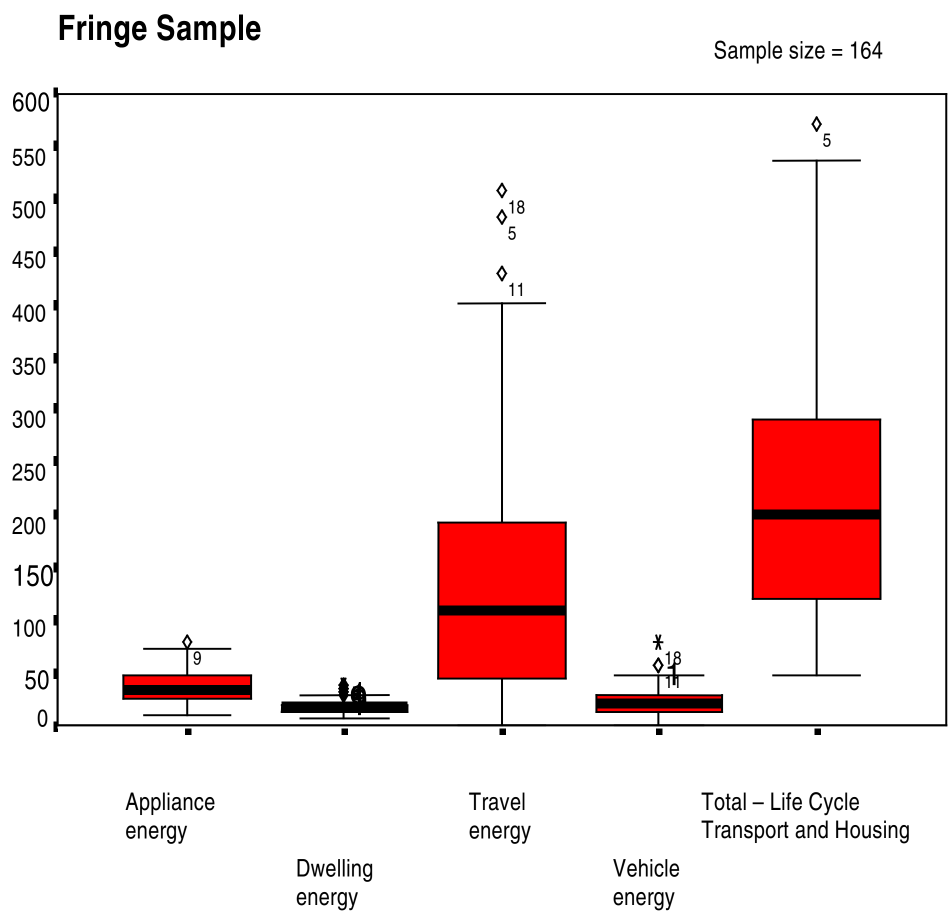
For the inner city households, annual life cycle transport and housing energy expenditure ranged from 59 GJ per household at the 10th percentile to175 GJ at the 90th percentile, a nearly threefold difference. For the fringe households the range was from 83 GJ per household at the 10th percentile to 372 GJ at the 90th percentile, a four and a half fold difference.

The shape and spread of the distribution of households for the two developments is summarised in the box plots in Figure 3. The spread of energy use was greater for the fringe than the inner city households.

The spread of energy consumption between households was greater for operational energy than for embodied energy. Although dwellings varied substantially in size, there was least variability in the energy embodied in the dwelling compared with the other response variables. The majority of dwellings were of brick veneer construction, with some being double brick and some two-storey terraces having reinforced concrete upper floors. The 90th percentile dwelling embodied approximately twice the energy of the 10th percentile, indicating the influence of size and urban form. Greater differences would be expected if the sample of dwellings incorporated more varied construction materials.

Figure 3: Distribution of delivered energy consumption across households for travel, vehicles, appliances and dwellings (*GJ per household p.a.*).





