The Impact of Physical Planning Policy on Household Energy Use and Greenhouse Emissions

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Thesis originality

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

(Peter Rickwood)

Thanks

Thanks foremost to Beth, for giving up so much to give me the opportunity to do my doctorate, and for caring for both myself and our two children, Jack and Lily, while I undertook this thesis. Thanks also to Jack and Lily for accepting my occasional absences during the last few months writing up, even when they couldn't really understand why dad was not around as much. Thanks to my supervisor, Garry Glazebrook, for his supervision, his encouragement, and his advice; our interactions were always edifying. Thanks also to Glen Searle, my co-supervisor, for his advice and encouragement, and for invaluable feedback on much of my writing. Thanks to Beth, Damien Giurco, Michelle Zeibots, Danny Rickwood, and Pete Gammie for their input and advice on various matters relating to this thesis. Thanks to Professor Malcolm Sambridge particularly for advice and assistance with some of the mathematics in Chapter 5. Thanks are owed to my mum and dad, for their love and support, and for letting me save time commuting to and from university by setting up a home office of sorts in their spare room for much of the duration of this thesis. Heinz Schandl at CSIRO provided administrative support, and was always helpful and friendly. Kerry Shaz, Grace Corpuz, and Annette Hay from the NSW Ministry of Transport were all helpful in providing data and advice for my analysis. Bee Thompson from the Independent Pricing and Regulatory tribunal was similarly obliging in providing data relating to in-dwelling energy use. Peter Maganov from Randwick City Council went out of his way to be helpful, and provided useful data on in-dwelling energy use. Pat Fensham and Rod Simpson were both of great help in providing their input and advice on various matters relating to the Sydney MetroStrategy. Thanks finally to Bev and Alejandra for being such generous (in time, spirit, and chocolate!) thesis companions in the post-graduate lab at UTS.

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Publications related to this thesis

Four peer-reviewed papers have been published (or accepted) that summarize some of the research carried out for this doctorate, with one additional paper currently in review. This thesis draws heavily on these published accounts.

Published Rickwood, P., Giurco, D., Glazebrook, G., Kazaglis, A., Thomas, L., Zeibots, M., Boydell, S., White, S., Caprarelli, G., and McDougal, J. (2007). Integrating population, land-use, transport, water and energy-use models to improve the sustainability of urban systems. *2007 State of Australian Cities Conference.*

Published Rickwood, P., Glazebrook, G., and Searle, G. (2008). Urban structure and energy – a review. *Urban Policy and Research*, 26(1):57–81.

Published Rickwood, P. and Glazebrook, G. (2009). Urban structure and commuting in Australian cities. *Urban Policy and Research*, 27(2).

Published Rickwood, P. (2009). Residential operational energy use. *Urban Policy and Research*, 27(2).

Contents

Abstract

This thesis investigates the impact of physical planning policy on combined transport and dwelling-related energy use by households. Separate analyses and reviews are conducted into dwelling-related and transport-related energy use by households, before a model is developed to investigate the city-wide implications of different land-use scenarios in Sydney, Australia.

The analysis of household energy use in Chapter 3 suggests that medium density housing (i.e. lose-rise apartments, townhouses, and terraces) is likely to result in the lowest per-capita energy use, while also allowing for sufficient densities to make frequent public transport service viable.

The analysis of transport energy in Chapter 4 confirms that increasing urban density is associated with decreased car ownership and use, independent of other factors. However, land use changes alone are likely to result in modest changes to travel behaviour.

The results of the scenario modelling in Chapters 7-9 support the view that changes to land use alone can reduce household energy consumption, but the changes, even over a long time period (25 years) are small ($\approx 0 - 10\%$) for all but the most extreme land-use policies. Instead, a coordinated (land-use/transport and other policy levers) approach is much more effective. The results confirm that it is transport energy that is most sensitive to planning policy, but that a combined consideration of dwelling-related and transport-related energy use is still useful. The micro-simulation model developed to assess the impact of different land-use planning scenarios allows the establishment of a lower-bound estimate of the effect that housing policy has on household energy use, assuming 'business as usual' transport policy, household behaviour, and technology.

Chapter 1

Introduction

This thesis is concerned with the effect that planning policy can have on household energy use (and resulting greenhouse emissions). More specifically, this thesis explores the impact of physical land-use and transport policy on household energy use. Land-use planning policy and land economics influence household energy use, as they determine not only where dwellings are constructed (affecting transport energy use), but also what type of dwellings are constructed (affecting in-dwelling energy use and building construction energy). However, the relationship is not well analyzed, and investigating the effect on *combined* transport and dwelling-related energy use is the aim of this thesis.

The nature, scope, and methods employed in this investigation are described in more detail in Sections 1.3-1.6. However, before narrowing the focus too much, it helps to place the issue in a broader context. Doing so provides the opportunity for a more complete understanding of the overall place, and importance, of the comparatively (and necessarily) narrow issues discussed in this thesis.

1.1 Cities and sustainability

> We are over-using our natural capital and the solutions must be linked to our cities .... The fight for sustainable development will be won or lost in our cities.
>
> Klaus Töpfer, executive director of the UN Environment Programme.

In the nineteen-sixties and seventies, consciousness of, and concern for, the planetary environment was stimulated through several influential publications. Rachel Carson's "*Silent Spring*" (Carson, 1962) is often credited with launching the modern environmental movement. Paul Ehrlich's "*The Population Bomb*" (Ehrlich, 1968), along with the Club of Rome's "*Limits to Growth*" (Meadows et al., 1972) both helped create an awareness of resource depletion, and of the finite capacity of the earth's systems to cope with human influences. James Lovelock's "*Gaia: A new look at life on Earth*" (Lovelock, 1979) extended the notion of the organism from the individual being to the entire planet – conceptualising the whole Earth as a single organism, with regulatory mechanisms (biosphere, atmosphere, oceans, soils) akin to the regulatory systems of a living being. It was evident those systems were under stress.

Initially, the environmental movement was concerned principally with non-urban 'wilderness' areas. It took some time before the importance of cities as large resource 'sinks' was widely recognised and studied. Analyses in urban settings had traditionally been economic and/or social in nature. The desire to conceptualise cities as more than social/economic realms prompted new approaches. Particularly influential was the work by Rees and Wackernagel (1994, 1996), with their notion of the 'ecological footprint'. Notwithstanding the problems with ecological footprint analysis (see, for example, van den Bergh and Verbruggen (1999); van Kooten and Bulte (2000)), this work has done much to break down the urban/non-urban environmental divide by allowing for the explicit linking of urban areas with the non-urban areas from which natural resources were sourced. Conservation of 'wilderness' thus became linked with urban sustainability.

As it turned out, the more pessimistic scenarios in "Limits to Growth" were not realized[1], although the more moderate of their predictions fit well with current data (Turner, 2008). The predictions of Ehrlich were overly pessimistic. In particular, specific (i.e. dated) predictions about resources shortages, and consequent increases in malnutrition rates and commodity prices turned out to be wrongEhrlich, and others, failed to anticipate the ability of humankind to innovate and adapt – the so-called 'Green Revolution' in agricultural production being the most notable example. In fairness, current evidence suggests that the warnings of resource shortages and over-consumption were essentially well founded, but mis-timed.

The apparent failure of many early predictions of environmental collapse ushered in a period of relative optimism, until, around the beginning of the new millennium, widespread concern over the Earth's capacity to sustain the world's population re-emerged. The most notable of these concerns relates to changes to the Earth's climate resulting from the burning of fossil fuels, and the resulting carbon-dioxide emissions. This re-emergence of environmental concerns is now taking place in a context where the importance of cities as resource sinks is well known, and this, coupled with dramatic world-wide population shifts to urban areas, has placed cities in a central position in the accompanying policy debate.

An interest in the role of planning policy in influencing energy-use dates back to at least the 1970s oil shocks, which prompted research into the use of oil in our urban transport systems (Kwast, 1980; Wood and Lee, 1980). Prominent research in the late 1980s by Newman and Kenworthy induced much debate on the role of land-use policy in influencing transport outcomes. For researchers interested in the environmental impacts of urban transport, climate change is now the most common motivation for studies into the link between planning policy and energy use (see Ewing et al. (2007); Glazebrook and Rickwood (2007); Brown et al. (2008)). Whatever the motivation for research into the effect of policy on energy use, the focus has been on *transport-related* energy use. This is understandable, as the link between planning policy and transport related energy use is clear, but there is a growing body of research into the impact of planning policies on residential in-home energy use, and embodied energy use. Estimating the *combined* energy from both transport and in-dwelling energy use is a new area of research, and is the aim of this thesis. As already noted, it seems natural to consider the two together, because planning policy affects both the type and location of residential dwellings, and these factors in turn are

[1]There is still dispute over whether the predictions in Limits to Growth were accurate or not, as the book contained numerous scenarios, some of which predicted near complete resource depletion by around the year 2000, and others, with more optimistic assumptions, around a century later. Most people at the time, however, focused on the more pessimistic and dramatic projections. See, for example, Baumol and Oates (1979, Chapters 7,9).

related to transport and in-dwelling energy use, respectively.

1.2 The land-use policy and energy debate

The principal motivation for the investigations contained in this thesis is the (still) ongoing debate over the effect that land use policy has on energy use. Since at least Newman and Kenworthy (1989), there has been an active debate over the effect of land use on travel behaviour and energy use. The findings of Newman and Kenworthy (1989), and others (Ewing et al., 2001; Bento et al., 2003; Næss, 2005), that more densely populated cities consume less transport energy per capita than sparsely populated ones, produced both a flurry of counter-findings (Gordon and Richardson, 1989; Kirwan, 1992; Brindle, 1994), and much further research and interest into the benefits and drawbacks of 'compact' cities (see, for example, Jenks et al. (1996)). More recent research has been more sophisticated in its analysis of the effects of land use policies. More complex measures of urban structure and land use have been used, such as land use mix, activity density, transit access, and general accessibility. There is also a trend to more disaggregated analyses – measuring land use variables effects at the neighbourhood and street level, and behaviour variables at the neighbourhood, household, or individual level. Good examples of more recent, more sophisticated analyses can be found in Hensher and Ton (2002); Geurs et al. (2006). Despite extensive research, however, the view expressed in the review by Boarnet and Crane (2001a) is still widely held:

> It thus appears premature to either conclude that the built environment can be reliably used as a transportation policy tool at the margin or that it cannot.

Boarnet and Crane (2001a, page 842)

Evidence that the debate is still an active one can be found by contrasting the findings of two more recent reviews:

> [O]ur expectations derived from theory regarding the relationship between density and travel patterns are ambiguous. Indeed, our review of the empirical studies regarding this relationship suggests that the evidence is equivocal.

Rodriguez et al. (2006, page 1883)

> [T]he 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).

Rickwood et al. (2008, page 76)

There is evidently still debate over whether land use can be used as a policy tool to influence travel behaviour. Even if it is conceded that land use policy can be used, the magnitude and mechanism of the effect requires further exploration.

I have sketched, in brief, the debate over the effect of land use policy on travel behaviour (and hence, energy use). This has been the principal focus of most researchers. However, because land-use policy affects the structure and size of buildings, it is also conceivable that land use policy will affect in-building energy use and the energy embodied in the structure of dwellings. Thus, there is a case for a combined investigation of the effect of land use policy on both transport energy and building energy, and this thesis provides just such an analysis. While some researchers have considered combined transport/building energy, this has only been at the building (Fay et al., 2000) or development scale (Perkins, 2002). I am not aware of any research on effects at a metropolitan scale, although intention to conduct such research through the use of integrated land-use/transport models has been declared (Anas, 2007, page 449).

1.3 Key motivating question

The central question addressed by this thesis is:

key motivating question

"To what extent can planning policy influence residential transport and dwelling-related energy use?"

This question, however, is very broad, and so, to make the task of answering it more manageable, the nature and scope of the inquiry must be clearly defined. This is done in Sections 1.5.1-1.5.2, following a brief discussion of the key concepts relating to the measurement of energy use (Section 1.4). The broad thesis question just stated is then broken down into a number of smaller, and more targeted, questions, which are posed in Section 1.5.3. These serve as the detailed questions that are directly addressed in this thesis.

1.4 A note on measures of energy use

It is necessary to cover a few key terms and concepts relating to energy use, before the broad thesis question is broken down into the three specific questions addressed by this thesis.

Given that energy use and resulting greenhouse gas emissions are the main outcomes of interest in this thesis, it is important to have an understanding of the different ways they can be measured. The following key terms have been used throughout:

Primary Energy Refers to the energy embodied in raw fuel (i.e. primary fuel energy), *plus* the energy required to extract and transport that fuel (through drilling, pumping, etc). Example: Energy embodied in 1 kg of coal, plus energy required to extract and transport that coal to a power plant.

Primary Fuel Energy Refers to the energy embodied in raw fuel alone. This measures the total thermodynamic potential energy of the fuel source; typically only a part of this potential energy can be converted into useful Secondary Energy. Example: Energy embodied in 1 kg of coal.

Secondary Energy Refers to energy stored in an intermediate, more convenient form, generated from a primary fuel source. Example: 1 kWh (3.6 MJ) of electricity, generated at a power station through the burning of coal.

Delivered Energy Refers to energy consumed at the point of use. Example: 1 kWh of electricity consumed by a television.

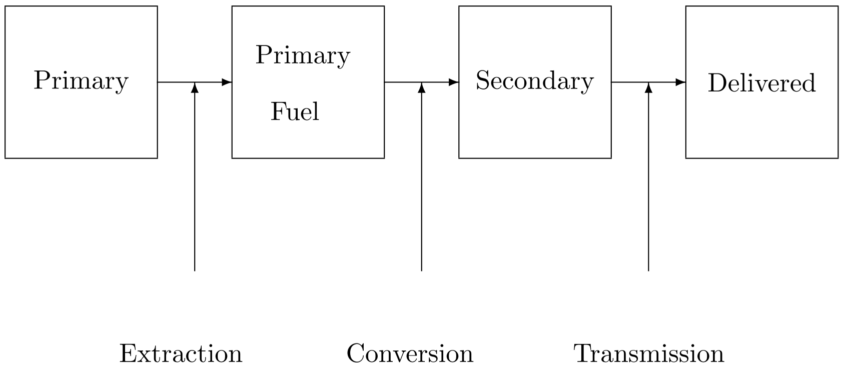


Figure 1.1: Different stages in the energy pipeline.

Figure 1.1 shows the energy 'chain', from primary energy in the ground, to end use (i.e. delivered). The easiest way to explain the figure is through an example. I will use coal→in-dwelling electricity to illustrate the key steps in the chain. Figure 1.2 shows a depiction of the coal→in-dwelling energy chain. Primary energy in the ground is the enthalpy (i.e. the thermodynamic potential) of the energy source, plus the energy cost of extracting that coal. For coal, primary fuel energy is the energy embodied in the coal[2] excluding the energy costs of extraction and transportation to a power station. Once the coal is extracted and transported to a power station, it must be converted into electricity, but only a portion of the primary energy embodied in the coal can be successfully converted into electricity. The conversion efficiency depends on the type/quality of coal used, and on the efficiency of the power-plant. For new black-coal fired stations, conversion efficiency approaches 40%, so over half of the primary energy embodied in the coal is lost in the conversion to electricity. The final stage is the transmission of electricity generated at the power station to appliances in the household. Losses in transmission are generally less than 10%, but depend on numerous factors, such as transmission voltage and transmission distance. As Figure 1.2 demonstrates, the amount of energy (in the form of electricity) available to a household is only a fraction (in Australia, less than $\frac{1}{3}$) of the total used in the whole energy chain.

Note that while I have used coal→in-dwelling electricity as an example, the same terminology can be applied in other circumstances. In particular, for petroleum spirit (henceforth 'petrol')

[2]Note that some power generation methods, such as electricity generating windmills, have no tangible 'fuel', and so primary energy is not easily defined. At present, it makes little difference how such unconventional sources are treated, as they currently provide less than 3% of Australia's stationary energy (Australian Greenhouse Office, 2007, page 16). However, possible future changes in energy generation technology, such as a shift from coal→wind, or a move to distributed power generation, need to be considered.

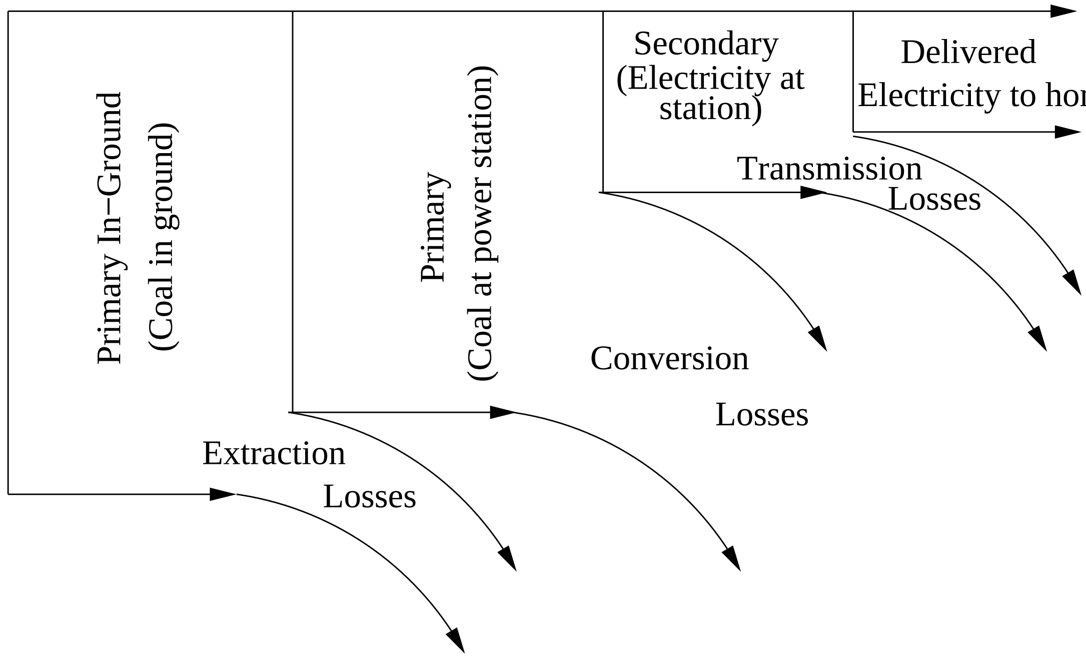


Figure 1.2: Energy chain for conversion of coal to delivered (in-dwelling) electricity

burnt in a car's internal combustion engine, extraction costs are obvious (discovery and development of oil fields, and pumping/extraction energy), conversion costs are the energy costs of converting the crude oil into petrol, and transmission costs are the energy cost required to get the petrol from the refinery to the petrol tank.

