# Urban structure and energy – a review

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**Abstract**

The nature and form of the urban environment is a critical determinant of the sustainability of our society, as it is responsible directly for a large proportion of consumed energy, and influences indirectly the patterns and modes of energy consumed in everyday activities. We examine the current state of research into the energy and greenhouse gas emissions attributable directly or indirectly to urban form. Specifically, we look at the embodied (construction) and operational energy attributable to the construction, maintenance and use of residential dwellings, and we review the literature on the relationship between urban structure and transport related energy consumption. While there is clear evidence from both intra and inter city comparisons that higher density, transit oriented cities have lower per-capita transport energy use, the effect of housing density on residential (in-house) energy use is less clear. More detailed research is needed to examine the relationships between urban form and overall energy use.

## INTRODUCTION

Climate models predicting global warming attributable to anthropogenic greenhouse gas emissions now seem to be generally accepted, both scientifically and politically, and debate now centres primarily on what political action is needed and will be most effective in curbing such emissions. Unsurprisingly, there has been an explosion in research into the energy and greenhouse gas intensity of different activities and industries (see McCarl and Schneider (2000); Price et al. (1998, 2002)), and numerous articles on economic and technological methods for curbing emissions in specific sectors (Capros et al., 1999; Kolstada, 2005; Springer and Varilek, 2004).

If we restrict our attention to energy[1] consumed by the domestic sector,

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[1] In this article, we discuss delivered energy, primary energy, and greenhouse gas emissions attributable to energy use. We asssume readers are aware of the relationship between these measures.

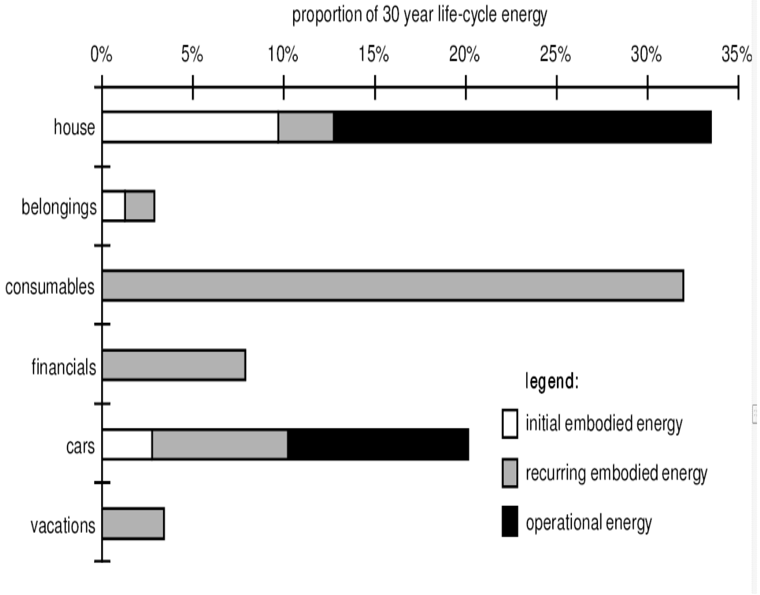

Figure 1: The proportion of primary energy consumed in different activities for a chosen Australian household (see Treloar et al. (2000)).

and consider the life-cycle energy[2] attributable to particular activities, we see in Figure 1 that housing and transport related energy use together account for over half of the energy use of a typical household[3]. In regard to housing energy, country-specific studies in the U.K (Department of the Environment, 1997), the Netherlands (Priemus, 2005), the U.S (Murtishaw and Schipper, 2001), and inter-country studies (Schipper et al., 1996; Tucker et al., 1993) confirm the importance of the home as an important site of energy consumption. It is thus understandable that energy use in residential dwellings has received much attention.

It is of course limiting to consider purely the material and energy inputs of a building shell, as there are often tradeoffs between building shell inputs and subsequent in-home energy consumption in the form of heating and cooling. Double-glazing, for example, requires more materials and embodied energy than traditional single-pane windows, but reduces the amount of energy required to heat or cool a dwelling. Whether the extra energy is recovered depends on numerous factors, such as building design, climate, and building use. These sorts of tradeoffs are commonplace, and make analysis of the sustainability of dwellings a difficult talk, because failure to consider the total net energy cost of a particular policy, rather than some more restricted measure, can lead to outcomes where measured energy savings are offset by unmeasured energy costs

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[2] In short, life-cycle energy is the direct and indirect embodied and recurrent energy attributable to an activity. For an explanation and rational of life-cycle energy analysis, see Treloar (1997); Treloar et al. (2000).

[3] Such life-cycle analysis is, however, sensitive to assumptions of life cycle length, especially for dwellings. The 30 year building life cycle used to produce Figure 1 is very short (50-100 years is more common), and so embodied energy in dwellings is likely over-emphasised.

outside the chosen restricted scope. A specific aim of this paper is to review research that contributes to an understanding of the total energy – embodied and operational – associated with different types of urban structure.

This paper also reviews the large body of research on the other main component of household energy use relating to transport and, specifically, its relationship to urban structure. The existence of a link between urban form/land-use and transport use is generally accepted, although the exact nature of the link is contested. Differences in urban form and structure are part of the explanation for the difference between Europe's comprehensive, well patronised public transport systems (Goodwin et al., 1991), and the limited, poorly patronised systems typical in Australian and U.S. cities (Kenworthy and Laube, 1999). It is understandable, then, that changes to urban form (mainly in the form of increased density) are put forward as the means of increasing public transport provision and patronage[4] (Bernick and Cervero, 1997; Newman and Kenworthy, 1999). Good reviews of the research on urban consolidation can be found in Badoe and Miller (2000) and Rodriguez et al. (2006), which focus on North America, and Stead and Marshall (2001), which has a Euro-American focus.

Researchers who have considered energy use have tended to restrict themselves to consider *either* transport energy *or* in-dwelling energy use, but not both. Buxton (2000) detailed some early research in this area (such as Office of the Environment (1993)), but as noted by Perkins (2003), there are few examples of contemporary research such as Perkins (2002) and Troy et al. (2003), which attempt to analyse the relationship between urban planning and *both* transport and residential energy, and nothing that amounts to a comprehensive analysis. We do note that Lenzen et al. (2004) provides a complete breakdown of end-use energy in Sydney, but does not relate this to urban or built form.

If we wish to reduce energy use and related greenhouse gas emissions, it is clear that energy use related to housing and transport must play a large role[5]. The important thing to note of both these activities is that they are influenced strongly by urban planning policies. While we know, from existing research, the energy consumed in different types of housing and different modes of transport, what has been lacking, in our view, is a substantial body of work looking at the expected effect that planning policies have on both housing related energy consumption *and* transport related energy consumption combined. Without considering both in combination, planners run the risk of simply redirecting energy use rather than reducing it overall.

Because urban planning policies affect both individual dwelling characteristics (lot size, dwelling size, dwelling type) and local area characteristics generally assumed to relate to travel behaviour (population density, physical proximity to activities, jobs/housing balance, land use mix, etc.), we contend that there are two important relationships that must be better understood if we intend to use urban planning as a tool for reducing energy consumption:

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[4] We are simplifying here, as more sophisticated strategies are evaluated, such as jobs/housing balance and land use mix (Van and Senior, 2000; Cervero and Duncan, 2006), but we restrict ourselves in this paper to discussing density, as it is the most contentious of the urban form variables, and increases in density are typically associated with the more sophisticated strategies in any case.