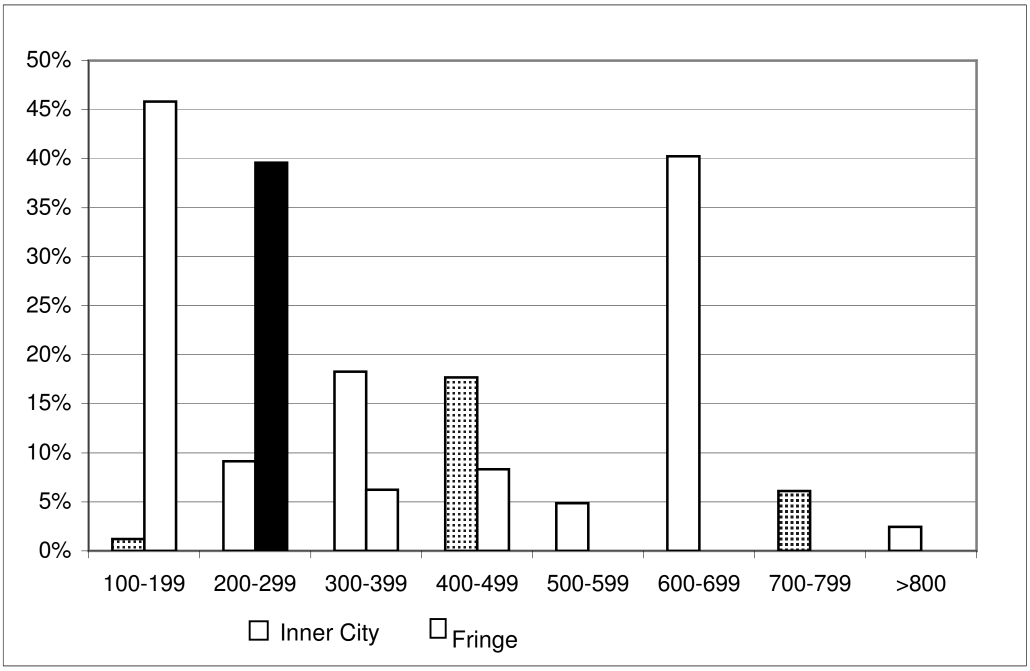
For vehicles, the 90th percentile household consumed approximately 5 times the energy of the 10th percentile household, reflecting differences in car ownership and size of vehicles (people in households without cars still consumed some embodied energy when travelling as passenger is other cars, buses, trains and taxis). For household appliances the difference from 90th to 10th percentile was approximately 4 times.

The greatest variability in energy consumption was in household travel, where there was an approximately 4 times variation from 90th to 10th percentile for the inner city households (9 to 33 GJ per hh p.a.), but a 14 times variation from 90th to 10th percentile for the fringe households (19 to 272 GJ per hh p.a.).

3.3 Explaining the variance in household energy consumption

The differences in life cycle energy consumption between the households in the two areas implied that the contrasts in urban form and location were relevant factors. 86% of the dwellings in the fringe development were detached housing forms (including courtyard and villa dwellings), whereas 46% of the inner city dwellings were terraces and 38% semi-detached. Site areas in the fringe development ranged from 200 to 800 m2, while in the inner development 85% of sites were less than 300 m2. The inner development had a regional employment density of 24 jobs per hectare compared with 2 jobs per ha at the fringe. Total shopping floor area within a 7km radius was 5,550 m2 compared with 815 m2, and public transport provision was 1,547 buses per week within 500 metres compared with 432 for the fringe development.

Figure 4: Comparison of site areas between the inner city and fringe developments.



The statistical analysis was undertaken to explore the apparent relevance of urban form in comparison with other potential socio-demographic explanatory variables such as household size and income (refer Appendix 1 for variables that were significant in the regression analysis).

50% of the variance between households in life cycle housing and transport energy consumption was explained. The highest proportion of variance was explained by the *site area* variable (30%), with the *location* variable being the fourth to enter the equation. *Site* *area* explained 35% of the variance between households in life cycle housing energy consumption and 27% of the variance between households in life cycle transport energy consumption.

The intuitively obvious consumption variables of *vehicles per household* and d*welling size* explained most of the variance in the embodied energy in vehicles and dwellings respectively. Consumption variables such as *car ownership* and *dwelling size* are in turn influenced by variables such as density, family size and income, and as such are intermediate variables in the chain of explanation.

The influences of a range of variables on car ownership were investigated separately using census data. The two key explanatory variables were the "*proportion of households with income less than $15,000 p.a*." (73% variance explained) and "*housing density"* (further 8% explained). "*Proportion unemployed*" and "*proportion children under 15*" explained a further 4.1% of the variance.