The appropriate measure of energy is context dependent. In an analysis of household in-dwelling energy use, the most appropriate measure, for the purposes of understanding household behaviour, may be delivered in-dwelling energy. On the other hand, if one is concerned with greenhouse gas emissions, primary energy is more appropriate, as this can be easily converted into greenhouse emissions (see Section 1.4.1).

The actual unit of energy used throughout the thesis is the Joule (J). Although electricity is usually measured in kWh, this is easily converted (1 kWh converts to 3.6 MJ).

1.4.1 Energy and greenhouse gases

Consideration of the link between energy consumption and greenhouse gases is important because reduction in greenhouse gases is now often the motivation for the development of programs and policies aimed at reducing energy use. Greenhouse gases are produced via the combustion of carbon based fuels (oil, coal, and natural gas), and can be related to primary energy through the use of conversion factors for particular fuels. Table 1.1, for example, shows the conversion factors for commonly used fuels in electricity production.

While Table 1.1 lists conversion factors relevant to electricity production, other conversion factors are relevant in different settings (such as when petrol is consumed in an internal combustion engine), but details of the relevant factors used are presented in later chapters. At this stage, the

Fuel	g CO_2-e per MJ fuel primary energy
Brown Coal	92.6
Black Coal	90.7
Natural Gas	51.3
Oil/Petroleum	71.4

Table 1.1: Greenhouse emissions intensity for electricity generation by fuel type in Australia (g CO_2-e emitted per MJ of fuel primary energy). Source: Australian Greenhouse Office (2007, page 15).

reader should simply be aware that energy can be converted into greenhouse emissions (and vice versa), provided relevant conversion factors are available. The reader should also be aware that Australia generates a large proportion of its electricity ($\approx 84\%$) through coal-fired power stations (Australian Greenhouse Office, 2007, page 15).

1.5 Thesis questions, scope & framework for analysis

The broad thesis question stated on page 4 is more usefully addressed by dividing it into smaller, more specific questions. The narrowing of thesis scope, and the statement of the more specific questions which are directly addressed by this thesis, takes place in the following sections (1.5.1-1.5.3)

1.5.1 Energy use: restricted to residential transport-related and residential dwelling-related energy

If all energy use in Australia is attributed to households at the point of consumption, direct energy use by Australian households accounts for around a third of total energy use, and a similar proportion of total emissions (Australian Conservation Foundation, 2007). This energy is directly consumed by households in their dwellings (through lighting, appliances, heating & cooling, and other end uses), and through petrol consumption to meet their travel needs/wants.

Planning policy can affect household travel behaviour, as it influences where households live, the transport infrastructure available, and other characteristics of the urban environment known to affect travel behaviour. Less obviously, planning policy affects what *types* of dwellings are built, and this, in turn, is likely to affect in-dwelling energy use. In particular, embodied and heating/cooling energy is likely to change with dwelling type, as dwelling size, construction materials, and thermal properties are all strongly influenced by dwelling form. Different dwelling types may also encourage different behaviours or appliance ownership levels. There are thus good reasons to believe that planning policy can play a role in reducing household energy-use/emissions[3] in urban environments. If one includes energy embodied in cars and dwellings along with energy consumed directly in the form of petrol, electricity, and gas, total household energy use is over 40 % of total household energy use[4]. I concern myself only with these components of household energy use in

[3]To avoid continually specifying that it is both energy use *and* resulting emissions that are of interest (which makes for awkward reading), I ask that this be taken as implicit from this point. Thus, when I refer to 'the impact on energy-use', please take this as shorthand for 'the impact on energy-use, and resulting greenhouse emissions'.

[4]And a similar proportion of emissions

this thesis, as they are most likely to be affected by planning policy.

Figure 1.3 shows the proportion of primary energy used in each of the household activities considered in this thesis. This is almost identical to the scope considered in similar work by Perkins (2002)[5]. The principal point of differentiation with Perkins' work is that while Perkins compared household energy use in two specific developments (i.e. at the development scale), I undertake a metropolitan-scale analysis. This important distinction is discussed in more detail in Section 1.5.3. Despite the difference in the spatial scale of the analysis, the similar scope of Perkins' work makes it a useful comparison study.

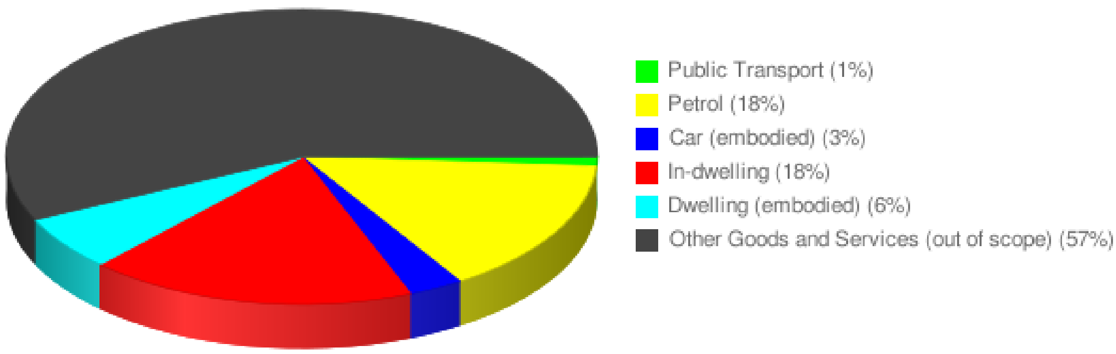


Figure 1.3: Household primary energy by end-use. Source: Author's calculations, based on Perkins (2003b), Australian Conservation Foundation (2007), and author's results from Chapters 7 and 9.

1.5.2 Planning policy: restricted to physical land-use and transport policies

A wide range of policies can be considered 'planning policy'. In this work, I will narrow my consideration of planning policy solely to physical *Land-use* policy and physical *Transport* policy. I do not consider non-physical components of these policies. For example, while I will consider the impact of residential housing development (i.e. physical land-use planning), I will not consider, in detail, the impact of road pricing or variations in public transport fares (economic transport planning).

Note also that while the aim of the analysis is to investigate the impact of physical planning policy on household energy use, planning policy is difficult to characterize directly, and so I take the common approach of instead using and analyzing structural variables that are indicative of particular planning policy approaches. Figure 1.4 shows this.

[5]Perkins also considers the energy embodied in some built infrastructure (such as roads), but this accounts for only a small proportion of primary energy use.

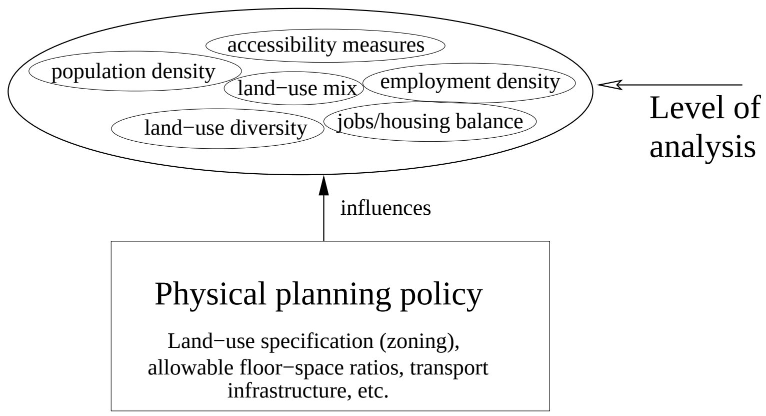


Figure 1.4: Physical planning policy and some important indicator variables linked/influenced by such policy.

1.5.3 Specific thesis questions

Now that I have restricted consideration of household energy use to transport-related and dwelling-related energy, and have furthermore restricted the nature and type of planning policies of interest, I am in a position to break down the broad thesis question ("To what extent can planning policy influence residential transport and dwelling-related energy use?") into three smaller questions which are subsumed by the broad question.

The first of these questions, which is addressed in Chapter 3, is:

Specific Question 1: Dwelling-related Energy Use

"How does dwelling type affect residential dwelling-related energy use?"

Figure 1.5 shows the analytical framework used to address this question. Land-use policy (specifically housing policy), affects the location in which new housing is built, and together with land-economic forces, determines the types of dwellings that are built. If housing policy encourages re-development in areas with high land values, for example, developers are generally only able to make a profit by developing housing that has a high ratio of habitable floor space to land area. The land-economic link between location and development intensity (i.e. dwelling-type) is well established in theory (Alonso, 1964; Mills, 1967; Muth, 1969) and practice (Alperovich, 1983; Bertaud and Malpezzi, 2003).

Given that housing policy affects both the location and dwelling type of newly constructed dwellings, one can then ask whether this has an effect on dwelling-related energy use. Dwelling related energy use can be broken down into two components: delivered in-dwelling energy; and the embodied energy in the dwelling structure itself. There has been a great deal of research into dwelling embodied energy (see Fay et al. (2000); Treloar et al. (2001b); Pullen et al. (2006)), but less (in Australia at least) on delivered in-dwelling energy use at the household level, which is surprising, given this is usually several times greater than embodied energy if one amortizes embodied energy over the lifetime of the dwelling. To give the reader some idea of the paucity of information about household energy use, the last major study of household energy end-use took place in 1994 (Pacific Power, 1994), and this study is still the source of much of what we currently 'know' about residential end-use (see Harrington and Foster (1999)). It is clear that dwelling type will affect embodied energy use, because dwellings of different types have different construction requirements, and are also typically of different sizes. It also seems plausible that dwelling type will affect in-dwelling energy use, as dwelling size and insulative properties will vary with dwelling type. The link between dwelling type and space heating/cooling energy has been the subject of many studies reporting results obtained from computer thermal simulation software (see Newton et al. (2000); Miller and Ambrose (2005) for examples), but it is still unclear how well these computer estimates of expected heating/cooling energy match with *actual* heating/cooling energy (see Williamson (2004)). Furthermore, it may be that dwelling type affects energy use in areas other than just space heating/cooling. It may be that more lighting is required in apartments, due to more limited natural lighting opportunities, or it may be that appliance sharing is less common in larger detached houses. What is clear is that the link between dwelling type and dwelling-related energy use requires further investigation[6], and this is the justification for asking specific thesis question 1.

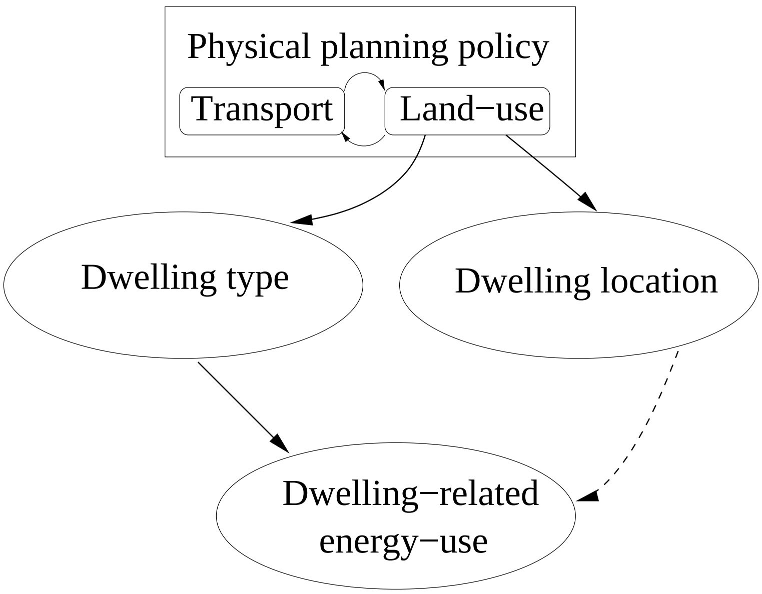


Figure 1.5: Framework for analysis in Chapter 3, for answering thesis question 1.

The second specific thesis question, addressed in Chapters 4 and 7, is:

[6]Dwelling location also affects energy use, due to intra-urban variation in climate, as indicated by the dashed link in Figure 1.5. However, in the detailed study in Section 3.3 I am unable to detect any such effect in Sydney, and, for this reason, the influence of intra-urban climate receives less attention in this thesis.

Specific Question 2: Transport-related Energy Use

"How does transport and land-use policy influence household travel behaviour (and resulting energy use)?"

Figure 1.6 shows the analytical framework used to address this question. Both land-use and transport policy affect household travel behaviour. Land-use policy affects the spatial distribution and concentration of households, the distribution of employment and other activities, which are known to affect household travel behaviour. Transport policy affects household travel behaviour by influencing travel times, determining which modes are available, and so on.

Transport and land-use policy is difficult to characterize directly, and so I rely, as already explained in Section 1.5.2, on indicator variables such as employment density, travel times, and accessibility measures, to investigate the role that planning policy might play. Such an approach is common in transport research (see Bento et al. (2003); Rodriguez et al. (2006)), however, I should note that, because the analysis relies on static (point-in-time) variables, it is not possible for me to properly investigate potentially important long-term feedback effects. The effects of transport↔land-use interaction can still be accounted for, as they become 'embedded' in static variables (such as accessibility measures and travel times), but an explicit investigation of the actual transport↔land-use interaction process is not possible. A detailed investigation of land-use↔transport interaction would require either longitudinal data, or extensive inter-urban data collection and analysis (such as in Newman and Kenworthy (1999); Geurs and van Wee (2006)), and could fill an entire thesis, (indeed, many theses). There is no possibility of conducting a full independent analysis in this thesis, given the other analysis necessary to answer the thesis questions. Some consideration *is* given to land-use/transport feedback effects in the integrated scenario modelling in Chapter 9. See, in particular, Section 9.3.

The third, and final, specific thesis question, addressed in Chapters 6-9, is:

Specific Question 3: Transport-related & Dwelling-related Energy

"How does housing location policy influence aggregate dwelling-related and transport-related household energy use?"

Figure 1.7 shows the analytical framework used to address this question. What is very different about this third question is that the spatial scale at which it is posed is broader than the first two questions, and this has important ramifications for how this question is best answered. Consider the diagram shown in Figure 1.8, which shows the different spatial scales at which analysis can operate. Question 1 (dwelling-related energy) is clearly posed at the building scale. Question 2 (transport-related energy) is at the neighbourhood and settlement scale, while question 3 (combined dwelling & transport) is at the settlement and region scale. Now, because question 3 is posed at such a coarse scale, it becomes more difficult to answer than questions 1 and 2. In question 1

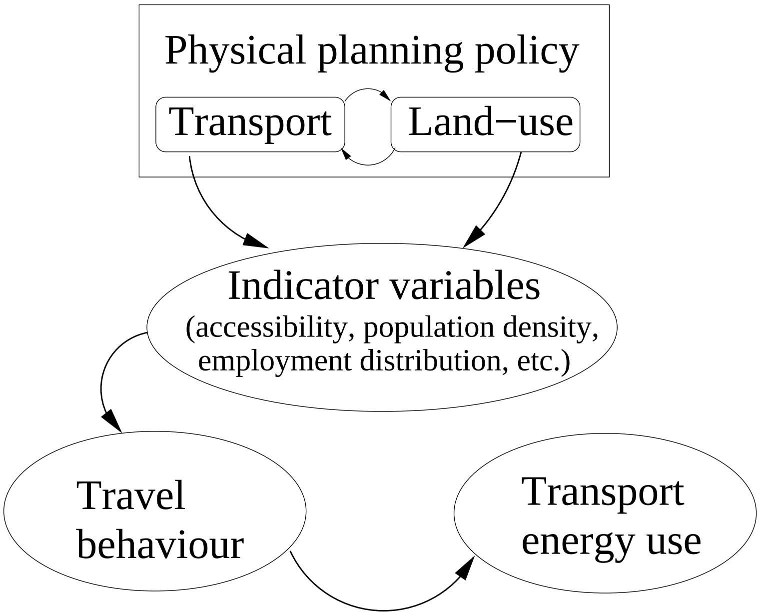


Figure 1.6: Framework for analysis in Chapter 4 and Section 7.3, for answering thesis question 2.

(at the building scale), analysis can be relatively self-contained, and can be answered by reference to data from individual dwellings (as in Treloar et al. (2000)). For question 2, this is not the case, but modelling of metropolitan scale interactions is not necessary. For example, it helps to answer the question by showing (say) that transport energy use is lower in mixed land-use neighbourhoods linked by public transport to major employment hubs than in traditional suburban developments. This does not, however, tell us all that we need to know if our aim is to investigate the role that planning policy can play. To see this, let us suppose that we know the 'answers' to thesis questions 1 and 2. Concretely, let us say that, in answer to question 1, we know that households in apartment dwellings use 20% less energy (all other things equal) than do households in detached dwellings; and, in answer to question 2, that households in urban hubs/centres use 20% less transport energy than those in traditional suburbs. This is useful, but still leaves us with many unanswered questions, such as:

- How many attached dwellings can be realistically built, given available development sites?
- Where can they be built, given land-economic constraints and household location preferences?
- Will households be willing to live in them? Which households?