[5] Reduction of energy attributable to consumables must also play a role, clearly, but we do not address energy related to consumables here, as it is more difficult to analyse and is not obviously linked to urban form, which is our focus.

1. The relationship between dwelling type and in-dwelling energy use;
2. The relationship between urban structure and transport related energy use.

It is these relationships that we focus on in this paper. We use existing research from the U.K., Europe, U.S., and Australia in the areas of the built environment and transport, and speculate on the research required for the development of a combined transport/land-use energy model.

We review the housing and transport sectors separately, and for each, consider how design, urban form, and individual behaviour affect energy use and greenhouse gas emissions in each of those sectors, before discussing the combined effect in the discussion section.

# HOUSING

The energy consumed in housing can be broken down into *embodied* energy: the energy inputs required to construct and materially maintain the building shell; and *operational* energy: the energy consumed within the building shell during its lifetime for heating/cooling, cooking, electrical appliances, and so on. The two are not independent, that is, one can almost always achieve a reduction in operational energy for heating/cooling by investing more embodied energy in the building shell (in the form of insulation, additional glazing, and so on). Minimising energy use overall requires careful consideration of this tradeoff, which will be different for each dwelling, depending on a range of variables, such as the local and regional climate, dwelling orientation, dwelling occupancy, and dwelling life.

Urban planning affects operational and embodied energy consumption indirectly, through zoning and development controls, which in large part determine the types of dwellings that are built, and where they are built. Building standards also play a major role. In particular, zoning can have the effect of increasing or decreasing dwelling densities, and it is the effect of housing density on energy consumption that this section focuses on. We leave the transport implications of density for a later section, and consider here only in-dwelling energy consumption, as it relates to dwelling densities and types.

## *Embodied energy in residential building*

The principal method of increasing density is by altering building form – from detached to semi-detached to low-rise to high-rise. It is surprising then, that there has been so little research into the implications of built form on embodied energy. While there are numerous studies into operational and embodied energy consumption in residential dwellings generally, there is little research on the influence of built-form on embodied energy. In an Australian context, limited evidence is available in studies of particular developments in Adelaide (Perkins, 2002) and Sydney (Pullen et al., 2006). We regret that research comparing the embodied energy consumed in residential dwellings *as determined by built form*, is so rare.

Basic physics would suggest that larger multi-unit buildings, with a lower surface-area to volume ratio, will have lower embodied energy per square metre

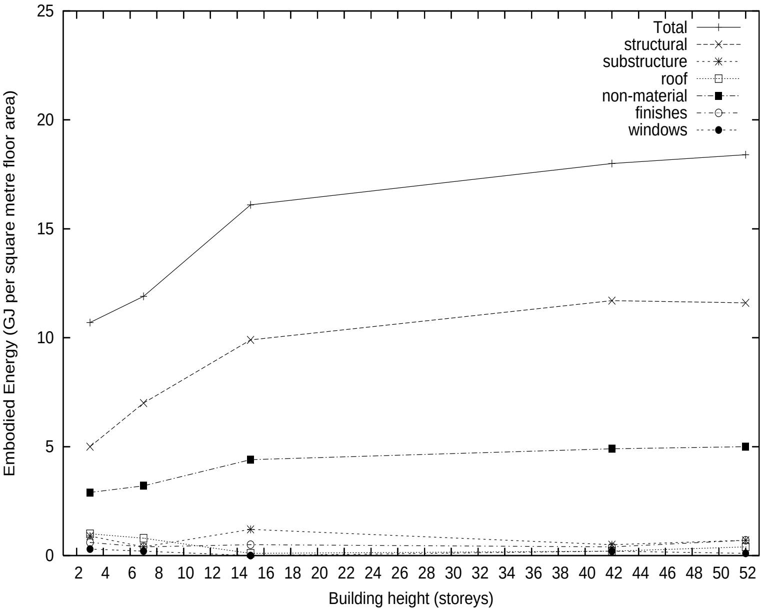

Figure 2: Embodied energy per square metre of floor area and building height (non-residential buildings of 3 storeys or more). Source: Treloar et al. (2001).

of floor area up to a point, beyond which the extra energy required to construct larger buildings (in the form of construction process energy and energy embodied in high strength materials such as reinforced concrete) would dominate. Support for this comes from Aye et al. (1999), who found that embodied energy was high for single storey buildings due mainly to poor surface area to volume ratio, and that as the number of storeys increased, embodied energy initially decreased, but then increased as the number of storeys approached 10. In a more detailed study of non-residential buildings of three or more stories, Treloar et al. (2001) found that total embodied energy per square metre of floor area building increased with height for buildings of 3 stories or more (see Figure 2)

Given the uncertainty associated with embodied energy analysis, the variety of methods used, and the absence of analysis for multi-storey residential buildings (Figure 2 is for non-residential buildings), it is difficult to compare embodied energy in detached dwellings with that in multi-storey buildings shown in Figure 2. Estimates for detached dwellings range from 6.21 GJ/m$^2$ (Troy et al., 2003)[6] to 14.1 (GJ/m$^2$) (Fay et al., 2000), but the methods employed to obtain each estimate are not comparable. The method of analysis in Fay et al. (2000) is more similar to that in Treloar et al. (2001), so we prefer the latter estimate, agreeing with Treloar's conclusion that: "it is plausible that detached houses are more energy intensive than low rise medium density, due to savings in shared walls, economies of scale and surface area to volume ratio. A cube-like shape is more efficient than a flat box, until height factors start creeping in – exponentially more structure, lobbies for the lifts...."(G. Treloar – personal communication 6/11/06). If we accept that the figures published in Treloar

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[6] This is the smallest estimate cited in this study, for the suburb of Hindmarsh in Adelaide, which has primarily detached dwellings.

et al. (2001) and Fay et al. (2000) are indicative of a general trend, correct for the fact that some floor area in multi-unit dwellings is for common areas[7], and assume that cosmetic and other non-structural factors are not significantly different in residential buildings compared to non-residential[8], then embodied energy of dwellings is similar (per unit inhabitable area) for detached and low-rise attached dwellings, with significantly higher embodied energy for high-rise dwellings. Using the figures quoted here, the ratio of embodied energy per unit inhabitable area for detached/3-storey/7-storey/15-storey/52-storey dwellings would be 1:0.95:1.2:1.6:1.9. This is partially corroborated by Newton et al. (2000), who found an embodied-energy ratio of almost exactly 1:1 when comparing a typical detached home against a 3-storey apartment dwelling. However, a couple of obvious complicating factors make this simple calculation unreliable: firstly, multi-unit dwellings are typically smaller than detached dwellings, so our comparison measure (GJ/m$^2$) favours detached dwellings; and secondly, it is not at all clear what the typical life-time of each built form is, and since this is a critical assumption in any consideration of embodied energy, it makes any fair comparison difficult.

If we expand our horizons somewhat, and consider the infrastructure required to service and maintain dwellings (water and sewerage pipes, road network, electricity grid, etc.), it seems likely that increasing density reduces the cost of infrastructure provision (as found in Office of the Environment (1993)), at least up to a point. It is plausible there is some intermediate level of dwelling density that minimises infrastructure costs (Gillham, 2002; Ladd, 1992), and possibly also embodied energy costs. Thus, there may be an optimal density where embodied energy is minimised and infrastructure is also relatively cheap to provide. More research is needed in this area, as it is still far from clear whether infrastructure costs decrease monotonically with density, as found by Carruthers and Ulfarsson (2003), or whether it is, as we suggest, U-shaped.