While 50% of the variance remained unexplained (perhaps, in part, dependent on people's attitudes and values rather than the range of variables available for analysis), the *site area* occupied by a household clearly emerged as a prominent predictor of total housing and transport energy use. The *household employment* and *household income* variables (closely correlated with each other at 0.66, p=0.000) were also significant explanatory variables, the former being of significance in explaining transport energy use, and the latter in explaining housing energy use. Nevertheless, they were not as significant as the *site area* variable or some consumption variables.

The significance of the urban form variables in the regression analysis and the percentage of variance that they explained is summarised in Table 1.

Table 1: Summary of the influence of urban form variables on life cycle transport and housing energy and emissions

ACTIVITY	ENERGY				EMISSIONS			
	Significant Urban Form Variables	Entered equation	Additional Variance Explained	Variance explained when forced	Significance of Urban Form Variables	Entered equation	Additional Variance Explained	Variance explained when forced
Travel	YES (2) *	1st	22%	N/A	YES (2)	1st	22%	N/A
Vehicles	YES (1)	2nd	1%	19%	YES (1)	2nd	1%	19%
Appliances	YES (2)	1st	25%	N/A	NO	-	-	-
Dwellings	YES (2)	2nd	6%	30%	YES (2)	2nd	5%	33%

YES (2) = there were 2 urban form variables that were significant in explaining travel energy consumption.
N/A = not applicable.

3.4 Sensitivity analysis

It was possible to conduct a simple sensitivity analysis of the results to test the magnitude of energy reductions that might be achieved through different policy interventions. The changes were applied separately to the Inner City and Fringe sub-samples, and the results are shown in Table 2.

By virtue of the combination of urban form and locational factors previously analysed, the average household in the inner city development consumes 49% less energy for transport and housing than the average household located in the fringe development.

Table 2: Results of sensitivity tests on inner city and fringe samples.

	Inner City Sample		**Fringe Sample**	
Initial GJ per household p.a.	***109***		***213***	
Scenarios Tested	GJ per household p.a. reduction	% reduction in life cycle housing & transport energy	GJ per household p.a. reduction	% reduction in life cycle housing & transport energy
All dwellings are 2 storey terraces	-5	-4%	-13	-6%
All household cars are small cars	-6	-5%	-43	-20%
Car ownership rate falls by 20%	-5	-4%	-23	-11%
Proportion of Car Travel replaced by 100% increase in public transport trips	-1	-1%	-5	-2%
Proportion of Car Travel replaced by 100% increase in walking & cycling trips	-2	-2%	-3	-1%
Revised GJ per household p.a.	***91***	***-16%***	***126***	***-40%***

For the Fringe development, a complete change of urban form from the predominantly single storey detached dwellings to the two-storey terrace dwellings that predominated in the Inner City development, would yield approximately a 6% reduction in total housing and transport energy consumption. The fringe households would have used just 13 GJ per household p.a. less energy, reducing their transport and housing energy total to 200 GJ per hh p.a. (if all of the inner city households had been in two storey terraces they would have used 5 GJ less reducing their total to 104 GJ). The implication is that constructing higher density dwellings on the fringe would deliver a relatively minor reduction in energy use compared with the reductions to be achieved by infilling the same dwellings in the inner city.

A scenario in which all households switched to small cars (reducing fuel consumption and the energy embodied in the vehicles) produced a more significant energy saving for the fringe households (43 GJ), but this was still substantially less than the 104 GJ reduction from locating in the inner city.

A 100% increase in public transport travel (replacing an equivalent number of car kilometres) had modest impact because of the small proportion of trips that are currently undertaken by public transport (4-5%). The impact was greater for the fringe development (5 GJ per hh p.a.) as public transport trips undertaken by fringe residents were longer.

4 Discussion and Conclusions

4.1 Does the calculation of embodied as well as operational transport and housing energy and emissions enhance understanding of the impact of greenhouse abatement policies?