These are all metropolitan-scale issues. The difficulty is that, even if we know the impact of certain decisions when all other things are equal, it is never the case that we are able to hold all other things equal in a dynamic functioning city, and planning decisions based on static analyses can have unintended consequences. Figure 1.9 outlines just one example of the difficulty in predicting the energy use consequences of a particular action. The difficulty in anticipating the consequences of the original action (re-development of a suburban area into a high-density centre/hub with

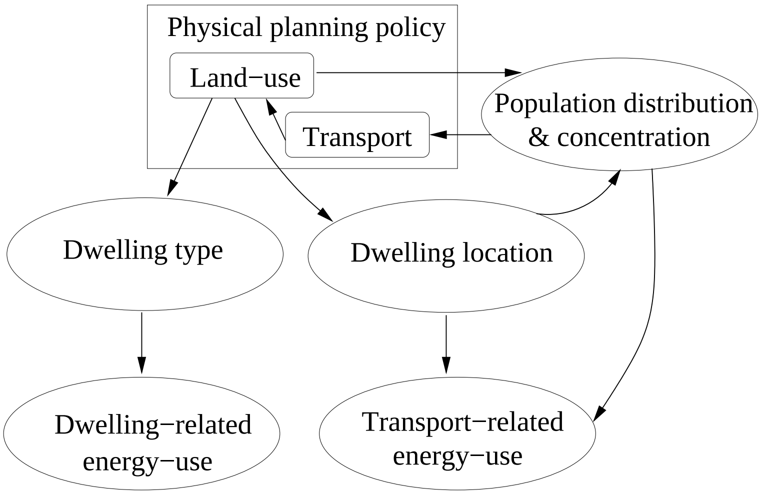


Figure 1.7: Framework for analysis in Chapters 6-9, for answering thesis question 3.

many apartments) arises from the fact that *households are mobile*. We cannot hold households in place and change their dwelling or the character of their neighbourhood and expect no reaction. It is very difficult to say what effect the original action will have without taking account of this intra-urban re-arrangement. Will the households that leave the area for other suburbs increase their energy use as a consequence of the move? By how much? To what extent will this offset the reduction in energy use of those households moving into the area? How palatable will the urban citizenry find such re-development? *These are metropolitan scale questions*. If the real question we are interested in is the impact of metropolitan-scale planning policy on household energy use, then it becomes important to conduct a detailed, metropolitan scale investigation. This is the approach taken to answering the third thesis question. Specifically, I develop a disaggregate (household-level) micro-simulation model capable of evaluating metropolitan scale housing policy scenarios. I then use this to investigate the city-wide impacts of different scenarios for the city of Sydney, Australia. Further justification for adopting a micro-simulation approach, and developing a new model (rather than re-using existing models), is given in Chapter 6.

1.6 The Contribution of this thesis

In the process of attempting to answer the three specific thesis questions, this thesis makes five notable contributions to the field. Each of these is discussed separately, below.

1.6.1 Contribution 1: specific analysis of the link between dwelling type and energy use

Answering the first specific thesis question requires new analysis of the link between dwelling-type and in-dwelling energy use, which must then by synthesized with existing research on dwelling-related energy use (embodied and in-dwelling). This is required because there is very limited information available on this topic. Combining new analysis with existing research provides a

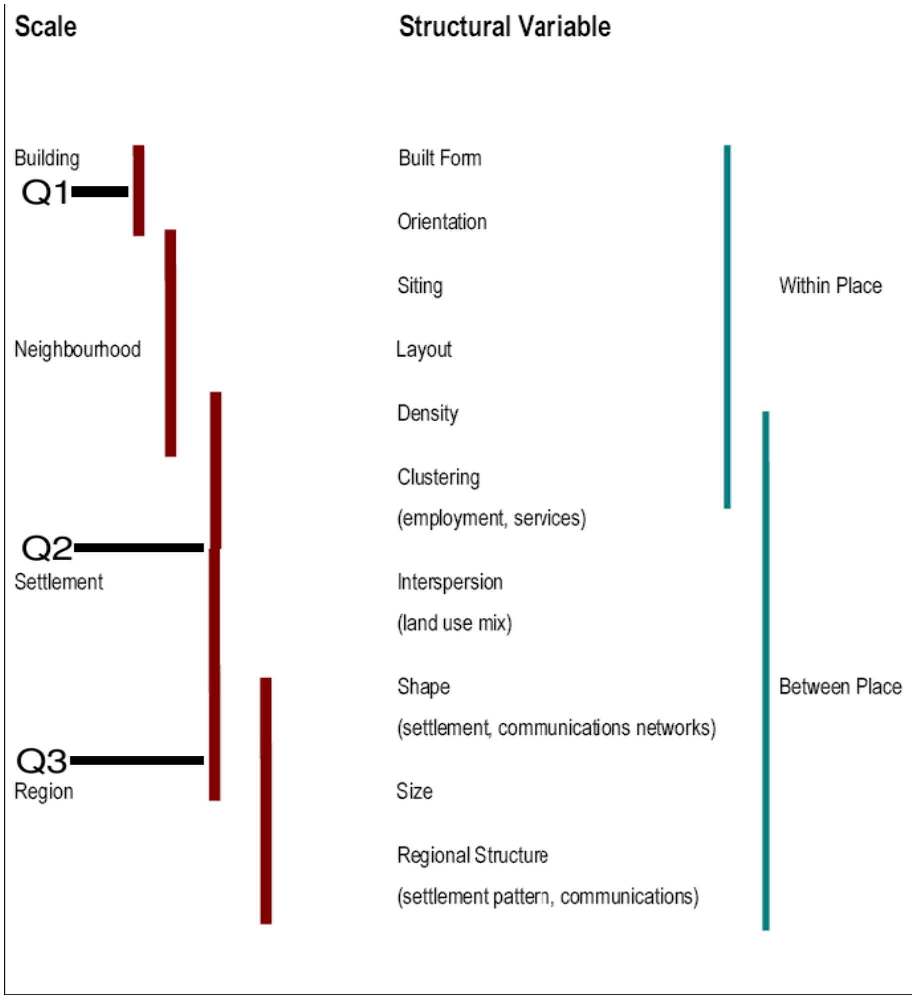


Figure 1.8: From Perkins (2002, page 3), adapted from Owens and Cope (1992).

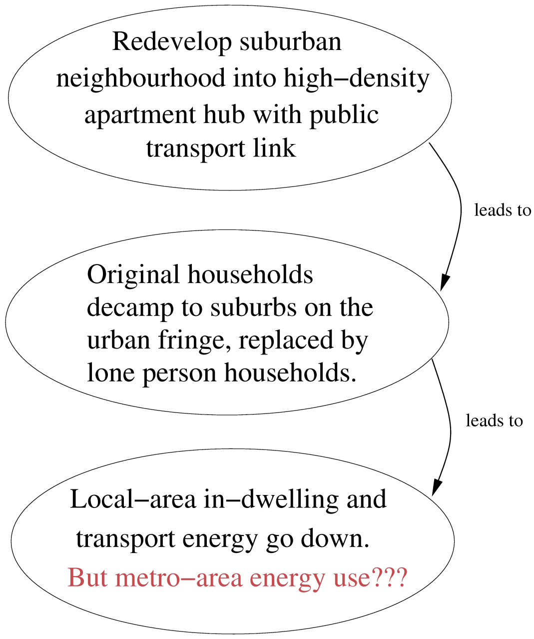


Figure 1.9: Unknown consequences from policy based on known effects

more complete picture of the influence that dwelling-type has on in-dwelling energy use. This represents an important contribution.

1.6.2 Contribution 2: specific analyses of factors influencing urban household travel

There is a large body of existing research into the factors influencing urban household travel behaviour (and associated energy use/emissions). This thesis contributes to this body of knowledge by adopting three different approaches to analyze household travel behaviour in Australian cities. Chapter 4 contains an analysis of mode choice in the mainland Australian state capitals using spatially aggregate data (Section 4.2); an analysis of mode choice in Sydney specifically using disaggregate data (Section 4.3); and a mathematical analysis of the link between urban structure and vehicle travel using computational geometry (Section 4.4). Chapter 7 also contains a detailed disaggregate (household-level) model of travel behaviour, including household car-ownership and vehicle travel models (Section 7.3).

1.6.3 Contribution 3: development of a model for integrated metropolitan-scale analysis

In order to answer the third question posed in this thesis, a method of analysis must be chosen. Chapter 6 discusses the possible methods that can be adopted, describes the method actually adopted, and provides reasons for the choice made. For the moment, let it suffice to say that a microsimulation model is chosen. However, existing microsimulation models are deemed unsuitable, for two main reasons; firstly, aspects of the usual approach to modelling residential location

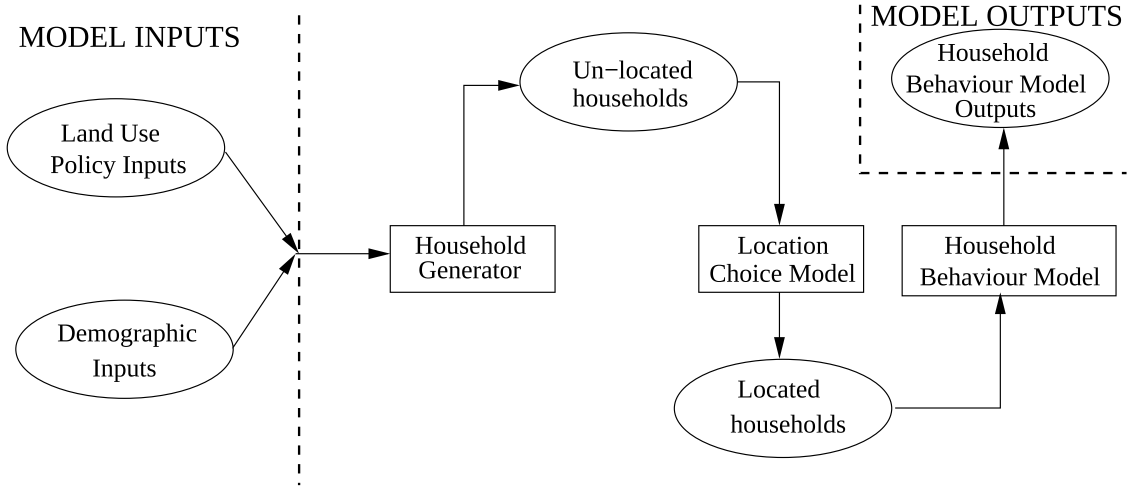


Figure 1.10: The core model structure. The core model is designed to be easy portable, and so requires only generally available data for calibration. Analysis-specific household behaviour models are attached as required, depending on available data and the outputs of interest. Chapters 7 and 8 provide details of how this is done.

choice seemed questionable, so a new approach was developed (see Chapter 5); secondly, most of the complex microsimulation models require such extensive calibration and data collection that they cannot be applied.

I have developed a microsimulation model that uses less data than other models, and so is more broadly applicable. The model structure is not specific to any metropolitan area. Nor does it dictate the output variables relating to household behaviour that must be modelled; they can, in principle, be economic, social, or environmental. In this thesis, however, Sydney is the principal city selected for analysis, and energy use and greenhouse gases are chosen as the output variables of interest.

The core structure of the model developed in this thesis is shown in Figure 1.10. The model itself is developed and explained in detail in Chapters 7 & 8, but Figure 1.10 shows the essential structure: policy and demographic inputs are required from the user, which are used to determine the location, and demographic characteristics of households (i.e. what households live where), and this information can be fed into a range household behaviour models. In this thesis, the household behaviour models are related to energy use, and determine how many cars each household owns, how much they drive, how much in-dwelling energy they use, and so on.

Note that as it stands, the model is restricted to evaluating the effects, on households, of changes to residential housing policy on households, given changing population demographics (i.e. changing number of households, changing household income distributions, changing household composition). The model could be further extended to consider other effects, or accept other data inputs (e.g. employment locations), and would make an interesting subject for future research and model development.

The household behaviour models that are attached to the core model can be estimated and attached to the core model structure in a flexible way, allowing for them to be developed to a level of complexity suitable given the purpose of the analysis, and data at hand. This additional flexibility comes at some cost, as it puts limits on the general complexity of the model. Similarly, the relatively simple structure of the core model itself limits the depths to which simulation can be taken. However, I felt that the intermediate ground, between heavy weight models such as RAMBLAS (Veldhuisen et al., 2000) and Urbansim (Waddell, 2002), and simpler statistical/descriptive studies (such as employed in Newman and Kenworthy (1989); Bento et al. (2003); Brown et al. (2008)), has been inadequately explored.

Because the model structure itself is part of the intended contribution of this thesis, a freely available software implementation of the model, with source code, is provided in a CD attached to this thesis (see appendix A).

1.6.4 Contribution 4: developing a novel model of housing choice that can be easily calibrated using census data

The most significant technical/analytical contribution of this thesis is the novel method of estimating residential housing preferences described in Chapter 5. A model of residential choice using the technique developed in Chapter 5 is at the heart of the overall integrated model (see Figure 1.10). The technique developed to estimate residential choice is a significant contribution to the field of choice modelling in its own right, as it allows the estimation of a spatially fine-grained choice model using only widely available census data, and is thus likely to have applications in other areas.

1.6.5 Contribution 5: application of the integrated model to estimating combined transport/dwelling-related energy use in Sydney

The final contribution made by this thesis is to apply the new integrated model that is developed (Contributions 3 & 4) to a concrete analysis of different policy scenarios for the city of Sydney. This both demonstrates the potential and applicability of the integrated model, and provides results which help to answer the question: "How does housing location policy influence aggregate dwelling-related and transport-related household energy use?".

1.7 Structure of this thesis

The structure of this thesis is shown in Figure 1.11. Chapter 2 contains a broad review of the literature, and Chapters 3 and 4 contain detailed analysis aimed at answering thesis questions 1 and 2, respectively. Chapters 5-8 then lay the foundation for the integrated modelling that takes place in Chapter 9. Together, these chapters address thesis question 3. Chapter 10 summarizes the main findings of the thesis, and contains some summary discussion and conclusions.

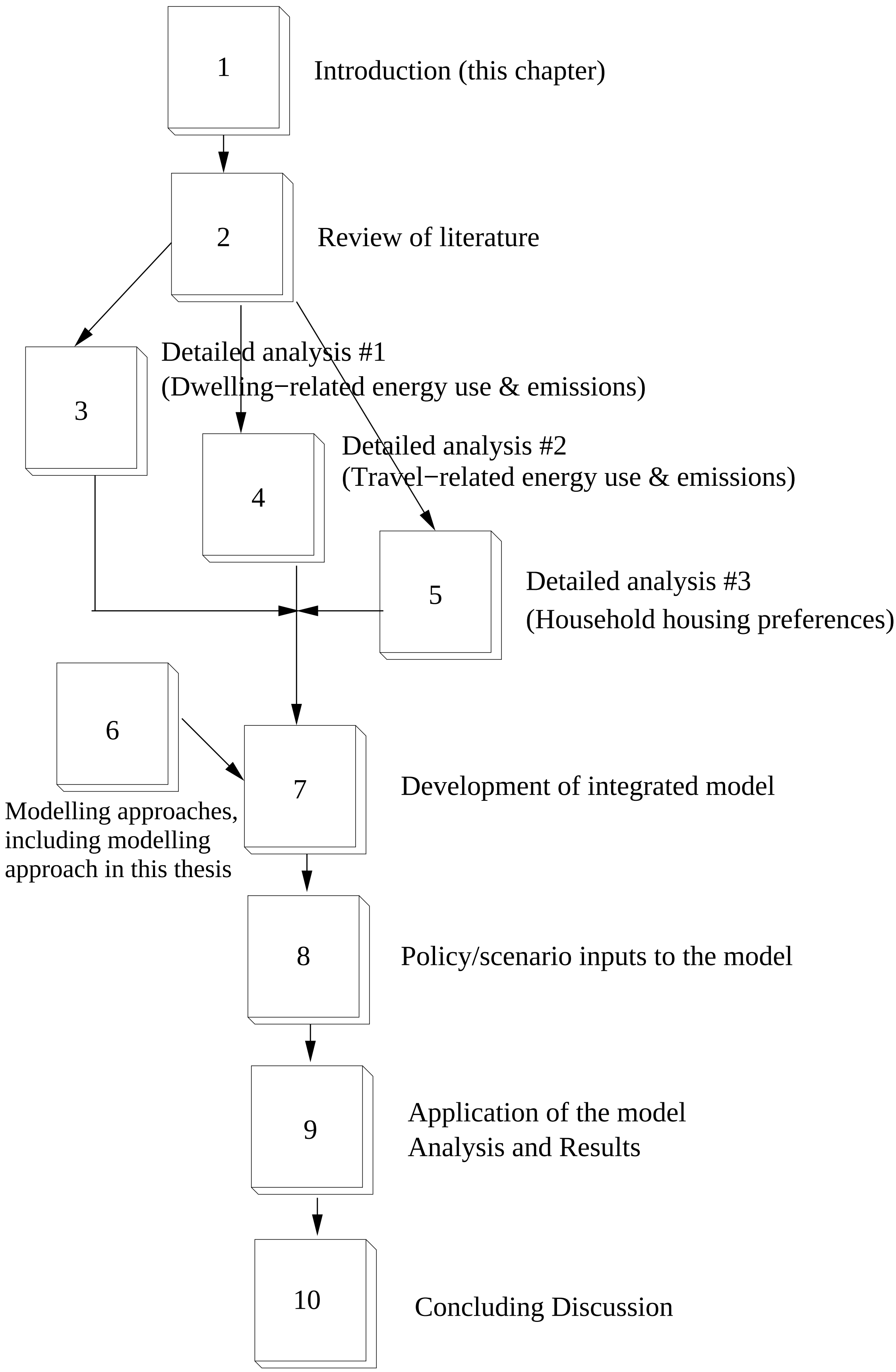


Figure 1.11: Structure of this thesis

1.8 Thesis setting – Sydney, Australia

Some readers of this thesis may not be familiar with the geography of Sydney. As Sydney is analysed extensively in this thesis, some familiarity with Sydney and its geography is required.

Figure 1.12 shows an aerial photograph of the Sydney area, home to over 4 million people. Some suburb/place names are also shown for the readers reference, as intra-urban locations are sometimes referred to specifically.