## *Operational in-building energy consumption*

The other main component of residential energy consumption is that required for on-going use/operation. Operational energy consumption is determined by many factors, and controlling for all other factors makes it a near-impossible task to determine the exact marginal effect of any single factor. Energy use is some potentially complex function of dwelling type, dwelling construction, dwelling design, dwelling size, number of inhabitants, inhabitant behaviour, climate, orientation, age of inhabitants, appliance and equipment type, fuel choice, and other factors. Despite the difficulty of the task, existing research does provide clear results in some areas.

Figure 3 shows the average residential energy consumption in Dutch and Australian homes, based on data reported in Priemus (2005) and Harrington and Foster (1999), respectively. The discrepancy in appliance energy is significant, and is partially explained by likely misclassification of portable heating/cooling appliances in the Australian study, which should be counted in the

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[7] Based on examination of floor plans, we assume 30% of Gross Floor Area is taken up in common areas in buildings over 3 storeys (requiring a lift), and 20% without.

[8] Since structural and sub-structural elements form the bulk of building embodied energy, and are the only elements that are dependent on building height, this assumption seems reasonable.

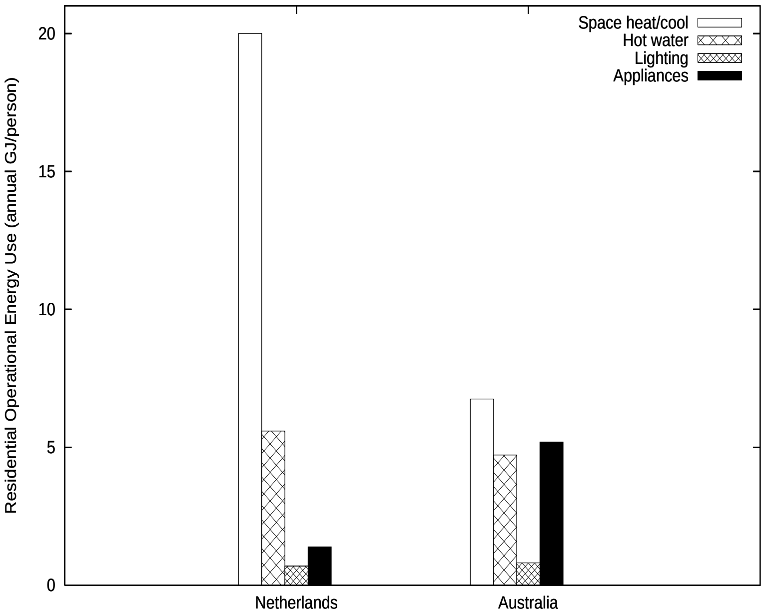

Figure 3: Residential operational energy consumption, Netherlands and Australia. Sources: Priemus (2005); Harrington and Foster (1999)

'Space heat/cool' category.

Looking specifically at the Australian/Dutch comparison in Figure 3, the similarity of water and lighting energy consumption is remarkable, given cultural differences, different energy and regulatory schemes, differences in climate and day length, and differences in how this data was collected/estimated in both cases. Space heating/cooling dominates in-residence energy consumption, with climate playing a large role, as shown in figure 3. Dutch houses exhibit better thermal performance than Australian houses, but require much more energy to heat due to climatic conditions. Because of the additional attention to insulation, Dutch housing would also require more embodied energy to construct. We should note that because average temperatures are higher in Australia, and there is more capability to use solar hot-water systems (which currently have a low market penetration of only 5% (Australian Bureau of Statistics, 2005)), energy use for hot water could be significantly lower than the current 5 GJ/person. Figure 6 shows the large reduction in greenhouse gas emissions made possible by merely switching from electric tank hot water to solar hot water.

Actual energy use figures for different built forms, obtained from energy company data and building audits in Myors et al. (2005) and reproduced in Figures 4 and 5, indicate how unclear the overall picture on operational energy use (as it relates to dwelling type) is. In that study, semi-detached and low-rise apartments had lower $CO_2$ emissions per dwelling than either detached dwellings or high-rise apartments (Figure 4), but after allowing for differences in occupancy, semi-detached dwellings have lower per-capita emissions than other building types, while high-rise apartments have the highest per-capita emissions (Figure 5). However, demographic differences in dwelling inhabitants were not controlled for. The estimates for high-rise apartments in particular do not really allow for a fair comparison with other dwellings, as many of the high-rise apartments surveyed used large amounts of energy to maintain heated swimming pools and/or spas, which, we would argue, are present due to demographic and housing supply factors not directly related to building type. These sorts of demographic differences make comparisons between all building types difficult. We know that demographic factors such as age, income, and family type affect energy use, but there is no comprehensive research attempting to control for these factors and examine the effect of building form alone. Research by Holden and Norland (2005) in Norway, where multi-unit dwellings are standard (and hence not associated with luxury features) shows in-dwelling energy use in detached dwellings is some 50% greater per capita than in attached dwellings, although the gap has been shrinking as detached design has been improving. One should also note that the better thermal properties of attached dwellings are more important in Norway than in a relatively milder climate like Australia.

Research in Troy et al. (2003) and Newton et al. (2000), as well as the results shown in Figures 6 and 7 both suggest (but hardly conclusively), that the independent effect of dwelling type in Australia is small relative to design and other factors. Myors et al. (2005) (from which Figures 4 and 5 are reproduced) suggest themselves that design is currently poor, and that large savings are possible simply through better design:

> Substantial greenhouse inefficiencies, such as electrically heated swimming pools and uncontrolled and inefficient lighting and ventilation systems, were commonly identified in the energy audits. With more thoughtful selection of common area technologies, many high-rise buildings could enjoy large energy and greenhouse savings. In fact, as none of the audited buildings boasted energy efficient design, it is likely that even [the more efficient high-rise buildings in our sample] could achieve substantial greenhouse savings with quite modest changes to common plant, systems, and apartment design. (Myors et al., 2005, page 115)

Clearly, dwelling size will have an effect on energy consumption, since dwellings with larger floor areas require a larger volume of air to be heated/cooled. Determining whether dwelling type has an effect on energy use independent of dwelling size is difficult. Figure 6 shows greenhouse gas emissions estimated by the NSW BASIX tool (see Vijayan and Kumar (2005) for a review of sustainability assessment tools, including BASIX) for different dwelling types with the same floor area in the two most populated climate zones in Australia, again suggesting that the independent effect of built form is small.

## *Design*

It is clear that buildings differ greatly in their design and construction characteristics, and that these characteristics substantially affect both embodied and operational energy consumption. Figure 8 shows the effect of construction type on unconstrained average heating/cooling energy for detached dwellings[9].

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[9] Actual use is substantially below this unconstrained figure (derived from NatHERS modelling), as building occupancy and behavioural factors reduce actual heating/cooling energy use by up to 85% below the unconstrained figures reported here.