43 GJ out of 189 GJ per household p.a. of delivered energy (23%) was embodied in the 'hardware' that supports the operation of the transport and housing systems. This would not have been attributed to transport and housing activities through an assessment of operational energy alone. 6.7 tonnes out of 19.5 tonnes of greenhouse gas emissions per household p.a. (34%) were embodied in the transport and housing systems, indicating that

the inclusion of embodied energy is more important for greenhouse emissions analysis, than for delivered energy analysis.

In an analysis of operational energy and emissions from motor vehicle travel, car ownership is generally accounted as an important explanatory variable of the VKT per household. When the analysis is expanded to include embodied energy and emissions, vehicle ownership is also identifiable as a direct source of energy consumption and emissions. The vehicles themselves embody substantial energy/emissions. The emissions embodied in a small car can be as little as half the emissions embodied in a large six/eight cylinder vehicle or a 4-wheel drive. For the sample households, the rate of car ownership was lower for the inner city households. The inner city households also possessed, on average, smaller vehicles.

Thus, inner city residents expended less transport energy and emissions per household by –

- Travelling fewer kilometres (less operational energy/emissions)
- Having more fuel-efficient cars (less operational energy/emissions)
- Having smaller cars with less energy/emissions embodied in them
- Having a lower car ownership rate, and hence less vehicle embodied energy/emissions per household.

The level of car ownership also had an indirect influence on the energy/emissions embodied in the dwellings. For the sample households, 3% to 15% of the total energy embodied in the dwelling was related to the transport task - for driveways, carports and garages. For the fringe dwellings, the average was 9%, and for the inner city households the average was 6%.

The inclusion of embodied energy/emissions had a greater impact on the variation in transport energy/emissions than the variation in housing energy/emissions. With an average life of 15 years[2], household cars often embodied more annual emissions than the dwelling (which can be expected to last over 50+ years and is built of generally lower energy materials).

The majority of the dwelling stock in the sample was of the same construction and materials, being mainly brick veneer, so that the influence of the urban form on the energy embodied in the dwellings could be discerned, rather than the influence of different materials. ….

Most transport emission reduction policies are directed at promoting less VKT. This research indicates that policies that encourage lower levels of car ownership and smaller cars, as well as less car travel, will deliver an additional emission reduction benefit.

4.2 Is the case for the compact city strengthened or weakened when the life cycle energy use and greenhouse gas emissions of urban developments are considered?

There have been several reviews of the, by now extensive, research into the urban form – travel relationship which have found it difficult to draw firm conclusions that specific urban form variables have a strong influence on travel activity (Steiner, 1996; Handy, 1996; Stead & Marshall, 1998; Badoe & Miller, 2000; Bunting, 2000; Crane, 2000). In part this can be attributed to differences in the interpretation of what is a significant influence, given that the subject matter is amenable to statistical interpretations of probabilities rather than the confident attribution of causality.

[2] There is only partial recycling of high-energy materials in motor vehicle manufacture, and there is still a significant energy and emissions expenditure involved in recycling.

Nevertheless, if one focuses on the influence of urban form variables on the travel energy response variable (usually reflected in studies as *vehicle kilometres travelled* – VKT), the relationship is reasonably clear.

While findings on the influence of urban form variables on *trip frequencies* and *modal split* are mixed, there is a much clearer trend in relation to *VKT*. Studies have generally shown that urban form variables are significant in influencing VKT and/or travel energy, and always in the direction that greater intensity of activity equates with reduced motor vehicle travel (Hanson S, 1982; Hanson S & Schwab M, 1987; Friedman B, Gordon S & Peers J, 1994; Dunphy R & Fisher K, 1996, Newman P, Kenworthy J & Lyons T, 1987, Naess P, 1993; Naess P, Larsen S L & Roe P G, 1994; Naess P, Roe P G, & Larsen S L,1994; Holtzclaw J, 1994; Cervero R & Kockelman K, 1997).

Most of the studies in which regression analysis has been undertaken, have indicated that urban form variables explain between 20% and 50% of the variance in VKT. Hence, the findings of this research – in which approximately 25% of variance in travel energy was explained by urban form variables (refer Appendix 1) - are consistent with a number of other studies.

However the research findings expand this relationship by finding that life cycle transport and life cycle housing energy consumption are also influenced to a significant degree by urban form. For all four energy consumption response variables – motorised travel, vehicle embodied energy, household appliance energy and dwelling embodied energy – the influence of urban form variables was significant.