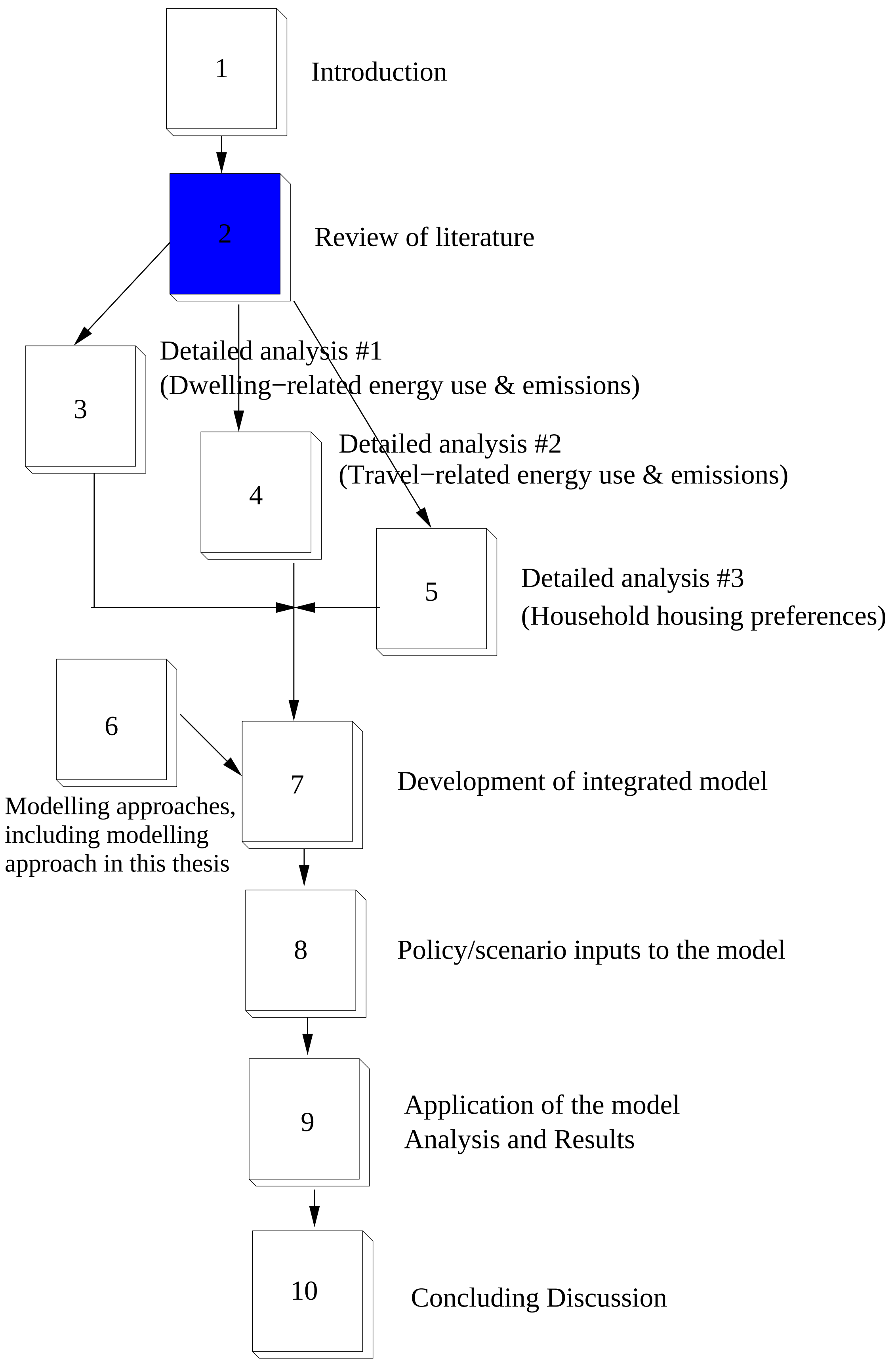
Some of the analysis, and most of the reporting in this thesis is conducted using spatially aggregated zones, and the zones comprising the study region are shown in Figure 1.13. These zones cover most of the urbanized area of the Sydney basin.

Figure 1.12: The region of the Sydney basin under study. The semi-transparent white box shows the broad area of interest.

Figure 1.13: The Sydney region and its partition into zones. Most analysis in this thesis takes place at the zone level (based mostly on, but not exactly equivalent to, the travel zones used by the NSW Transport Data Centre). Note in particular that some land areas are within the broad study region (Figure 1.12), but are excluded from analysis as they cover army bases, national parks, and the like.

Chapter 2

Review of Literature


1
Introduction
2
Review of literature
3
Detailed analysis #1
(Dwelling−related energy use & emissions)
4
Detailed analysis #2
(Travel−related energy use & emissions)
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Detailed analysis #3
(Household housing preferences)
6
Modelling approaches,
including modelling
approach in this thesis
7
Development of integrated model
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Policy/scenario inputs to the model
9
Application of the model
Analysis and Results
10
Concluding Discussion

2.1 Scope of the literature review

This literature review summarises the research to date on urban structure and energy use (especially in an Australian context). The review identifies knowledge gaps and points to areas where more research is needed.

A review paper based heavily on the contents of this chapter has been published as:

> Rickwood, P., Glazebrook, G., and Searle, G. (2008). Urban structure and energy – a review. *Urban Policy and Research*, 26(1):57–81.

To avoid repetition, some additional material not covered in this review is covered later, in Chapters 3 and 4. For example, the broad review of transport literature in this chapter is mainly concerned with the most basic measure of urban structure (i.e. density), on the basis that this is (still) the most readily available and widely used measure. To supplement this, a discussion and review of the relevant literature on travel behaviour in relation to more complex land use variables is included in Chapter 4.

The following section covers general literature pertaining to energy use, but does include a review of different modelling/simulation approaches to modelling urban energy use. Consideration of the benefits of various approaches is postponed to Chapter 6, prior to the development of the model structure used in this thesis. Subsequent chapters with supporting analysis on in-dwelling (Chapter 3) and transport (Chapter 4) energy use also allow for some additional consideration of published research, because of their narrower focus.

2.2 Introduction

> If the energy used to make building materials and the energy used for travelling from home to employment and shopping are added to the equation, the design and planning of the built environment probably accounts for more than three quarters of all fossil fuel use.
>
> Vale and Vale (1993, page 94)

Climate models predicting global warming attributable to anthropogenic greenhouse gas emissions (Barnett et al., 2005; IPCC, 2001, 2007) are now generally accepted, both scientifically and politically, and debate 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; Springer and Varilek, 2004; Kolstada, 2005).

If attention is restricted to energy[1] consumed by the domestic sector, and we consider the

[1] In this review, I discuss operational energy, primary energy, and greenhouse gas emissions attributable to energy use. It is assumed that readers are aware of the relationship between these measures.

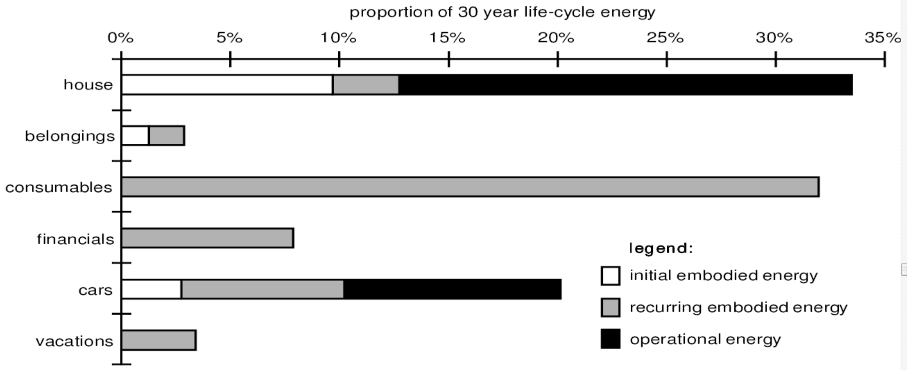


Figure 2.1: The proportion of primary energy consumed in different activities for a chosen Australian household (see Treloar et al. (2000)).

life-cycle energy[2] attributable to particular activities, we see that housing and transport related energy use together account for over half of the energy use of a typical household[3] (see Figure 2.1). 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 (Tucker et al., 1993; Schipper et al., 1996) confirm the importance of the home as a significant 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 task. This is largely 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 outside the chosen restricted scope.

The existence of a link between land-use and transport 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 most 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]. Good reviews of the research on urban consolidation

[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 2.1 is very short (50-100 years is more common), and so embodied energy in dwellings is likely over-emphasised.

[4] I am 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 this review is restricted primarily to discussing

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 research in this area (such as Office of the Environment (1993)). But as noted by Perkins (2003a), there are few examples of contemporary research such as Perkins (2002); Troy et al. (2003) and Brown et al. (2008), which attempt to analyse the relationship between urban planning and *both* transport and residential energy, and nothing that amounts to a comprehensive analysis. 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, we must consider energy use related to both housing and transport[5]. The important thing to note of energy used in dwellings and transportation is that they are strongly influenced by urban and transport 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 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.

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.). In this context, there are two important relationships that must be better understood if urban planning is to be used as a tool for reducing energy consumption:

1. The relationship between dwelling characteristics and in-dwelling energy use;

2. The relationship between urban structure and transport-related energy use.

It is these relationships that I focus on in this review. I 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.

I 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 Section 2.5.

2.3 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 delivered *in-dwelling* energy: the energy consumed within the building shell during its lifetime for heating/cooling, cooking,

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 (Bernick and Cervero, 1997; Newman and Kenworthy, 1999).

[5]Reduction of energy attributable to consumables must also play a role, clearly, but I 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.

electrical appliances, and so on. The two are not independent, that is, one can almost always achieve a reduction in in-dwelling 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 in-dwelling 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. I 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.

2.3.1 Embodied energy in residential buildings

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 in-dwelling 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). It is regrettable 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 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. (2001a) found that total embodied energy per square metre of floor area building increased with height for buildings of 3 stories or more (see Figure 2.2)

Given the uncertainty associated with embodied energy analysis, the variety of methods used, and the absence of analysis for multi-storey residential buildings (Figure 2.2 is for non-residential buildings), it is difficult to compare embodied energy in detached dwellings with that in multi-storey buildings shown in Figure 2.2. 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. (2001a), so I 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,

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

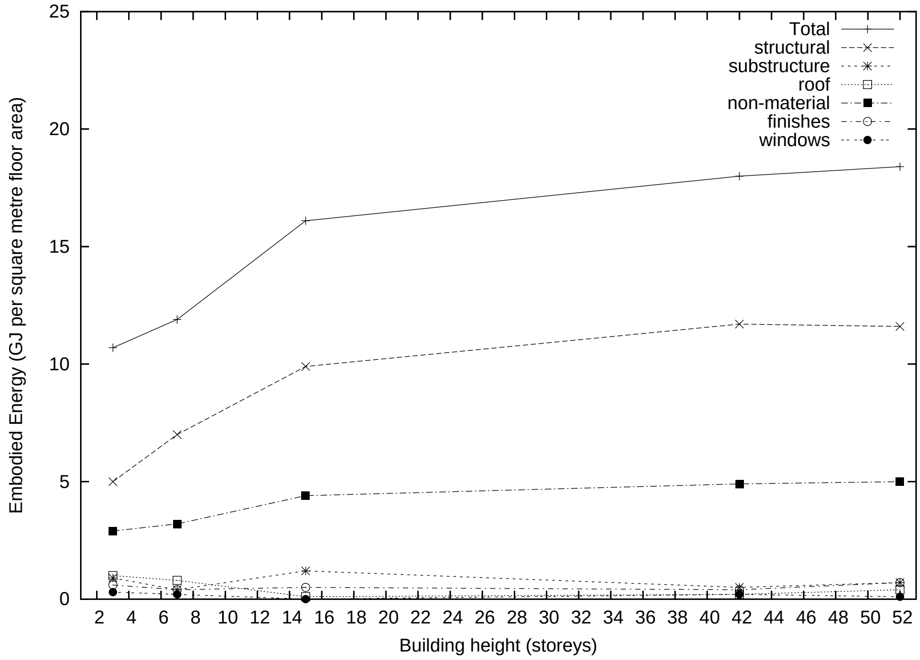


Figure 2.2: Embodied energy per square metre of floor area and building height (non-residential buildings of 3 storeys or more). Source: Treloar et al. (2001a).

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 et al. (2001a) 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 per square metre 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

[7]Based on examination of floor plans, I 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.

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 (Ladd, 1992; Gillham, 2002), 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 U-shaped.

2.3.2 In-dwelling energy consumption

The other main component of residential energy consumption is that required for on-going use. In-dwelling 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 2.3 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 'Space heat/cool' category.

However, differences in appliance energy are unlikely to be entirely an artefact of allocation errors between the two studies, since other cross-country reviews have found European countries use significantly less energy in appliances than do the U.K. and the U.S. (Schipper et al., 1996). We can see that residential energy use is dominated by space heating/cooling, and the effect of climate is large. Although space heating/cooling dominates energy use, between country differences in appliance, lighting, and water heating energy are still significant. The difference between the least energy intensive OECD country (Japan) and the most (U.S.), for example, amounts to ≈ 12 GJ per capita (Schipper et al., 1996), with U.S. non-heating energy consumption three times Japanese levels, and around twice European levels (Schipper et al., 1996).

Looking specifically at the Australian/Dutch comparison in Figure 2.3, 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. 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. 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, 2005b)), energy use for hot water in Australia could be significantly lower than the current 5 GJ/person. Figure 2.6 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

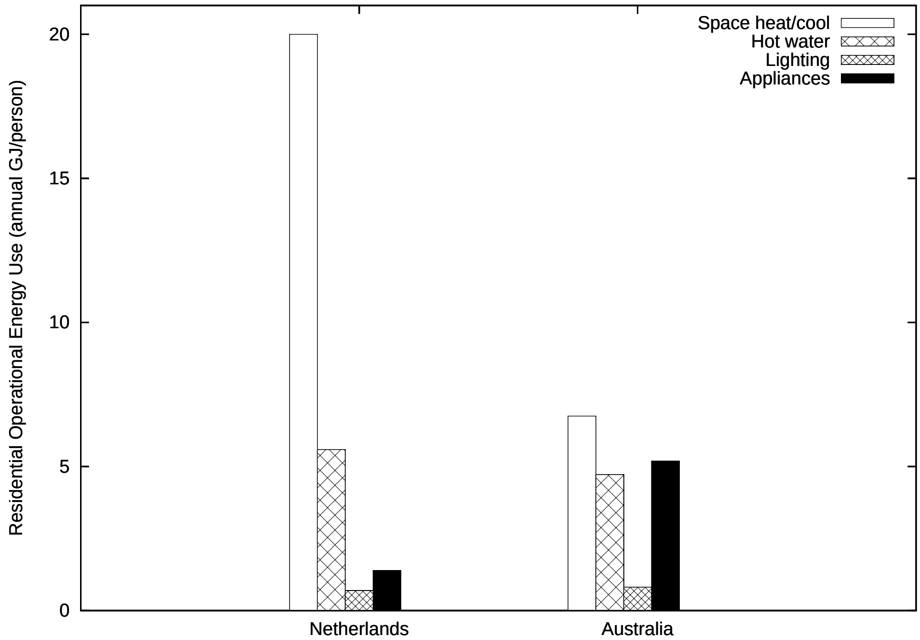


Figure 2.3: Residential in-dwelling energy consumption, Netherlands and Australia. Sources: Priemus (2005); Harrington and Foster (1999)

building audits in Myors et al. (2005) and reproduced in Figures 2.4 and 2.5, indicate how unclear the overall picture on in-dwelling energy use (as it relates to dwelling type) is. In this study, semi-detached and low-rise apartments had lower CO_2 emissions per dwelling than either detached dwellings or high-rise apartments (Figure 2.4), but that 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 2.5). 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, I 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 2.6 and 2.7 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 2.4 and 2.5 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)

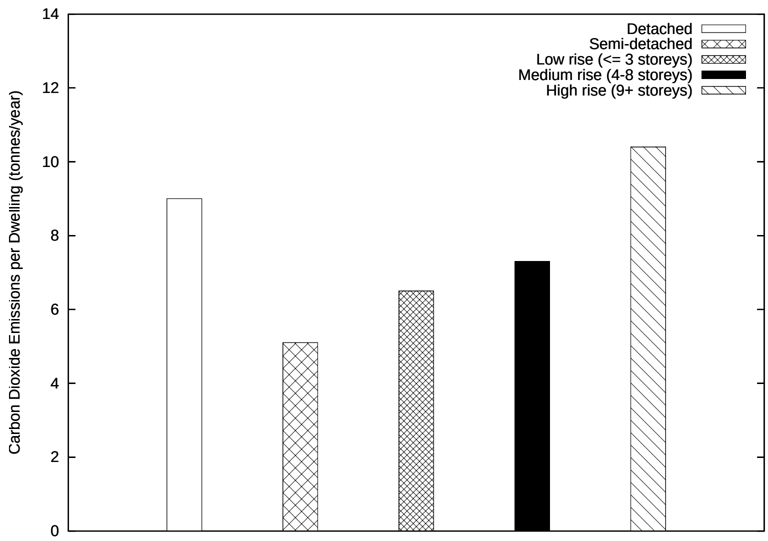


Figure 2.4: In-dwelling energy carbon dioxide emissions per dwelling, by dwelling type, from actual energy company data. Source: Myors et al. (2005).

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 2.6 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.

2.3.3 Design

It is clear that buildings differ greatly in their design and construction characteristics, and that these characteristics substantially affect both embodied and in-dwelling energy consumption. Figure 2.8 shows the effect of construction type on unconstrained average heating/cooling energy for detached dwellings[9].