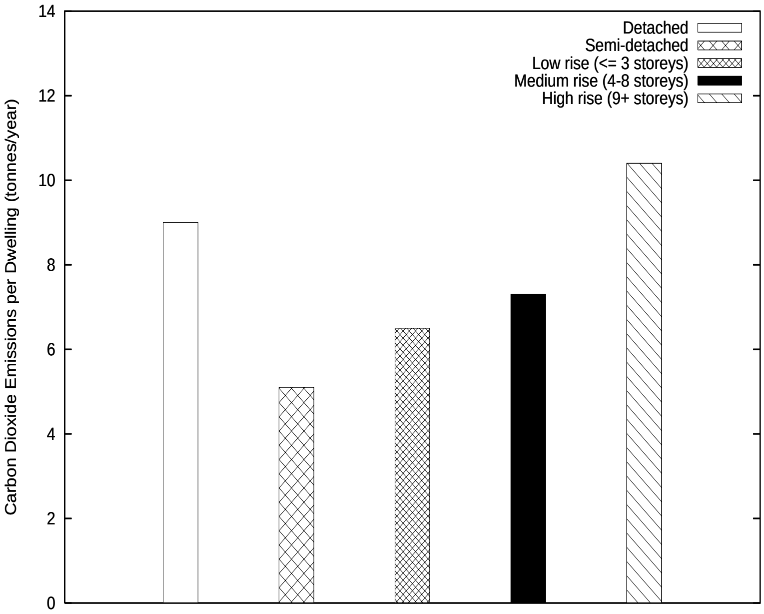

Figure 4: Operational energy carbon dioxide emissions per dwelling, by dwelling type, from actual energy company data. Source: Myors et al. (2005).

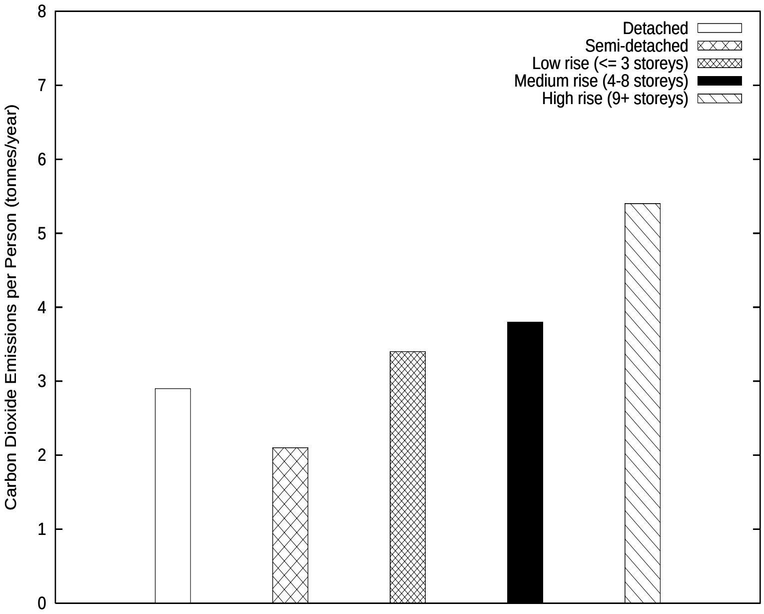

Figure 5: Operational energy carbon dioxide emissions per person, by dwelling type, from actual energy company data, using occupancy data from the ABS 2001 census. Source: Myors et al. (2005).

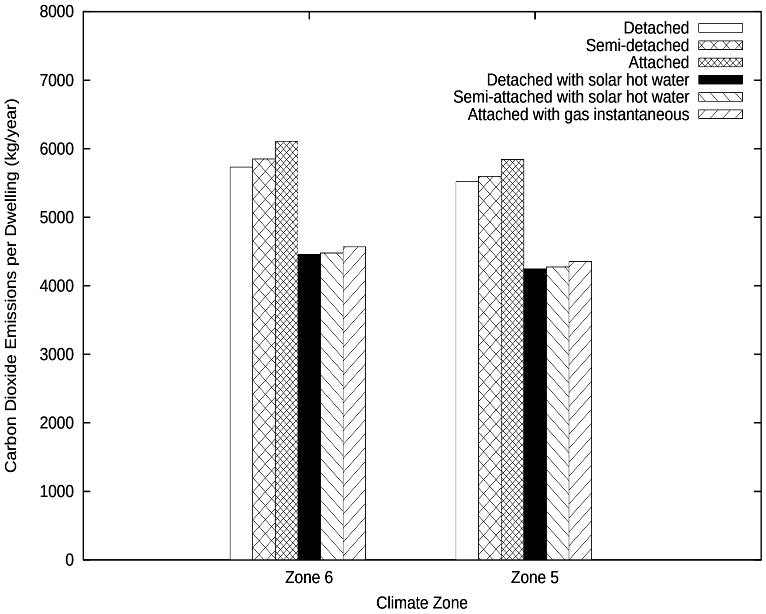

Figure 6: Operation energy carbon dioxide emissions by dwelling type and climate zone. Floor space and other parameters held constant. Source: Author's calculations using BASIX tool.

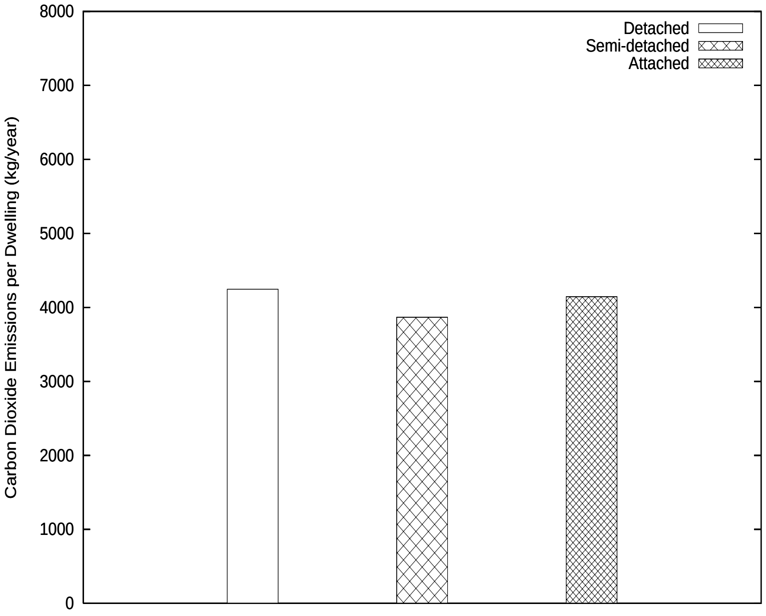

Figure 7: Operational energy carbon dioxide emissions by dwelling type. Source: Author's calculations using BASIX tool. Note: we use a detached/townhouse/unit floor space ratio of 1.5:1:1.

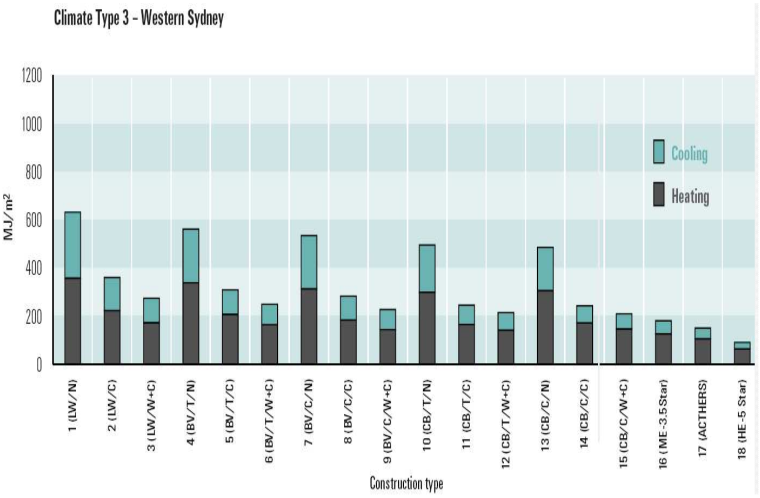

Figure 8: Unconstrained average heating/cooling energy required to maintain constant temperature for 18 different construction types applied to generic detached dwelling house plans, in the Western Sydney climate region. Source: Harrington and Foster (1999).