Of the nine urban form explanatory variables that were analysed, the *site area* variable was the most influential (Appendix 1). The *location* variable had a minor influence on the variance in motorised travel energy between households, and the dwelling heating and cooling *energy efficiency rating* and measure of attachment (‘*number of shared walls*’) variables influenced the variance in appliance energy consumption and embodied dwelling energy consumption. However, it was the *site area* variable that had the main influence.

The significance of the ‘site area’ variable

Most studies into the influence of urban form on travel energy have only measured density at the neighbourhood level, as an average value for each neighbourhood, inclusive of site area, road space and local facilities. In cases where urban form and socio-demographic variables have all been derived at the aggregate level from small-area census data, the variability between households is masked, and the explanatory power of the studies consequently reduced. In cases where household-specific socio-demographic data has been compared with neighbourhood-scale urban form data, it is likely that some of the variability in the urban form data has been lost.

In this research, the use of socio-demographic and urban form data at the household level maximises the variability for all sets of variables at a comparable scale. Of particular interest is the emergence of the *site area* variable as the most significant explanatory variable. *Site area* did not correlate to any significant degree with the socio-demographic variables (e.g. 0.08 for *income* and 0.43 for *children per household*). It did however correlate with other urban form variables - *dwelling type*, *number of shared walls* and *location*. The conclusion that can most readily be drawn is that, for this sample of households at least, the *site area* variable is the most effective representation of a grouping of urban form variables that significantly influence the transport and housing energy and emissions of households.

4.3 How significant are compact city policies compared with other transport and housing related greenhouse abatement measures?

None of the households in the survey had taken particular energy conservation measures (other than, in some cases, determining the orientation of dwellings). So in this respect the comparison was of like-with-like. It can be tentatively concluded that, where you live, the size of your block and the form of the dwelling you live in will have a major influence on the energy consumption and associated greenhouse gas emissions produced by your household, regardless of your income, the number of people in your household, age or the type of family you are a part of.

If you live in an outer suburb in a relatively low density environment of predominantly single storey detached houses, your household is likely to use substantially more housing and transport delivered energy than your inner urban counterpart – perhaps as much as 90 per cent more. Your household's transport energy consumption is likely to substantially exceed housing energy consumption – it may be three times as great. It is likely that you will have to travel long distances for some key trip purposes, such as going to work, and these trips may be the most significant determinants of the total transport and housing emissions from your household.

The results suggest that the adoption of attached dwelling forms on smaller lots in outer and fringe suburbs would deliver some reductions in housing energy consumption. However, the bigger energy reductions for outer suburbs depend on reducing transport energy consumption, either by reducing the need for some of the longer trips, or by achieving substantial mode switch to public transport for the longer trips.

In the short- to medium-term, the most energy conserving urban form for the city as a whole may be achieved by pursuing infill development policies in the inner and middle suburbs, in particular in those areas that have access to the greatest density of urban services and employment opportunities.

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Appendix 1

Summary of stepwise regression analysis

Response Variable	Significant Explanatory Variables	% Variance Explained
Dwelling energy	Dwelling size	44.3
	Site area	5.9
	Insulation level	3.1
	Household income	1.5
	Energy efficiency rating	1.1
Appliance energy	***Site area***	25.1
	Household income	6.3
	Persons per hh	3.6
	No. shared walls	-2.2
	Conditioned floor area	1.5
Life cycle housing energy *(dwelling plus appliance energy)*	***Site area***	35.2
	Conditioned floor area	10.8
	Household income	3.1
	No. shared walls	-2.6
	Family composition	1.4
Vehicle energy	Vehicles per hh	74.3
	Site area	1.1
Travel energy	***Site area***	22.1
	Employed per hh	12.3
	Location	3.1
	Vehicles per hh	2.4
	Family composition	1.8
Life cycle transport energy *(vehicle plus travel energy)*	Vehicles per hh	27.2
	Site area	9.5
	Employed per hh	5.0
	Location	2.9
	Family composition	1.7
Life cycle housing and transport energy	***Site area***	29.8
	Employed per hh	14.2
	Family composition	2.5
	Location	1.9
	Persons of driving age per car	1.2
	Variance explained	***49.6***