[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

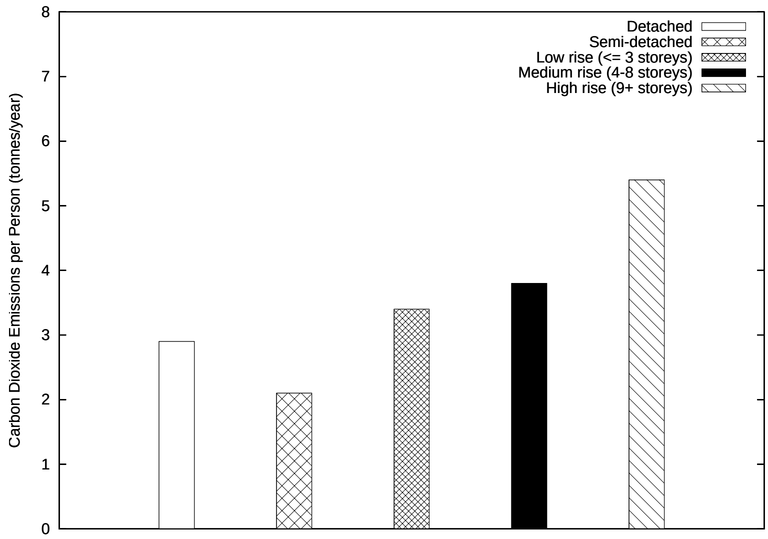


Figure 2.5: In-dwelling energy carbon dioxide emissions per person, by dwelling type, from actual energy company data, using occupancy data from the ABS 2001 census. Source: Myors et al. (2005).

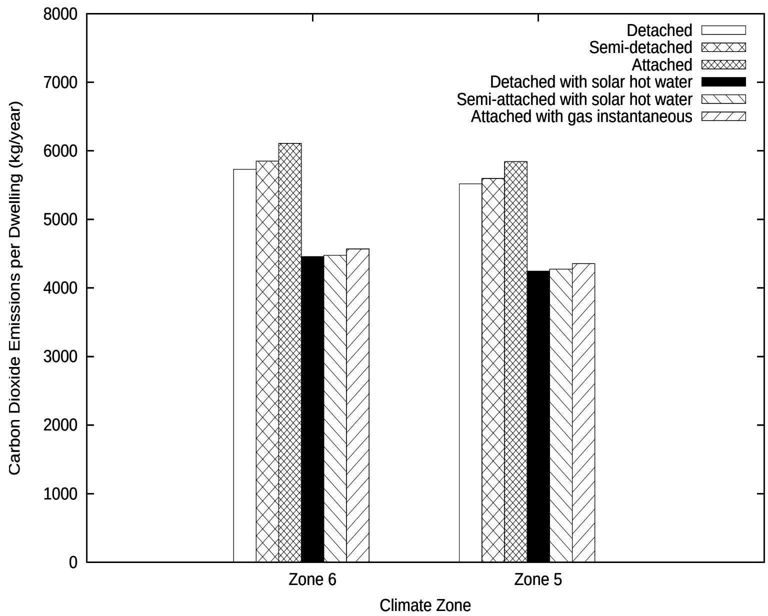


Figure 2.6: In-dwelling energy carbon dioxide emissions by dwelling type and climate zone (climate zones 5 and 6 cover coastal and non-coastal Sydney, respectively). Floor space and other parameters held constant. Source: Author's calculations using BASIX tool.

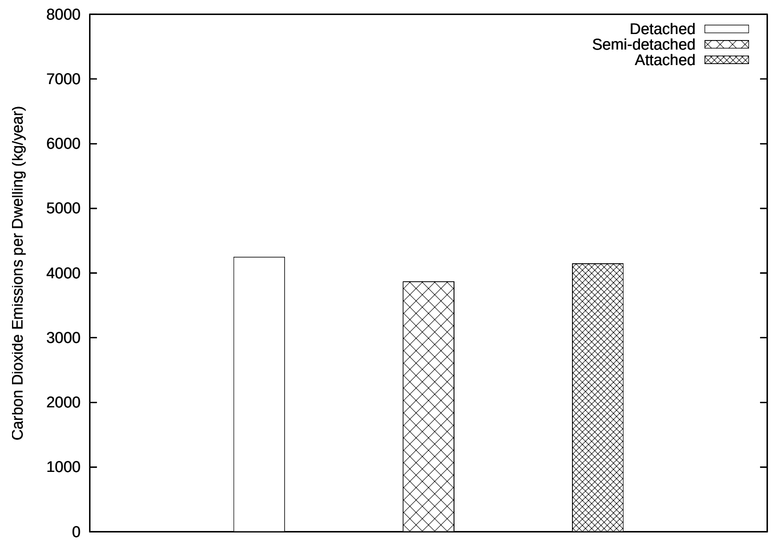


Figure 2.7: In-dwelling energy carbon dioxide emissions by dwelling type. Source: Author's calculations using BASIX tool. Note: I use a detached/townhouse/unit floor space ratio of 1.5:1:1.

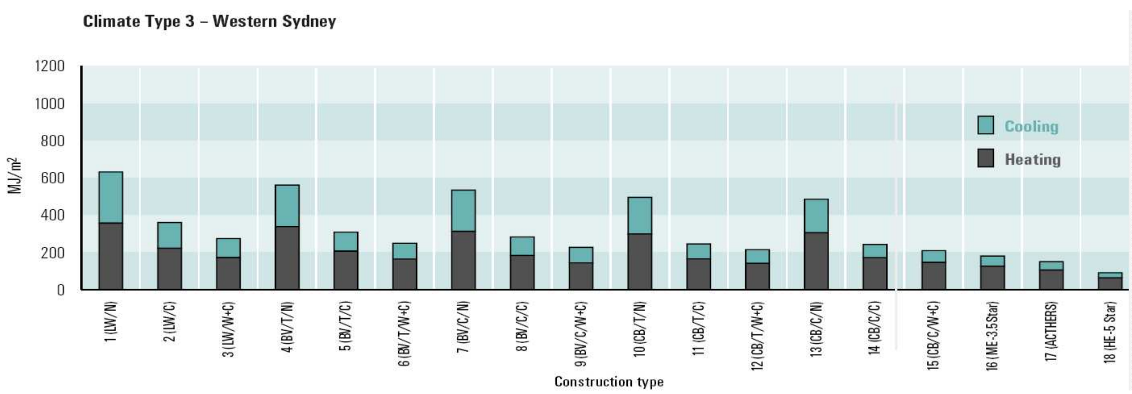


Figure 2.8: Unconstrained average heating/cooling energy required to maintain constant temperature for 18 different construction types applied to generic detached dwelling house plans, in the Western Sydney climate region. Source: Harrington and Foster (1999).

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 2.6 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. The large saving possible through low-cost insulation is particularly important, given the relatively slow turnover in housing stock. Retrofitting with just ceiling insulation would result in significant savings at very little cost. A survey in the U.K. found 71% of houses with wall cavities had the cavities unfilled, and 49% of all lofts had less than 100mm of insulation (Department of the Environment, 1995; McEvoy et al., 1999). In Australia, 40% of dwellings have no insulation at all (Australian Bureau of Statistics, 2005b).

Given that good building design can play such a large role, it is worthwhile noting that the potential for innovations in design and infrastructure seem greater for higher density dwellings. For example, the U.K. Department of Environment, Transport and Regions noted that a District Heating scheme allows space heating/cooling to become a service provided by a local substation, with much better efficiency than in-home systems (Department of the Environment, Transport, and Regions, 1998a). There is also more scope for architects and green building professionals to be involved in multi-unit design and construction, due to economies of scale. Given the importance of design and design-moderated behaviour, this may be very important.

The potential for design savings in other areas, such as appliances and water heaters, should not be ignored. In the U.K., for example, one can achieve 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, 1998b). The high turnover of some appliances and heating/cooling devices means that significant gains can be made in the near to medium term (IPCC, 1996). Since appliances typically have a much lower ratio of embodied energy to in-dwelling 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 in-dwelling energy savings (McEvoy et al., 1999).

2.3.4 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

figures reported here.

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) are likely to be taken 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.

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.

2.3.5 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-dwelling energy use is lowest, in both per dwelling and per occupant terms, in townhouse-style dwellings, and highest in high-rise apartments. Low-to-mid rise apartments have lower energy use per dwelling than detached dwellings, but, at current occupancy rates, are comparable in per-capita in-dwelling 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) in-dwelling energy use.

Given that attached dwellings are smaller, and have better thermal properties, than detached dwellings, it is striking in the limited number of existing Australian studies of in-dwelling energy use in detached/attached buildings that actual estimated savings per person are found to be at best quite small, and, in poorly designed buildings, non-existent (Myors et al., 2005). These results also do not conform to the results of 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 in-dwelling energy savings in attached dwellings, and current practice. Explanations for this gulf are offered by Pears (2005). In addition, it seems clear (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, I should note that there are several trends 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

[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.

a more sustainable city, it is the energy use of typical new dwellings, not average energy use in existing stock, that is most useful. More research is needed in this area.

2.4 Transport

Australian cities can still support public transport systems that are much more energy efficient than automobiles, despite being less dense than the major European and Asian cities with the most efficient public transport systems, 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, 2002b). Furthermore, public transport is found to be more energy efficient than cars across the day, even in off-peak periods (see Figure 2.9). European and wealthy Asian cities have typically higher public transport efficiency than Australian cities (Newman and Kenworthy, 1989; Schipper et al., 1992), and American cities even less so (Newman and Kenworthy, 1989; Davis and Diegel, 2006).

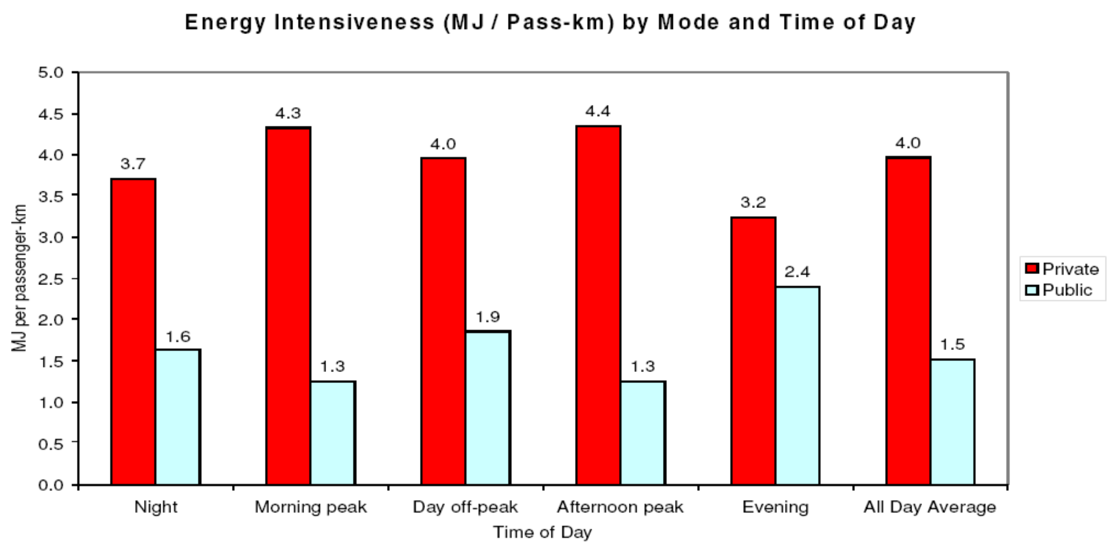


Figure 2.9: Public transport energy efficiency in Sydney, by mode and time of day. Source: Glazebrook (2002b).

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. Transport energy accounted 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, I 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. I focus on broad measures of urban form, in particular density, as this is where much

[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.

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 studied, such as neighbourhood accessibility, land use mixing and land use balance (Kockelman, 1996; Krizek, 2003; Cervero and Duncan, 2006), but have been less thoroughly debated in the literature. The notion that jobs-housing balance reduces commute travel distance, for example, is less contentious than claims about urban density.

2.4.1 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 Gordon and Richardson (1989); Gomez-Ibanez (1991); 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 I 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 Figures 2.10 & 2.11). Total energy use decreases with increasing density, despite the fact that density typically decreases the efficiency of private vehicular transport (see Figure 2.11). 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 2.11), and these factors more than outweigh possibly decreased vehicular efficiency. The first of these claims (VKT decreases with density) is most often contested. I discuss the major objections and alternate views in the following section.

2.4.2 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 the marginal effects of increasing density or providing public transport is flawed, a view shared by Badoe and Miller (2000). With this in mind, I present and critique alternate hypotheses and objections to Newman and Kenworthy's original study.

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

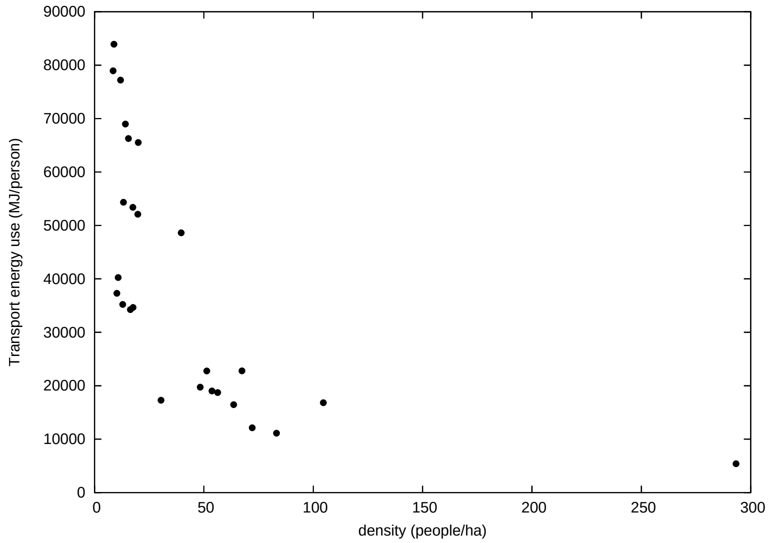


Figure 2.10: City-wide average urban density and transport energy. Source: Newman and Kenworthy (1989).

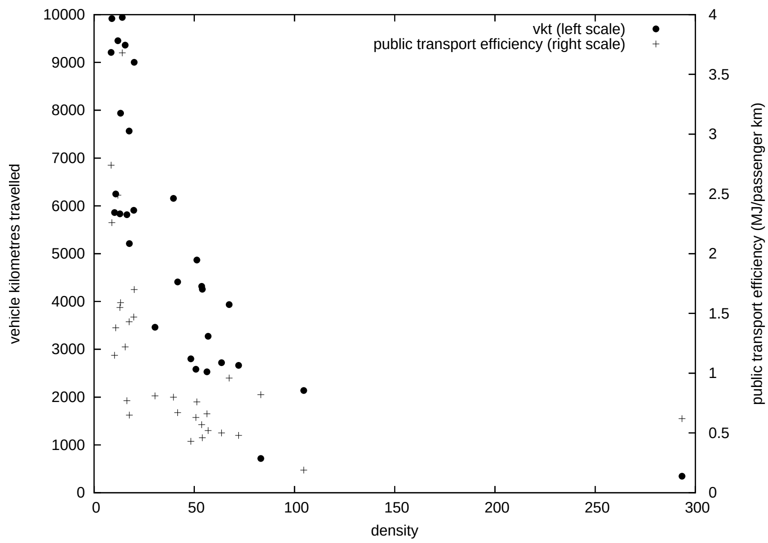


Figure 2.11: Urban density, private VKT, and public transport energy use (MJ/passenger-km) outcomes. Source: Newman and Kenworthy (1989).

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 a transportation policy tool 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 Handy (1996); Boarnet and Sarmiento (1998); Crane and Crepeau (1998); Boarnet and Crane (2001a)). 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. Kain (1992); Crane and Crepeau (1998); Bertaud (2003)), 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); Holtzclaw et al. (2002); Golob and Brownstone (2005)).

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 (Ewing et al., 2001, 2002; Holtzclaw et al., 2002; Bento et al., 2003), 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; Næss, 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

People do not locate themselves to minimise the combination of housing costs and travel costs (Hamilton and Roell, 1982), as is assumed by the classic mono-centric city model arising from the work of Alonso (1964); Mills (1967); Muth (1969). Combined with the fact that commute times are shorter in more decentralised, sprawl-type cities (Gordon et al., 1989), this has 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

[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 on numerous measures.

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 largely 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 (2004) 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 some of 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 of the road network will be more effective.

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. Since this one of the main methods advocated to reduce transport energy use (Cervero and Kockelman, 1997; Newman and Kenworthy, 1999; Cooper et al., 2001), not wholesale densification, this argument is 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 (Gordon and Richardson, 1989; Boarnet and Crane, 2001b; Bertaud, 2003).

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, though it is worth noting that almost the 'gains' made through improved engine efficiency in the past 3 decaded have not resulted in lower per-kilometre fuel consumption, as cars have become heavier and have more energy-consumping features (such as air-conditioners). 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, 2004) 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; Newman and Kenworthy, 1999; Curtis, 2006), 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; Næss, 2005; Geurs and van Wee, 2006).

2.4.3 Summary of transport-related energy use

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). The expected negative links are found between VKT and fuel price (Johansson and Schipper, 1997; Glaister and Graham, 2002; Rodriguez et al., 2006) and public transport travel times and patronage (Camagni et al., 2002). Also un-contentious is the general claim that public transport is more energy efficient than the car in all but the most unfavourable circumstances (Newman and Kenworthy, 1989; Schipper et al., 1992; Kenworthy and Laube, 1999; Lenzen, 1999; Glazebrook, 2002b).

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 and vehicle ownership (Kain, 1992; Richmond, 2001; Bertaud, 2003; Garrett, 2004; Glaeser and Kahn, 2004; Baum-Snow and Kahn, 2005). 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 I do not address here, and is doubtless the root cause for much of the antipathy toward rail by economists, it appears 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, 2007, page 16), italics mine.