NatHERS modelling shows that theoretical heating/cooling requirements for attached dwellings are around 35% lower than for detached dwellings (Harrington and Foster, 1999). Assuming that actual energy use is correlated to NatHERS predictions, as is commonly done, this would translate to a saving of around 2-3 GJ per person per annum, a not insubstantial amount. Reconciling this with the BASIX results shown in Figure 6 is difficult, and points to the need for more work on looking at the relationship between modelling predictions and actual (measured) energy use.

Design and construction effects go beyond the building shell. As noted in Harrington and Foster (1999), for example, many buildings meet mandatory insulation requirements, but exhibit poor thermal performance due to poor non-construction design (shading, orientation, ventilation) – requiring over double the energy of a well designed house.

From existing research into building design, we know that significant savings are possible through very low (or zero) cost design measures, such as insulation retro-fits.

U.K. research estimates a 40% saving in energy though the replacement and/or retrofitting of space and water heating/cooling devices and more efficient appliances (Department of the Environment, Transport, and Regions, 1998). The high turnover of some appliances and heating/cooling devices means that significant gains can be made in the near to medium term (Intergovernmental Panel on Climate Change, 1996). Since appliances typically have a much lower ratio of embodied energy to operational energy, the inclusion of embodied energy in the overall calculation would make the case for action in this area even more compelling, as the embodied energy cost of new appliances are quickly recouped through operational energy savings (McEvoy et al., 1999).

## *Behaviour*

The inability of sophisticated household heating/cooling models (using such tools as NatHERS) to accurately predict actual heating/cooling energy use gives some indication of the important role that behaviour plays in determining energy consumption. We do not have a clear picture of the relationship between behaviour, building insulation, and energy use. Poorly insulated homes are typically heated much less than necessary to achieve reasonable thermal comfort levels (Harrington and Foster, 1999), and we are still a long way from a clear understanding of what low or zero energy counter measures (such as putting on a jumper) people are likely to take in poorly insulated homes. The importance of actual behaviour is very significant, when one considers that predicted heating/cooling energy use can be several times greater than actual use, with large variance (Myors et al., 2005).

A further indication of the importance of behaviour is contained in studies of people's actual responses to standard economic tools for reducing resource usage. For example, Beerepoot and Sunikka (2005) review European initiatives and studies aimed at reducing energy consumption, and find several countries that have implemented energy taxation without much change in actual behaviour, while in other countries, appliance labelling alone resulted in significant reductions in energy use. Anker-Nilssen (2003) argues against simple energy taxing schemes, citing political and behavioural reasons for their ineffectiveness in curbing actual energy use.

It is possible that behaviour changes according to dwelling type and density, and that this affects energy consumption. However, controlling for demographic and self-selection effects is exceedingly difficult, requiring a thorough treatment that, for reasons of brevity, we consider outside the scope of this review. We do, however, consider the specific case of the effect of dwelling density on travel behaviour, in our Transport section.

## *Summary*

The limited work that has been done on energy use in different dwelling types does not, overall, provide a clear picture. What does seem clear is that, in Australia, in-dwelling operational energy use is lowest, in both per dwelling and per occupant terms, in townhouse-style dwellings, and highest in high-rise apartments. Low-mid rise apartments have lower energy use per dwelling, but, at current occupancy rates, are comparable with detached dwellings in operational energy terms. However, the current state of research does not allow us to determine how much of these observed differences are due to dwelling type and size, and how much are due to differences in building codes, energy regulation, and inhabitant profiles. Given the strong trend to lower household size in Australia, it is important for us to understand this better. Regardless of built form, design is very important in reducing (or increasing) operational energy use.

Given that attached dwellings are smaller, and have better thermal properties, than detached dwellings, it is a striking finding in the limited number of existing Australian studies on operational energy use in detached/attached buildings that actual estimated savings per person are at best quite small, and, in poorly designed buildings, non-existent (Myors et al., 2005). These results also do not conform to international studies (Holden and Norland, 2005). NSW BASIX concessions for multi-unit dwellings[10] are a clear sign of the gulf between the clear theoretical potential for operational energy savings in attached dwellings, and current practice. Explanations for this gulf are offered by Pears (2005). In addition, it seems clear to us (again, despite limited research work in the area), that beyond some moderate number of storeys (perhaps around 7), there are significant embodied energy costs associated with attached dwellings over and above those associated with detached and low-rise dwellings.

Finally, we should note that there are several trends in Australian housing that are masked by aggregate analysis of energy use in different built forms. Figures for average energy use in detached dwellings, for example, reflect energy use in the current stock of detached housing, but much of this is quite old, and very different from the typical detached dwellings being constructed today, which are typically larger, and almost always come with air-conditioning as standard. If we are to plan for a more sustainable city, it is the energy use of typical new dwellings, not average energy use in existing stock, that is most useful. We would like to see more research in this area.

# TRANSPORT

Australian cities, despite being less dense than the major European and Asian cities with the most efficient public transport systems, can still support public transport systems that are much more energy efficient than automobiles. In Sydney, for example, rail and bus energy efficiency is 0.29 and 1.11 MJ/passenger-km, compared with 3.13 MJ/passenger-km for car in secondary-energy terms[11] (Glazebrook, 2002). Furthermore, public transport is found to be more energy efficient than cars across the day, even in off-peak periods (see Figure 9). European and wealthy Asian cities are typically significantly more efficient than Australian cities (Newman and Kenworthy, 1989; Schipper et al., 1992), and American cities less so (Davis and Diegel, 2006; Newman and Kenworthy, 1989).

Lenzen (1999) reviewed the total energy used in different transport modes in Australia, and calculated that private passenger automobile use was responsible for over 60% of all transport related energy use. With transport energy accounting for one quarter of total energy use (ABARE Economics, 2006), this means that automotive passenger transport accounts for over 14% of all energy use in Australia, similar to the U.S. (Davis and Diegel, 2006), and significantly higher than the other OECD countries (Schipper et al., 1992).

In the following consideration, we ignore freight transport, despite its significant contribution to transport energy use, as its relationship to urban form is less clear than that of passenger transport. We focus on broad measures of urban form, in particular density, as this is where much of the debate has focused up to this point, and density is still the most commonly used land-use measure in most transport studies. More complex measures of urban form are

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[10] Large multi-unit developments are required only to reduce per capita emissions by 25% from the current NSW average, compared with the 40% target for other dwellings.

[11] Secondary energy is energy measured at the point of consumption. Converting to primary energy (so called 'energy in the ground') still shows public transport as some three times more energy efficient.