Furthermore, economists 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 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 (Newman and Kenworthy, 1989; Schipper et al., 1992; Kenworthy and Laube, 1999). It is still possible to argue that density is not an important causal factor, but the common argument for the observed reduction in transport energy in densely populated cities is strong: there is a positive feedback loop between transport and land use such that public transport friendly land use (such as increased density) 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 and Gihring, 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). One of the comprehensive intra-city studies, conducted in Copenhagen by Næss (Næss, 2005) 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 (Newman and Kenworthy, 1989, 2006; Kenworthy and Laube, 1999) but also by others (Holtzclaw, 1994; Levinson and Kumar, 1997; Golob and Brownstone, 2005). Data on commute mode choice and population density in Sydney and Melbourne (see Figure 2.12) 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. Work in Rickwood and Glazebrook (2009) suggests that distance from the CBD and local area density act, together, as reasonable proxies for access provided by transit, and are both highly correlated with demographic variables that are associated with reduced private vehicle use. For example, they find a strong correlation between the proportion of households without children and local area density. Such complications are typical in any analysis of the effect of density.

2.5 Discussion

The focus of this review has been to examine the available literature on the combined residential (in-house) and transport energy use of households, on which there has been a general dearth of research. While there is some existing research that has explicitly considered combined transport/in-dwelling energy, such as Perkins (2002); Brown et al. (2008), the general lack of a large body of research on combined transport/in-dwelling energy use leads to the conclusion that, in general, not even approximate estimates of combined in-house/transport energy can be made from existing

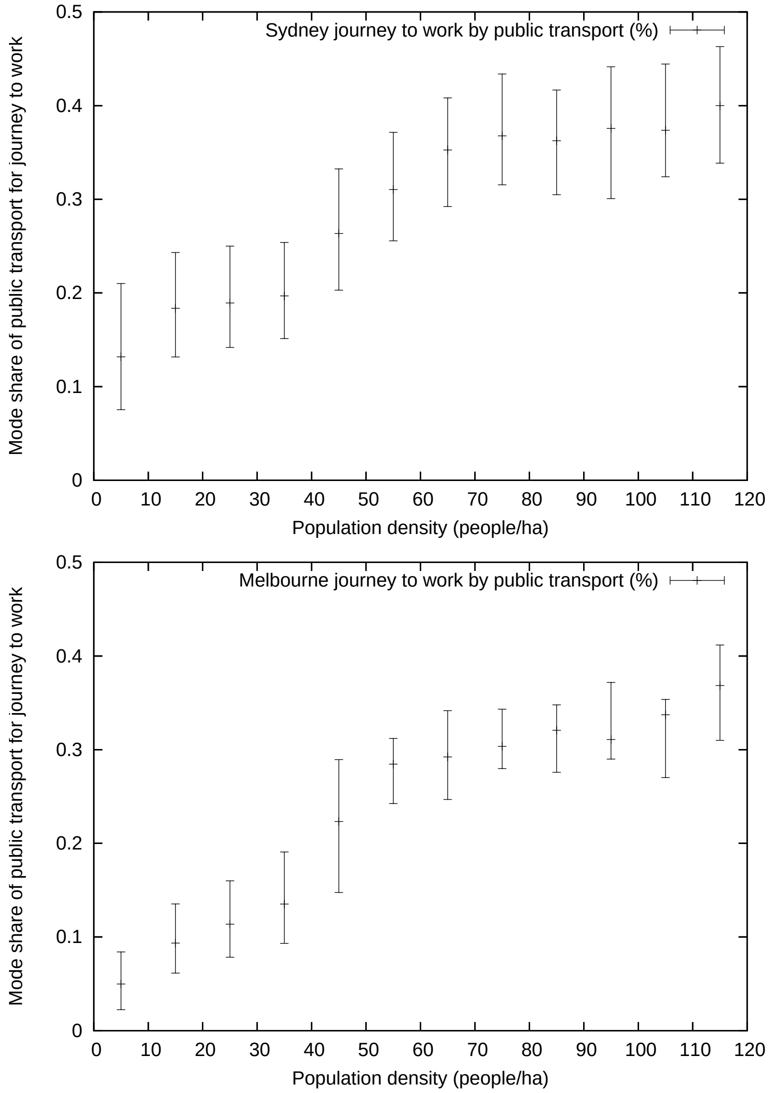


Figure 2.12: Population density and share of public transport for journey to work at ABS Collection District level in Sydney (top) and Melbourne (bottom). Median and upper/lower quartiles shown for particular density ranges. Source: Author's calculations from 2001 ABS Census data.

research.

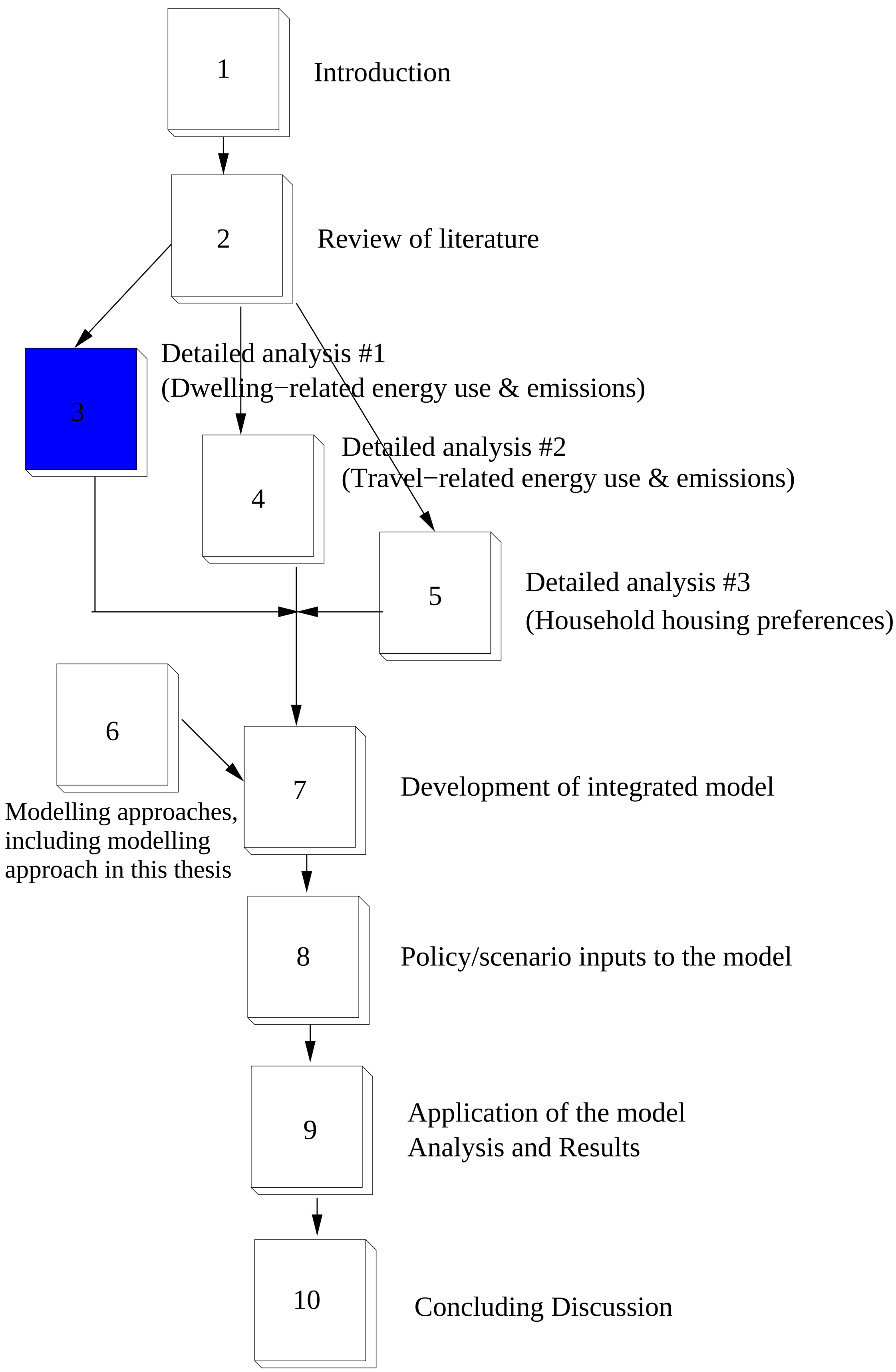
One critical issue for this review concerns the extent to which household energy use is related to urban form as opposed to other factors. As already mentioned, there are very few papers that have explored the combined residential (in-house) and transport energy use of Australian households. The pilot 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 (2003a)), 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. He concludes 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 (Holden and Norland, 2005; Geurs and van Wee, 2006). The research covered in this review 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 review 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 (Newman and Kenworthy, 1989; Kenworthy and Laube, 1999), inter-city (Levinson and Kumar, 1997; Bento et al., 2003), intra-state (Golob and Brownstone, 2005), and intra-city (Næss, 2005) 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 (Gordon et al., 1989; Ladd, 1992; Levinson and Kumar, 1997; Golob and Brownstone, 2005).

Overall, the research surveyed 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. The evidence on the high in-dwelling and embodied energy costs of high-rise buildings is 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. 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.

Chapter 3

Detailed Analysis – Dwelling-related Energy Use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3.1 Introduction

This chapter provides a more detailed consideration of energy related to private residential dwellings, including both the energy used within dwellings (for appliances, heating/cooling, and so on), and energy 'embodied' in the materials used to construct dwellings. Because this chapter relates specifically to dwelling-related energy use, it also covers some material omitted from the more general review already presented in Chapter 2.

The chapter consists of three parts. Section 3.2 reviews the current literature on dwelling-related energy use. Section 3.3 (drawing heavily on the work in Rickwood (2009)) is a study of in-dwelling energy use for households in Sydney, and Section 3.4 contains a summary discussion.

3.2 Dwelling-related energy use

This section is divided into two subsections. Subsection 3.2.1 discusses the literature on in-dwelling energy use (i.e. energy used for heating/cooling, appliances, lighting, etc.), and Subsection 3.2.2 discusses the (largely separate) literature on the energy embodied in dwelling materials.

3.2.1 In-dwelling energy use

Figure 3.1 shows the breakdown of greenhouse gas and energy used within residential dwellings by end-use in Australia. Energy use is dominated by space heating/cooling, water heating, and appliances. The split for greenhouse emissions is more even, with those activities relying solely on electricity (such as appliances, refrigeration, lighting) featuring more prominently than those with lower-greenhouse energy source alternatives. Space heating, for example, can be performed through the burning of natural gas, which has much lower greenhouse emissions per MJ of delivered energy than electricity sourced from a coal-fired power station. Figure 3.2 shows the breakdown of greenhouse emissions and energy by end use for New Zealand households, for comparison with the Australian results in Figure 3.1.

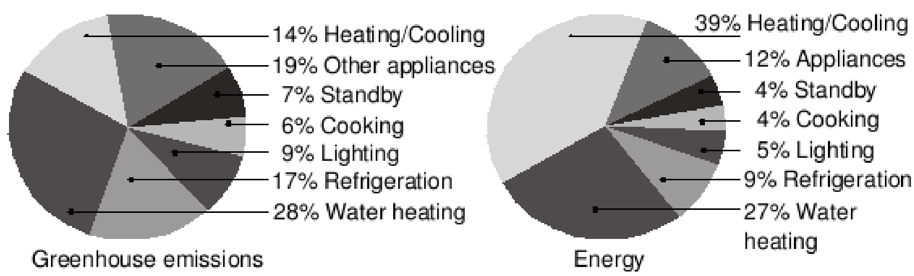
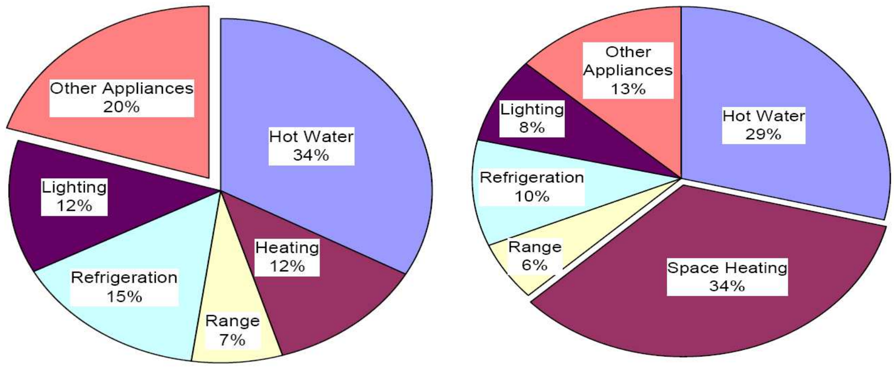


Figure 3.1: Breakdown of greenhouse emissions and energy use by end-use (average for Australian households). Source: Reardon (2005)

Information about residential energy by end-use is hard to come by, certainly in Australia, but also in most other countries, as obtaining this information generally requires appliance-level



(a) Greenhouse emissions (b) Energy use

Figure 3.2: Breakdown of greenhouse emissions and energy use by end-use in New Zealand homes. Data Source: Isaacs et al. (2006). NB: 'Range' means kitchen appliances (see Isaacs et al. (2006, page 12)).

metering, which is expensive to collect. In Australia, most of the information on residential end-use is derived from a single study by Bartels and Fiebig (2000), which relied on data originally reported in Pacific Power (1994). This data is doubtless quite out-of-date given the change in appliance energy use patterns (much larger TV's, audio-visual equipment, increased penetration of air-conditioners). The data was only collected for 290 households in New South Wales and the Australian Capital Territory, and yet has been used to produce end-use breakdowns for households in other climatic regions of Australia (Harrington and Foster, 1999). Although such a practice is questionable, there are few other options, as there little other information on appliance level end-use available. Many Australian researchers are unaware that many of the most cited sources on residential end-use energy consumption in Australia rely, crucially, on an old, and quite small, data-set, collected in a single state.

Although appliance-level data is ideal, if one wishes to obtain detailed information about household energy use, it is possible to obtain information indirectly through other means. Shimoda et al. (2004), for example, develop a model of household energy use using widely available time-use survey data for Japanese households.

It is important to note that most ($\approx 60\%$, estimated in Australian Bureau of Statistics (2006)) of the energy consumed within residential dwellings in Australia is in the form of electricity generated from power stations, with the remaining 40% made up mostly of natural gas. 84% of the electricity generated within Australian power stations is from coal, with gas-fired stations 12.2% and the remaining 3.8% comprised of hydro, wind, solar, petrol, and bio-fuel. This makes Australian electricity some of the most greenhouse-intensive in the developed world, measured in terms of greenhouse emissions per kilowatt-hour of electricity produced.

Figures 3.3 and 3.4 show household energy consumption by household size and type in Sydney, reported in NSW Independent Pricing and Regulatory Tribunal (2006). The data from this study, and from an earlier study (NSW Independent Pricing and Regulatory Tribunal, 2004), are used as the basis for the analysis in Section 3.3, and so, despite being one of the largest household samples available on the energy used in residential dwellings, is not discussed further here. There have been other recent reports on household energy use in Australia, such as Randolph and Troy (2007), but that report focused mainly on household attitudes, and did not involve analyzing metered household energy use.

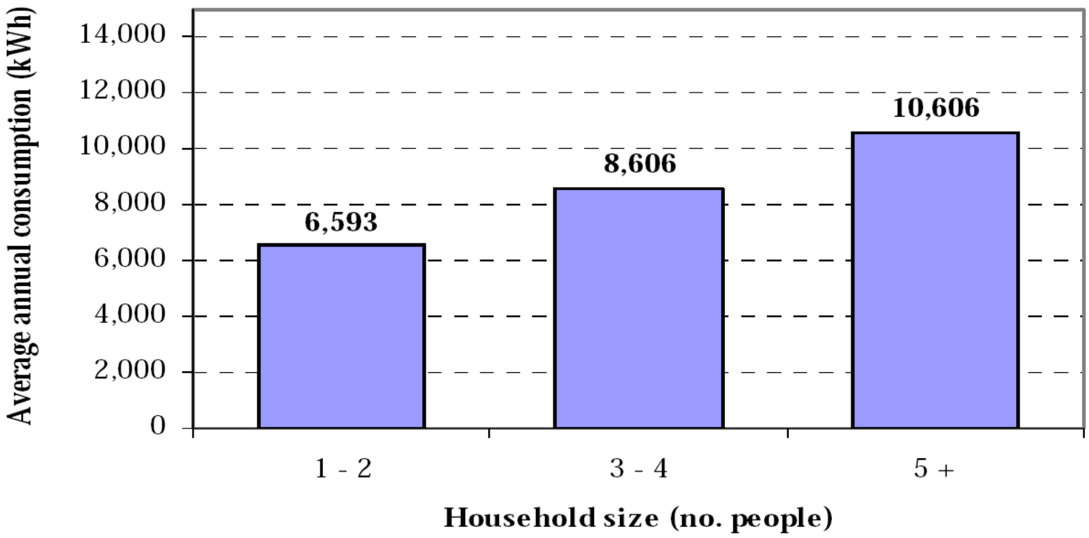


Figure 3.3: Residential energy use by household size. Source: NSW Independent Pricing and Regulatory Tribunal (2006).

Probably the most comprehensive study of residential energy use anywhere in the world is the long-running Household Energy End-use Project (HEEP) in New Zealand (Isaacs et al., 2006). Because New Zealand is culturally and economically similar to Australia, and because there is no information available for Australian households that even approaches the detail available in the HEEP study, I refer extensively to findings from the HEEP study in the following sections on in-dwelling energy use, as they are likely to be relevant in Australia (and, indeed, most other developed countries).

Key trends in appliance ownership and energy use

One of the most striking trends in Australia has been the increase in ownership (and use) of air-conditioners. In 1970, only 15% of Australian households owned air-conditioners (Energy Efficient Strategies, 2006, page 8), but this has grown to over 60% currently, and is projected to continue to increase. In the study by NSW Independent Pricing and Regulatory Tribunal (2006), 55% of Sydney/Illawarra/Newcastle households owned an air-conditioner, up from 48% just three years earlier (NSW Independent Pricing and Regulatory Tribunal, 2004), with a further 16% stating that they planned to install one. The increase in use of air-conditioners has been particularly concerning for power-generating companies, as they tend to generate high peak loads on hot summer days that power companies find more difficult to service. Increased use of air-conditioning on hot summer days, for example, has recently resulted in the summer peak energy use exceeding the previous winter peak (Myors et al., 2005).

The trend to increased ownership and use of air-conditioning is itself part of a more general

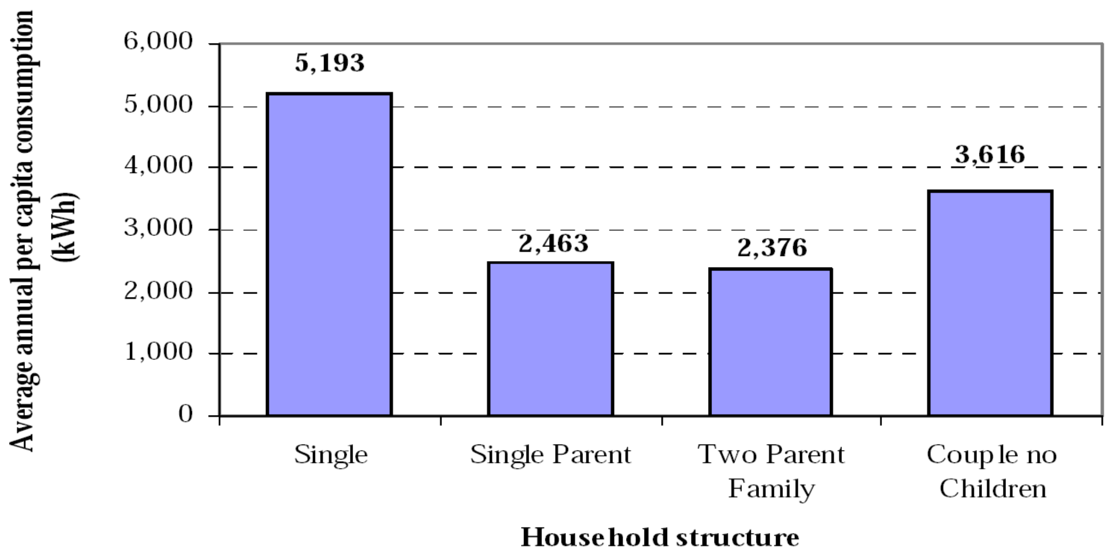


Figure 3.4: Residential energy use by household type. Source: NSW Independent Pricing and Regulatory Tribunal (2006).

trend for households to demand higher levels of thermal comfort in their homes. Both Pears (1998) and Harrington and Foster (1999) remark on this trend. There is additional corroboration for the trend from the New Zealand HEEP dataset (Isaacs et al., 2006), which reports that mean indoor temperatures have been rising at a rate of about 0.25° per decade[1] in New Zealand, and that better insulation does not translate directly into energy savings for heating/cooling, but instead is partly used to achieve higher levels of comfort. Because of the demand for increased levels of comfort, there has been a move, in most Australian states and territories, towards mandatory heating/cooling energy efficiency requirements for newly constructed dwellings. This was aided by the development of the Nationwide Housing Energy Rating Scheme (NatHERS) software (Delsante, 2000), which can calculate the heating/cooling energy required to maintain a dwelling at a particular temperature. New South Wales went further than regulating building shell construction for heating/cooling, and developed the Building Sustainability Index (BASIX), with the aim of reducing greenhouse emissions from in-dwelling energy use. Regulations accompanying BASIX require that all new residential dwellings constructed in NSW have to have energy-efficient design and/or appliances, with the aim of reducing greenhouse emissions from in-dwelling energy use by 40%. The means used to achieve this reduction is left up to developers, but achieving a 40% reduction usually requires a solar hot water system, energy-efficient lighting, and a design that allows efficient heating/cooling. It remains to be seen, however, whether the estimated savings are realized when households move into newly developed dwellings. The fact that the team originally responsible for developing and maintaining BASIX (and monitoring post-occupancy energy use in newly constructed dwellings) has been disbanded does not augur well for our ability to measure these savings.

The end-use with the fastest growth in energy consumption is appliance energy use (Harrington

[1]New Zealand's cooler climate means that increased thermal comfort in New Zealand is mostly attained through increased indoor temperature.

and Foster, 1999). This trend is evident in New Zealand also, where appliance energy has risen from 28% of household energy consumption in 1971 to 47% in 2006 (Isaacs et al., 2006, page 12). The bulk of this increase has not been related to traditional home appliances such as refrigerators, washing machines, and microwaves, that have for some time been near-universally present in Australian homes. Instead, households have increased their purchases of home faxes, audio-visual equipment, computers, scanners, dishwashers, home theatres, and other appliances formerly less common. Increasing affluence, and declining prices for consumer appliances, has allowed more households to own more appliances, and those appliances have become larger and, on the whole, require more energy, despite technology-driven efficiency gains. For example, even though older cathode-ray based televisions are less efficient than their modern LCD and plasma-screen cousins, they often require less energy than modern sets, due simply to the larger screen size of modern televisions. Similarly, computers are now more efficient (in terms of Joules per operation) than they formerly were, but because they are so much faster (i.e. they carry out more operations per second), they end up consuming more energy than the older, less efficient computers. It is little wonder that cheap appliances, coupled with cheap electricity has resulting in rapidly growing energy use from household appliances. The number and penetration of appliances (particularly home entertainment appliances) are also responsible for a significant increase in 'standby' power use – power drawn by appliances not in use. Figure 3.5 shows a breakdown of standby power use from the HEEP study in New Zealand.

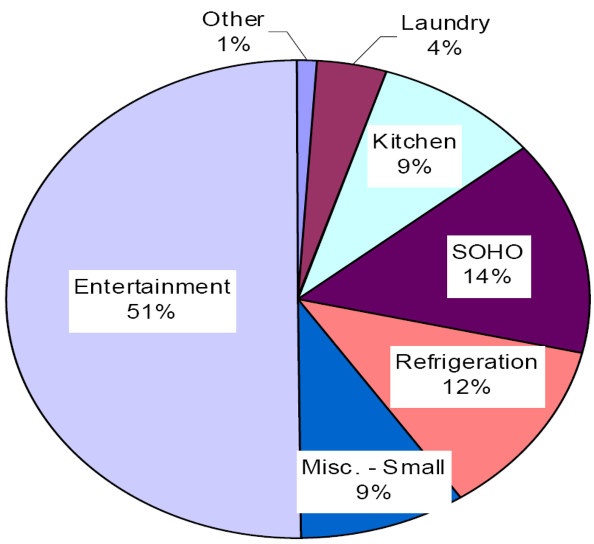


Figure 3.5: Breakdown of standby power use by appliance type. Data Source: Isaacs et al. (2006, page 61). NB: SOHO are 'home office' appliances, such as faxes and computers.

The influence of design

Thermal simulation software such as NatHERS demonstrates the potential energy savings from efficient dwelling design. Although it seems reasonable to assume that dwelling design affects energy use, there has been surprisingly little research into the link. Williamson (2004) argues against design as an important factor, claiming that variation in occupant behaviour is far more important, and that there is no demonstrable link between the heating/cooling energy predicted by thermal modelling software and the actual heating/cooling energy used. Despite the clear need for more research to demonstrate a link, it is hard to believe that more thermally efficient dwellings will not result in any savings to in-dwelling energy use. The longitudinal HEEP study found that more recently constructed houses used less heating/cooling energy than older, less well insulated houses (Isaacs et al., 2006). There is no reason to believe that this pattern is not repeated in Australia.

Ratti et al. (2005) looked at the effect of different facade styles (Mediæval, Georgian, and Modern) on energy use, and found a 10% effect from these variables alone, independent of other factors. Skinner (2006) shows that roof-top gardens can make a big difference to both general urban microclimate, but also building energy use. Related to Skinner (2006), modelling by Simpson and McPherson (1998) suggests that the tree foliage can have a significant effect in reducing residential net space heating/cooling energy use. This is important to remember when thinking about policies such as urban consolidation, because some styles of urban consolidation require the removal of urban vegetation.

Income and energy use

Figure 3.6 shows that, despite a significant economic expansion, per-capita residential energy use in Australia has only been growing slowly for some decades, and has plateaued since the year 2000. The trend is similar in New Zealand – see Figure 3.7. This suggests that the link between household income and energy use is not a strong one, and there is research to support this claim: Reiss (2005), in a study of household energy use under California's variable rate energy tariffs, found that price elasticities varied substantially by appliance type, and income by itself had no effect. Instead, the author suggests that income influences energy use in-directly by influencing appliance ownership:

> [T]he income effects are mostly statistically insignificant and negligible as a practical matter. This is not entirely surprising, given that our analysis is conditional on households' appliance stocks. To the extent that income affects electricity consumption, it is evidently through households' choices of appliances rather than through utilization behaviour.
>
> Reiss (2005, page 868)

This is consistent with prior studies finding no appliance utilization income elasticities (Parti and Parti, 1980; Dubin and McFadden, 1984). Reiss (2005) also found a lot of heterogeneity in price elasticities. He found an overall marginal price elasticity of -0.39, more or less in line with other studies, but report that this masks a huge heterogeneity at the household level. Fully 44% of California households exhibit no sensitivity to price at all! The rest range all the way up to -2.0. These elasticities do vary with income, but not much, so the heterogeneity is large even within income brackets.

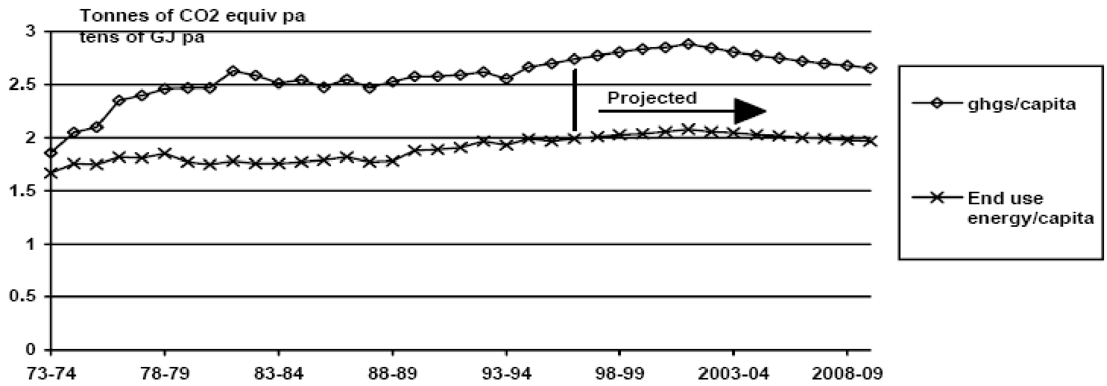


Figure 3.6: Historical trend in Australian residential in-dwelling energy use. Source: Pears (1998, page 4)

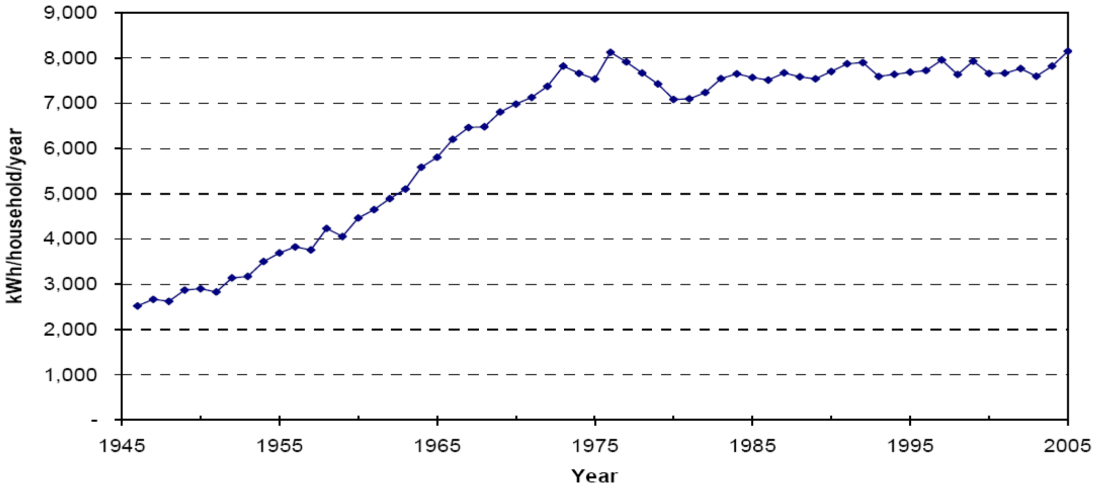


Figure 3.7: Historical trends in New Zealand residential in-dwelling energy use. Source: Isaacs et al. (2006, page 11).

3.2.2 Embodied energy in dwellings

There is a long history of research investigating the energy 'embodied' in residential buildings. Materials to be used in buildings must be extracted from the earth, manufactured variously into bricks, concrete, and steel, and then put together on-site to make a dwelling. The energy required in this manufacturing and construction process is many times greater than the energy used within a dwelling in a year. Treloar et al. (2001b) calculate that a 123 m^2 two storey house in Melbourne required $\approx$ 1800 GJ of energy to construct. Compare this with the amount of primary energy used by an average household in a year, which might be in the order of 150 GJ. Dwellings, however, last a long time, but even if one amortises the energy cost over an assumed 70-year life-span for the dwelling, the annual energy cost is still significant, at around 20% of the average in-dwelling energy consumption.

A number of different methods can be used to calculate the energy embodied in building construction, but it is beyond the scope of this thesis to review these methods. The interested reader is referred to Bullard et al. (1978)'s classification of methods for embodied energy analysis, which still serves as an accurate guide. The different approaches that can be taken in calculating embodied energy in buildings means that there is no single correct value that can be relied upon for the embodied energy content of a building. One researcher, using one approach, may calculate values substantially different from another researcher, even for an identical dwelling. Readers should bear this in mind when reading the rest of this Section, and concentrate on the findings that are consistent across different studies, rather than on the particular values (for GJ/m^2) reported.

One clear finding in embodied energy research has been that embodied energy costs increase with increased dwelling height, at least beyond three storeys (Aye et al., 1999; Treloar et al., 2001a).

For low-rise residential dwellings, where most research has taken place, Treloar et al. (2001b) report a value of 14.3 GJ/m^2 for a semi-detached Melbourne dwelling, and 14.1 GJ/m^2 for another in Fay et al. (2000). These figures included all land-scaping and appliances and the like. However, appliances are only 4% of the total, which is mostly made up of structural and basic fit-out (i.e. carpets). Thus, the actual value is likely between 13-14 GJ/m^2. Pullen et al. (2006) used an approach similar to Fay et al. (2000) to estimate the embodied energy in residential developments in Sydney. Though an IO-based hybrid approach was used, it was different to that used in Fay et al. (2000); Treloar et al. (2001a,b), and so, strictly speaking, one cannot compare them.

Table 3.1, from Pullen et al. (2006), reports embodied energy values for developments that include replacements over the lifetime of the buildings, and are average values for all dwellings in each development. Pullen et al. (2006) also calculated energy embodied in the infrastructure required to service each development (roads, piping, etc), and the results are shown in Figure 3.8. The results indicate that with the exception of roads, infrastructure items are much less important (from an embodied energy perspective) than the dwellings themselves. Figure 3.9 shows Pullen et al. (2006)'s estimate of the proportion of annual energy that is embodied, versus that delivered (i.e. in-dwelling). Notice that the embodied energy content, when amortised over the life of the dwelling, is around a quarter of the in-dwelling energy used, in close agreement with the value of 20% estimated at the start of this section on embodied energy use.

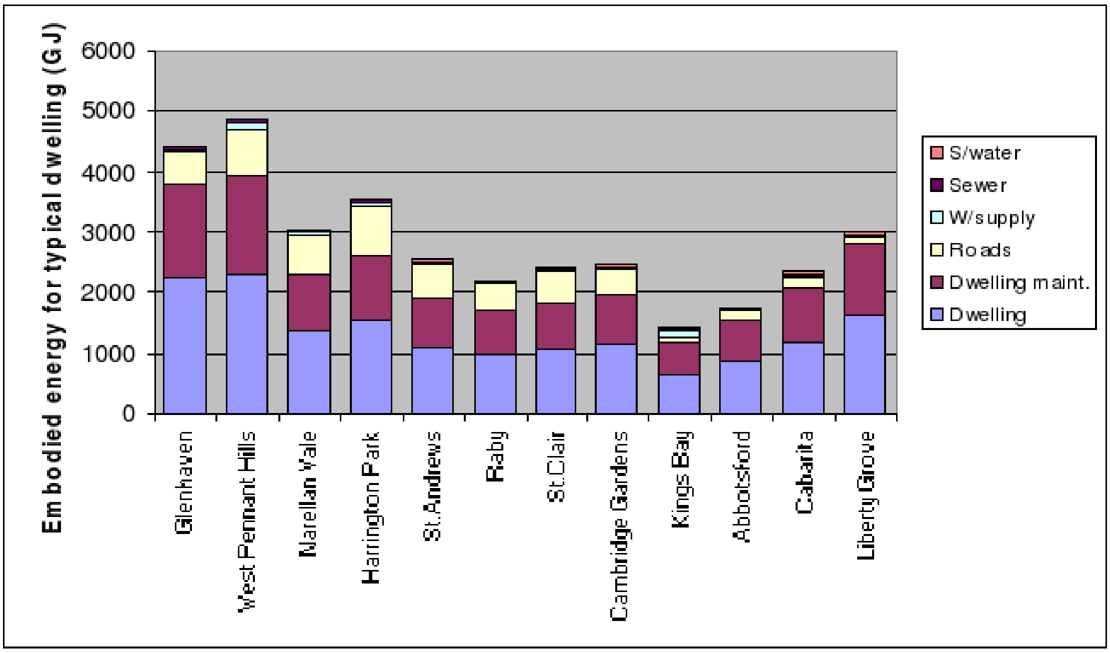


Figure 3.8: Energy embodied in residential dwellings in various Sydney suburbs. Source: Pullen et al. (2006).