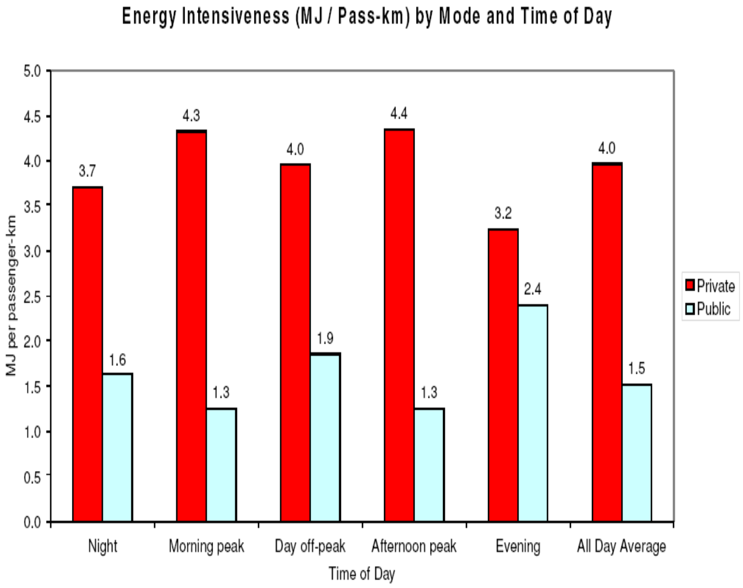

Figure 9: Public transport energy efficiency in Sydney, by mode and time of day. Source: Glazebrook (2002).

studied, such as neighbourhood accessibility, land use mixing and land use balance (Cervero and Duncan, 2006; Kockelman, 1991; Krizek, 2003), but have been less thoroughly debated in the literature. The notion that jobs-housing balance reduces commute VKT, for example, is less contentious than claims about urban density.

## *The effect of urban form*

Still the most compelling work suggesting a strong link between urban form and energy use is Newman and Kenworthy (1989). Although criticised by some on methodological grounds (see, for example Gomez-Ibanez (1991); Gordon and Richardson (1989); Rodriguez et al. (2006)), there is still nothing amounting to a refutation for their posited relationship between population density and energy consumption, and plenty of empirical support, which we outline in this section. The study is still one of the most comprehensive (in terms of data collection) of any international study on the effect of urban form. While the authors concentrated on gasoline consumption and automobile dependency, data was also collected for total (private and public) energy use, and follows a similar trend (see Figure 11). Total energy use decreases with density, despite the fact that density typically decreases the efficiency of private vehicular transport (see Figure 11). The explanation most offered is that automobile vehicle kilometres travelled ('VKT') decreases with density and public transport use and efficiency increase with density (see Figure 10), and these factors more than outweigh possibly decreased vehicular efficiency. The first of these claims (VKT decreases with density) is most often contested. We discuss the major objections and alternate views in the following section.

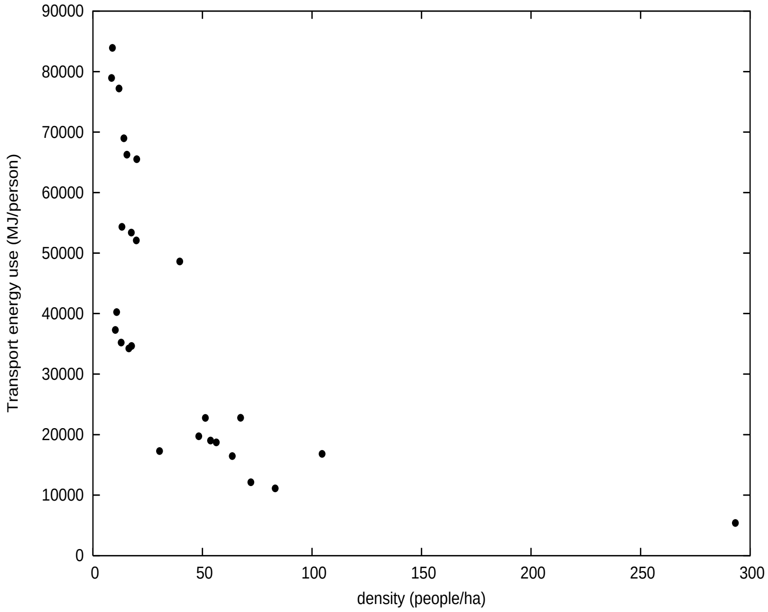

Figure 10: Urban transport density and energy. Source: Newman and Kenworthy (1989).

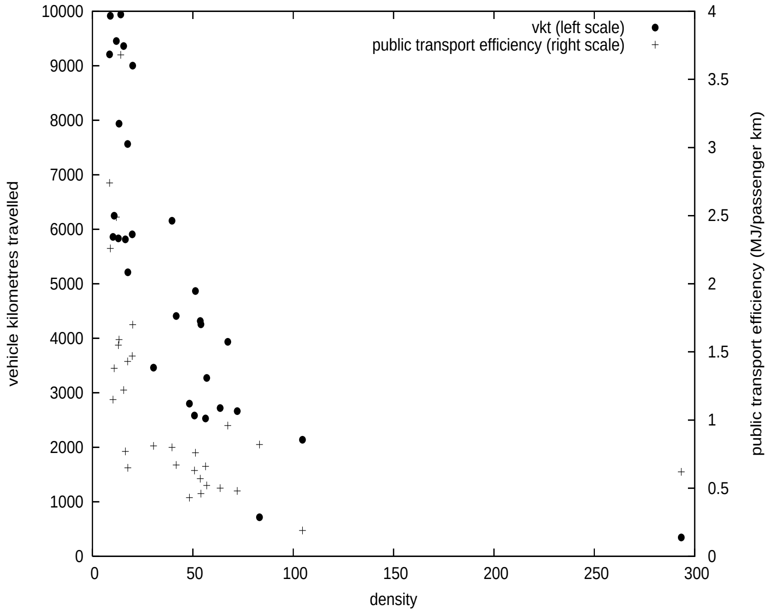

Figure 11: Urban density, private VKT, and public transport (MJ/passenger-km) outcomes. Source: Newman and Kenworthy (1989).

## *Alternate views*

Showing a correlation between urban density and energy use (or other transport related outcomes such as VKT) is one thing. Establishing a causal link is more difficult, as transport and land use are not independent. The complex interaction between transport and land-use is acknowledged by planners, and makes the task of establishing independent effects from either challenging. Increasing density far from activities, with no public transport provision, would increase private VKT, and building a heavy rail link from one empty field to another would have the immediate effect of decreasing public transport efficiency. These are clearly unrealistic cases, but they do indicate that the popular econometric approach of estimating marginal effects of increasing density or providing public transport is flawed, a view shared by Badoe and Miller (2000). With this in mind, we present and critique alternate hypotheses and objections to Newman and Kenworthy's original one.

### Objection 1: Density isn't an important variable that influences transport energy

Boarnet and Crane (2001a) and others (Maat et al., 2005) argue that the relationship between land use and travel behaviour is complex, and that simple proxies that are commonly used, like population density, are not useful, and, at worst misleading. In U.S. cities, for example, dense neighbourhoods are commonly low income neighbourhoods, and so un-tangling demographic effects from urban form effects is difficult. In a review of studies of the land-use transport interaction, Boarnet and Crane (2001a) conclude that if land use does influence travel behaviour, it is not directly, but through indirect influences on travel speed and distance, and that:

> It thus appears premature to either conclude that the built environment can be reliably used as transportation policy tools at the margin or that it cannot. (Boarnet and Crane, 2001a, page 842)

It is not uncommon for studies of U.S. cities by economists to fail to find any *marginal* effects of increased density (see Boarnet and Crane (2001a); Boarnet and Sarmiento (1998); Crane and Crepeau (1998); Handy (1996)). This, however, is not surprising, given the time-lagged nature of the transport/land-use interaction, and the fact that U.S. cities are extreme in their lack of density. Given that many U.S. studies are of cities with low densities (e.g. Bertaud (2003); Crane and Crepeau (1998); Kain (1992)), the difficulty in detecting marginal effects between very sparsely populated areas and slightly less sparsely populated areas may well be due to the fact that U.S. cities do not approach densities that can support bus services, let alone rail. It is worth noting that in those few U.S. cities that do approach the 30 people/ha critical point postulated in Newman and Kenworthy (1989), studies have detected marginal effects of density on VKT (see Baum-Snow and Kahn (2005); Bento et al. (2003); Golob and Brownstone (2005); Holtzclaw et al. (2002)).

Studies that have not concentrated on detecting marginal effects within a single city and instead looked at US-wide variation have concluded that some measure of population and employment centralisation[12] does matter (Bento et al.,

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[12] Bento et al. (2003) reject density as the important variable, and instead use a more sophisticated measure of population centrality. Ewing et al. (2002) use a sprawl index based

2003; Ewing et al., 2001, 2002; Holtzclaw et al., 2002), even after accounting for self-selection, income, race, and weather. Both Bento et al. (2003) and Ewing et al. (2002) estimate a 25% reduction in VKT between a sprawling city like Atlanta and a relatively more compact one like Boston, and a 10% reduction in car ownership. Some smart growth advocates have reported reductions of up to 55% in VKT for particular developments (Litman, 2003), but these sort of reductions may not be possible on a broad scale, and may be illusory, as selection bias was not controlled for. In addition, non-US studies typically find density to have an independent effect on travel behaviour (Dieleman et al., 1999; Geurs and van Wee, 2006; Naess, 2005). It seems fair to conclude, both internationally and within the U.S., that some measure of population or activity density is a good predictor of lower automobile ownership and use, even after controlling for other factors.

#### Objection 2: Density *increases* energy use

The fact that people do not locate themselves to minimise housing costs and travel costs (Hamilton and Roell, 1982), as is assumed by the classic monocentric city model arising from the work of Alonso (1964); Mills (1967); Muth (1969), and that commute times are shorter in more decentralised, sprawl-type cities (Gordon et al., 1989) have led some to question the usefulness of urban consolidation policies in reducing transport energy, even if it does reduce VKT, as it also increases congestion. However, complicating factors make simple arguments like this unreliable, as pointed out by Boarnet and Crane (2001a). The fact that larger cities tend to have higher densities and higher commute times tends to limit the usefulness of such observations, and indeed, research by Ewing et al. (2002), found no reduction in commute times for sprawling cities after controlling for city size.

#### Objection 3: Density matters, but it's too late for Australian and U.S. cities

One can argue that it is for historical reasons that European cities are densely populated, and can support rail. The essential argument is that because Australian and U.S. cities developed in the age of the automobile, they had a transport mode available around which to organise their cities that other countries did not. See Giuliano and Small (1995); Glaeser and Kahn (2003) for examples of this line of argument.

To choose a specific case of this line of argument, consider the study by Bertaud (2003) of urban consolidation and transit policies in Atlanta. Atlanta is one of the least densely populated cities in the U.S., which has the least densely populated cities in the world. Bertaud (2003) calculates that, even with continued population growth at the long term average, and an absolute ban on new development for 20 years, two thirds of Atlanta's currently developed housing stock would need to be demolished for Atlanta to approach the 30 people/ha limit suggested in Newman and Kenworthy (1989) for public transport to become viable. Other U.S. and Australian cities, while not as extreme as Atlanta, would still require such extreme reorganisation to achieve densities seen in Europe that many have argued that alternate measures to increase the efficiency

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on numerous measures.

of the road network will be more effective. Proposed alternative measures are discussed next.

While it may be true that Australian and U.S. cities will never approach European or Asian densities, it is possible that density can be increased around transport hubs, and since this one of the main methods advocated to reduce transport energy use (Cervero and Kockelman, 1997; Cooper et al., 2001; Newman and Kenworthy, 1999), not wholesale densification, we find this argument unconvincing.

#### Objection 4: Density may matter, but there are other ways

U.S. (and to a lesser extent Australian) cities are currently laid out in such a manner as to make it difficult for public transport to be a viable alternative for many trips, especially between suburbs. The fact that land-use changes and major public transport infrastructure projects take some time to produce any effect makes it possible to argue that reducing energy use requires only that we use our cars more efficiently. Improvements in efficiency are proposed through congestion pricing of roads, improved automobile technology, smaller cars, car-sharing, and alternate fuels (Bertaud, 2003; Boarnet and Crane, 2001b; Gordon and Richardson, 1989).

It is difficult to argue that measures other than land-use and transport measures are unimportant. A smaller, lighter vehicle fleet with technological improvements in the form of hybrid engines would make a large difference. Congestion pricing (or other pricing of road externalities) would encourage more efficient use of road space in those areas suffering congestion, and may actually be the catalyst for changes to employment and residential distribution. High oil prices, coupled with congestion and other charges, may encourage faster reorganisation of urban form than would a regulatory planning approach, so in some sense one can see congestion pricing and pricing of automobile externalities as an alternate mechanism for enforcing changes to land use.

Others have argued for decentralisation (Glaeser and Kahn, 2003) instead of densification, on the basis that congestion and long commutes are primarily caused by too many centralised jobs. However, decentralisation and concentration are not mutually exclusive, and proponents of smart growth are generally in favour of multi-centred cities linked by transit, rather than mono-centric ones (Cervero, 1995; Curtis, 2006; Newman and Kenworthy, 1999), so the essential disagreement is not about decentralisation versus concentration, but about the method of the decentralisation. Australian research by Newton (1997) indicated that decentralisation results in higher energy use than compact mono and multi-centred cities. European research reaches similar conclusions (Dieleman et al., 1999; Geurs and van Wee, 2006; Naess, 2005).

### *Summary*

The literature on transport is clear on some points. Some obvious relations hold – there are positive links between: road provision and VKT (Rodriguez et al., 2006); rail supply and ridership (Bento et al., 2003); income and car ownership (Bento et al., 2003); income and fuel use (Golob and Brownstone, 2005); public transport travel times and patronage (Camagni et al., 2002). The expected negative link is found between VKT and fuel price (Glaister and Graham, 2002;

Johansson and Schipper, 1997; Rodriguez et al., 2006). Also un-contentious is the general claim that public transport is more energy efficient than the car in all but the most unfavourable circumstances (Glazebrook, 2002; Kenworthy and Laube, 1999; Lenzen, 1999; Newman and Kenworthy, 1989; Schipper et al., 1992).

Despite the clear trends within and between cities, mass transit (particularly rail) is unpopular with many economists, as noted in reviews by Balaker and Kim (2006) and Voith (2005). Some economists are sceptical of rail's ability to attract riders away from the car and reduce vehicle kilometres travelled (VKT) and vehicle ownership (Baum-Snow and Kahn, 2005; Bertaud, 2003; Garrett, 2004; Glaeser and Kahn, 2003; Kain, 1992; Richmond, 2001). Much of this dissenting analysis is based on a failure to detect marginal effects of proximity to transit in low density U.S. cities, and so is of limited use, as longer term land-use/transport interactions are ignored or inadequately modelled (Badoe and Miller, 2000). While the economic case for rail is something we do not address here, and is doubtless the root cause for much of the antipathy toward rail by economists, we find that the depth of feeling has clouded judgement sufficiently that even the environmental benefits of rail are questioned. Only a North American economist could write the following, given the weight of contrary evidence:

> A greater share of rail ridership has, *at best*, an ambiguous effect on the environment. (Winston and Maheshri, 2006, page 16) [italics ours].

Furthermore, we find economists to have a consistent predilection for analysis of marginal effects with linear models, and ignore land-use and other non-linear feedbacks – a point made by Newman and Kenworthy (1992) in their initial response to criticism of a posited link between density and automobile dependence, but which is still inadequately addressed. Badoe and Miller (2000) make a similar argument for an integrated land-use transport modelling, in their review paper on North American research, after concluding that methodological and data limitations are endemic in much of the current research into the effect of urban form on transport behaviour.

While there is still debate about the causal mechanism involved (Badoe and Miller, 2000; Rodriguez et al., 2006) it is clear that on an aggregate level, densely populated cities use less transport energy per capita, and per passenger kilometre, than do sparsely populated ones (Kenworthy and Laube, 1999; Newman and Kenworthy, 1989; Schipper et al., 1992). It is still possible to argue that density is not an important causal factor, but it seems to us that the common explanation is the most convincing: there is a positive feedback loop between transport and land use such that public transport friendly land use encourages less automobile travel and more public transport travel, which in turn encourages public transport friendly land use, and so on. Some cities that have managed to generate this cycle can fund their rail infrastructure at least in part through value capture (Smith, 2006). In-depth longitudinal studies of the Netherlands, which has had physical planning with compact urban form as the goal for decades, support the thesis that compact urban forms reduce car dependence and energy use (Dieleman et al., 1999; Geurs and van Wee, 2006). Probably the most comprehensive intra-city research, conducted in Copenhagen by (Naess, 2005),

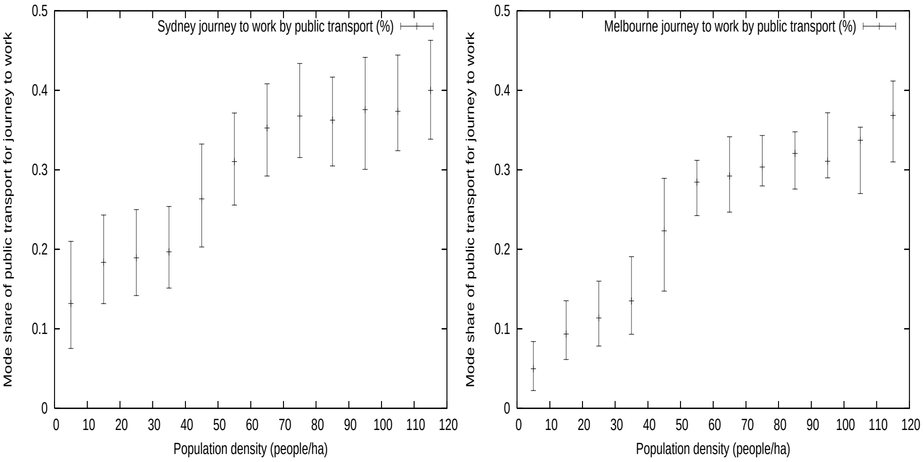

Figure 12: Population density and share of public transport for journey to work at ABS Collection District level in Sydney (left) and Melbourne (right). Median and upper/lower quartiles shown for particular density ranges. Source: Author's calculations from 2001 ABS Census data.

also found strong effects of urban form/location on travel behaviour, among all demographic sub-groups studied.

The theory that there is some critical population or activity density where effects from the positive land-use transport feedback start to become large is plausible, and supported by research not just by the original proponents (Kenworthy and Laube, 1999; Newman and Kenworthy, 1989, 2006) but also by others (Golob and Brownstone, 2005; Holtzclaw, 1994; Levinson and Kumar, 1997). Our own research for Sydney and Melbourne at the ABS Collection District level (see Figure 12) suggests that while there is significant variation due to other factors, there is also a clear, and non-linear, association between higher density and greater public transport use, with the largest effects taking place at up to 70 people/hectare, beyond which returns are more marginal. However, given that population densities typically decrease with distance from the CBD, the true underlying effect may partly or wholly relate to distance from the CBD, rather than density. Such complications are typical in any analysis of the effect of density.

# DISCUSSION

The focus of this paper has been to examine the combined residential (in-house) and transport energy use of households, on which there has been a dearth of research.

While there is some existing research that has explicitly considered combined transport/in-dwelling energy, such as Perkins (2002), the general lack of a large body of research on combined transport/in-dwelling energy use leads us to conclude that, in general, not even approximate estimates of combined in-house/transport energy can be made from existing research.

One critical issue for this paper concerns the extent to which household energy use is related to urban form as opposed to other factors. As already mentioned, there are very few papers that have explored the combined residential (in-house) and transport energy use of Australian households. The pilot study by Troy et al. (2003) indicated that while urban form may be a factor, other factors are at least as important. However, given the methodological problems acknowledged in Troy et al. (2003) (and expanded-upon in Perkins (2003)), the need for more detailed research is clear. Moriarty (2002) argues that while there are differences in resource use in urban and non-urban areas, the differences, when one takes into account indirect consumption, are small; that even dramatic changes to urban form will have small effects; and alternate or complementary approaches are needed. These findings, however, seem premature, given international research in countries like Norway and the Netherlands that have a strong physical planning tradition (Geurs and van Wee, 2006; Holden and Norland, 2005). Research canvassed in this paper suggests that while the independent effect of dwelling type may be relatively small, significant total energy savings are possible through a combination of dwelling type, dwelling design, and dwelling location.

On a transport front, the research analysed in this paper consistently points to a reduction in vehicle travel in communities with land use that allows for the provision of efficient public transport. This conclusion is supported when city-size is controlled for, and sophisticated measures of urban form are used (rather than just population density). It is supported by evidence from both inter-country (Kenworthy and Laube, 1999; Newman and Kenworthy, 1989), inter-city (Bento et al., 2003; Levinson and Kumar, 1997), intra-state (Golob and Brownstone, 2005), and intra-city (Naess (2005), Figure 12) comparisons. Debate often now centres on what exactly constitutes ‘public transport friendly land use’, with criticism of simple measures such as population density, although most authors still find population or activity density both a convenient, and useful measure (Golob and Brownstone, 2005; Gordon et al., 1989; Ladd, 1992; Levinson and Kumar, 1997).

Overall, the research surveyed in this paper suggests that the planning required to reduce household energy consumption needs to be varied according to the nature of the energy consumption. For ‘in-house’ consumption, appliance and building design seem likely to be at least as important as built form. For transport consumption, urban form is critical, though more research is needed to identify the best means of transforming current urban structures to more energy efficient ones. We find the evidence on the high operational and embodied energy costs of high-rise buildings disturbing, given that apartments in the more populated cities of Australia are increasingly being provided in high-rise towers. It may be that building smaller detached dwellings, townhouses, terraces, and low rise apartments is a preferable way of increasing urban density, and that high-rise should be limited to those few situations where very large transport energy savings can be expected. This may be the case for high-rise dwellings immediately over the air space of major rail stations, or in city CBDs, for example. Currently, though, we can do little more than make educated guesses. Given that many Australian metropolitan strategies include plans to increase density around particular hubs, it is important that future research provide further information on the energy implications of the different strategies that can be employed to do this. This implies the development of more sophisticated land-use/transport energy models, as already argued for in Perkins (2003); Troy et al. (2003). This need not necessarily be done from the ground-up, as sophisticated transport/land-use models already exist which perform much of the underlying modelling necessary for a more complete energy model.

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