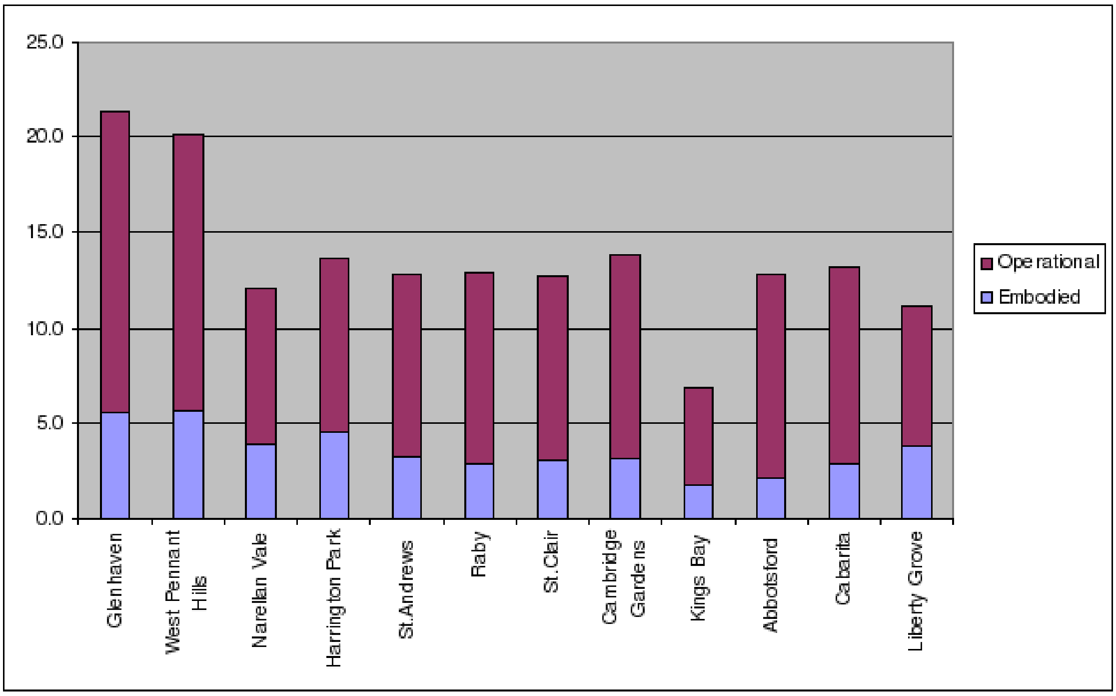


Figure 3.9: Embodied and in-dwelling energy consumption in residential dwellings in various Sydney suburbs. Source: Pullen et al. (2006).

Construction Date	Suburb	Dwelling Types	GJ/m^2
late 1980s	Glenhaven	1 and 2 storey detached	12.2
early 1990s	West Pennant Hills	1 and 2 storey detached	11.9
late 1990s	Narellan Vale	1 and 2 storey detached	11.6
late 1990s	Harrington Park	1 and 2 storey detached	11.1
early 1980s	St Andrews	1 storey detached	11.1
early 1980s	Raby	1 storey detached	11.2
late 1970s	St. Clair	1 storey detached	11.0
late 1970s	Cambridge Gardens	1 storey detached	10.9
late 1990s	Kings Bay	2-4 storey terraced and 3 storey apartments	9.6
late 1990s	Abbotsford	4 storey apartments	14.6
late 1990s	Cabarita	2-storey detached and 5 storey apartments	13.8
late 1990s	Liberty Grove	2 storey detached	11.5

Table 3.1: Embodied energy in various Sydney residential developments . Source: Pullen et al. (2006).

Another study by Newton et al. (2000) compared a 203 m^2 project home with an 88 m^2 2 bedroom apartment in a 3-level apartment complex of around 200 apartments. They found that the embodied energy per unit floor area was nearly identical for the different dwellings, reporting 5.01 GJ/m^2 for the project home and 5.06 GJ/m^2 for the apartment. Fay et al. (2002) also find that the embodied energy per square metre in apartments is roughly the same as in detached.

Ignoring the different values reported by different authors, we see that there is, stunningly, near universal agreement on the fact that embodied energy per square metre does not vary greatly for different dwelling types, assuming average/conventional construction. In other words, all the research covered here finds that *the per square metre embodied energy in a detached dwelling is similar to the per square metre energy of a terrace or low-rise apartment building.* It thus seems that, with the exception of high-rise dwellings, dwelling *size* is a far more important factor in determining embodied energy than dwelling type. Certainly, the observable variation in embodied energy per square metre *within* a particular dwelling type is larger than any potential variation *between* dwelling types.

3.2.3 Summary

While per-capita in-dwelling energy use has grown only slowly over the past few decades in Australia, this overall trend masks significant changes to the composition of household energy use. In particular, households are consuming significantly more energy through the use of appliances, and there seems little prospect of this trend abating. Similarly, the trend towards the use of air-conditioners to maintain year-round comfort levels shows no signs of abating. There is no clear evidence in the available literature on the link between in-dwelling energy use and building structure, although thermal simulation studies in Newton et al. (2000) and Miller and Ambrose (2005) suggest heating and cooling energy should be lower in attached dwellings – an effect partly attributable to the smaller size of those dwellings, and partly due to their better insulation (due to shared walls). However, there is no conclusive research of actual household energy use that demonstrates that these theoretical savings are actually achieved in practice – something which the regression analysis of household energy use in the following section aims to address. With regard to embodied energy, the picture is much clearer. Embodied energy per square metre does not vary substantially with dwelling type, with similar values per square metre for detached, terrace, townhouses, and low-rise apartments. The more important factors are dwelling size and construction materials. This is also the finding in Fuller and Treloar (2004), who examine changes to embodied and in-dwelling energy for a 'typical' Melbourne household from 1950 to today, and find that embodied energy increased significantly, primarily due to an increase in dwelling size. The only exception to the observation that per-square-metre embodied energy is more or less independent of dwelling type is that dwellings in apartment buildings more than perhaps 5-7 storeys tall do require more embodied energy per square metre.

3.3 Study of residential in-dwelling energy use in Sydney

3.3.1 Introduction

Our understanding of the household-level factors influencing residential in-dwelling energy consumption is limited by the availability of detailed household level end-use data accompanied by demographic and dwelling structure data. While studies of aggregate consumption data have provided estimates of income elasticities of demand for energy, and can even include aggregate-level demographic influences, the lack of recent Australian household-level energy consumption analyses limits our ability to predict the changes in energy consumption that are likely to result from particular planning policies, such as urban consolidation, or even from social and economic trends, such as the strong one toward increasing dwelling size. For those interested in how planning can influence energy use, this is clearly a problem. This study contributes to alleviating the problem by first reviewing existing work in the area, and then analysing three detailed household level datasets of energy use in Sydney. The datasets used are, to my knowledge, the largest used in any peer-reviewed research on household level factors influencing residential energy use in Australia.

3.3.2 Prior related work

The sheer number of studies on energy use makes it impractical to detail them all, and so only a selection of what are regarded as most relevant is covered. Research published prior to 1995 is not covered, as the well documented changes in energy use patterns, such as the trend toward air-conditioning and higher appliance-related energy use, is sufficiently strong that older research is of limited use in understanding contemporary energy use patterns. With a few exceptions, attention is focused on research into energy use in Australian households, as inter-country differences in household energy use provide limited insights due to differences in energy resource availability, prices, and social norms. A great body of work by economists and econometricians analysing aggregate energy consumption is also not reviewed, as it is of limited use in understanding household level residential energy use. While acknowledging the importance of embodied and transport-related energy consumption, this study is concerned only with in-dwelling energy use. Recent Australian reviews of the influence of urban form on both embodied and in-dwelling energy use have been provided by Bunker and Holloway (2006) and Rickwood et al. (2008), both of which highlight the need for more quantitative research to resolve some fundamental, but long-standing questions about the sustainability of different forms of urban development.

Agreeing with Perkins (2003b, page 6), I consider in-dwelling delivered (i.e. end-use) energy as the most appropriate measure for determining the effect of built form on in-dwelling energy use. Changes to fuel mix and electricity generation sources (such as coal→wind), or improvements in generation efficiency will alter household primary energy use and greenhouse gas emissions (GGEs), but are of less relevance in a planning context, as they usually occur more-or-less independently of changes to dwelling type and household structure.

Descriptive studies

Many studies have been concerned with obtaining an accurate picture of how energy is used in residential households, but stop short of a concerted attempt to determine the underlying factors driving energy use. For example, the NSW Independent Pricing and Regulatory Tribunal (NSW Independent Pricing and Regulatory Tribunal, 2004, 2006) provides detailed break-downs of household in-dwelling energy use by different household types, and by households on different incomes. The study shows, unsurprisingly, that larger households use more energy, and higher income households use more energy. However, higher income is associated with other variables (such as home-ownership) that may also affect energy use. Without an attempt to control for demographic differences, such descriptive work is useful in providing general understanding and awareness, but cannot be relied upon for assessing the independent effect of dwelling type, and so is of limited use in informing planners. Similarly, the study by Myors et al. (2005), which reported high per-capita energy use in high-rise apartments (compared to detached houses), has been useful in challenging assertions by advocates of urban consolidation that higher density living is necessarily less energy intense (Randolph and Troy, 2007). It does not, however, constitute conclusive evidence that high-rise apartments result in increased energy use, as the study did not control for things such as dwelling age, dwelling design, or occupant income and demographics.

The most plentiful source of descriptive information on household energy use is the Australian Bureau of Statistics (ABS). Numerous studies detail the trends towards smaller households, larger dwellings, and increased use of air-conditioners (see Australian Bureau of Statistics (2007a) for the most recent study). Information on attitudes to energy use and conservation, and appliance ownership, is also provided on an irregular basis through studies such as Australian Bureau of Statistics (2005b). While the ABS does not publish household level energy use data, expenditure on energy is available at the household level through Household Expenditure Surveys (HES) (Australian Bureau of Statistics, 2004b).

The much cited study by Harrington and Foster (1999), which has been widely relied upon for information on residential energy use in Australia, contains valuable descriptive information, much of which is sourced from an end-use study of around 300 NSW households (Pacific Power, 1994). A separate detailed study by Pears (1998) also provides a valuable and detailed description of residential energy trends in Australia. In addition to trends already apparent from ABS data, both studies note the trend to air-conditioned dwellings, and the increase in the relative contribution of household appliances to total energy use.

Troy et al. (2003) estimated embodied and in-dwelling energy use, as well as transport energy use, for selected districts in Adelaide, but the authors themselves pointed out that the lack of demographic and other control variables did not allow them to draw any conclusions that might be useful in informing planning policies.

Although it is not a study of Australian households, the study by Isaacs et al. (2006) of New Zealand households should be mentioned, as it constitutes the most recent, most comprehensive study on household energy use in any country that can be regarded as culturally similar to Australia. At a descriptive level, New Zealand household energy use reported by Isaacs et al. (2006) follows broadly similar patterns to those in the Australian research: higher income households use more energy; larger households use more energy; air-conditioning use is increasing; energy use by household appliances, and especially audio-visual equipment, is increasing more rapidly than overall household energy use.

Regression models based on household surveys/audits

With a regression approach, household energy-use data is used to estimate a regression model with relevant variables describing the household's socio-economic status, the dwelling occupied by that household, the appliances owned by that household, and the behaviour of the household. The complexity of the regression model that can be estimated is limited by the data available. In the rare case where detailed appliance ownership data is available together with appliance specific energy use information (i.e. appliance logging), a detailed conditional demand analysis (CDA) can be performed. Let $y_{i,j}$ be the amount of energy used in end-use j by household i and ζ_i be a vector of household variables (income, household type, dwelling type, etc.) about household i. The detailed CDA regression model then takes the form:

$$y_{i,j} = C_j + \psi_j \zeta_i + \epsilon_{i,j} \tag{3.1}$$

where C_j is a constant, ψ_j are the parameters to be estimated relating to the household variables ζ_i, and $\epsilon_{i,j}$ is the error term. Bartels and Fiebig (2000) use just such a model to analyse the data from a household energy end-use study by energy utilities (Pacific Power, 1994). Results from these two studies jointly provide much of the detailed information we currently have about residential end-use energy consumption in Australia.

The expense of direct metering still makes studies such as that by Bartels and Fiebig (2000) rare, and most CDA regressions rely on household level metering only, together with detailed appliance ownership information for each household. In the absence of detailed appliance ownership data, a simpler regression approach is to relate household and dwelling characteristics (ζ_i) to total household energy use, as shown in equation 3.2, where C is a simple constant, ψ is a simple vector of coefficients for the household-specific vector ζ_i , and ϵ is a randomly distributed error term.

$$y_i = C + \psi \zeta_i + \epsilon \tag{3.2}$$

Perkins (2003b) performed a linear regression, with household in-dwelling energy as the target variable, in a study of 212 households in Adelaide, and found that site area was by far the most useful variable in predicting household energy use, responsible for explaining 25.1% of total variance in a model with an overall r^2 of 38.6%. Household income, number of householders, and air-conditioned floor area explained 6.3%, 3.6%, and 1.5% of variance, respectively, with the number of shared walls negatively related to energy use and explaining 2.2% of variance. However, one would not expect a normal error term in a simple linear regression, and it is unclear if this was considered in the analysis by Perkins (2003b).

Isaacs et al. (2006) used generalised linear regression models for specific household end-uses, and showed, interestingly, that a significant part of the energy savings made possible through a tightening of building regulations in the 1970s was largely consumed in the form of greater thermal comfort and larger air-conditioned areas. The study also suggested that appliance ownership is not strongly related to the number of householders.

Household expenditure derived regression models

As part of a larger analysis on energy use by households in Sydney, Lenzen et al. (2004) found (using expenditure survey data), that the per capita in-dwelling (delivered) energy consumed by households was positively related to income (richer households use more energy than comparable poor households), negatively related to the number of people in the household (per-capita energy use decreases with household size), and positively related to detached dwelling occupancy (energy use is higher in detached dwellings, all other things equal) (Table 4, page 391 of Lenzen et al. (2004)).

Given the availability of household expenditure data (through the ABS), and the scarcity of large sample household energy use surveys, it is surprising that no detailed study of residential energy use has been undertaken using ABS household expenditure survey data. The analysis in the study by Lenzen et al. (2004) is necessarily cursory, given the article was concerned more broadly with the embodied energy used in all expenditure categories, but there is nothing preventing a detailed study of in-dwelling energy alone. Given that the ABS expenditure surveys are nationwide, and allow access to unit-record (household level) data with detailed socio-demographic information, an extremely thorough study could be performed.

Engineering (end-use) models

In contrast to regression models of household energy use, which seek to estimate a model that closely approximates household energy use, but which have no direct physical modelling basis, engineering models[2] take an explicit physical approach to calculating household energy use.

The general concept underpinning the engineering approach is that total energy use can be broken down into its constituent components: space heating; space cooling; cooking; audio-visual; and so on. Each of these tasks is undertaken by a particular device or appliance, and so provided one has detailed information about end-use efficiency, one can calculate the amount of energy required to perform each task.

One area in particular that has received much attention is home heating/cooling. Computer simulation tools such as NatHERS and BERS (now superseded by 2nd generation tools such as AccuRate)[3] use detailed specifications of floor plan, construction materials, insulation, orientation, location, ventilation, and climate, together with mathematical descriptions of the various thermal transfer mechanisms, to calculate the total heating/cooling energy required to maintain a given building at a specified temperature. Predicting actual household energy use, however, is a good deal more complicated than this, and requires, crucially, additional assumptions about, or a detailed specification of, occupant behaviour. In the absence of a detailed behavioural model, one common approach has been to assume that space heating/cooling energy is proportional to the (unconstrained) energy required to maintain a specified temperature, and a single coefficient is used to relate unconstrained total heating/cooling energy to actual usage. This approach was taken, for example, in Harrington and Foster (1999), and is also included in the heating/cooling component of the BASIX modelling software used by the NSW government to assess new residential development applications[4].

As is clear from the above description, the principal difficulty in using engineering models is that they require extensive specification and calibration. They also do not easily allow for the inclusion

[2] Also called ‘end-use’ analysis.

[3] NatHERS stands for Nationwide Housing Energy Rating Scheme. Details about the scheme, and the software (such as NatHERS, BERS, and AccuRate) used in rating dwelling energy efficiency can be found at http://www.nathers.gov.au/software/index.html

[4] Personal communication with Rob Helstroom, of the NSW BASIX team, 23/4/2006.

of demographic information, as occupants (and their behaviour) are exogenous to engineering models, and must be estimated and/or specified separately, in addition to the specification of the engineering model itself. Harrington and Foster (1999) used engineering models to develop future heating/cooling energy use forecasts under different building regulation scenarios in Australia. Isaacs et al. (2006) use a quasi regression/engineering approach for predicting the future household energy consumption in New Zealand households under different scenarios.

3.3.3 Method

Each of the three types of household energy study described in Section 3.3.2 (descriptive, regression, and engineering) have different benefits and data requirements. Descriptive studies provide a broad understanding of household energy consumption and behaviour, and can be conducted using aggregated data. Regression studies require more detailed household level energy use and demographic data, and engineering models require very detailed appliance and behavioural models and data. Given that the focus of engineering models is on appliances and end-uses, they are most appropriate for analysis of changes to appliance efficiency, building shell design, and so on. For general analysis of household energy use in the absence of detailed appliance and building stock data or assumptions, a regression approach is more appropriate. For this study, a simple regression approach is taken, as the available data does not permit a CDA-style regression model to be reliably estimated[5].

3.3.4 Data

Three datasets are used for the main regression analysis. The NSW Independent Pricing and Regulatory Tribunal (IPART) conducted two end-use household surveys in 2003 (NSW Independent Pricing and Regulatory Tribunal, 2004) and 2006 (NSW Independent Pricing and Regulatory Tribunal, 2006), which consisted of 2604 and 2632 household level in-person questionnaires, respectively, that were then matched with metered gas and electricity data obtained from utility companies. The third dataset was obtained from Randwick City Council, and also consisted of a household questionnaire (within Randwick City Council's borders only), combined with metered gas/electricity data. For the purposes of the following analysis, the main difference between the datasets is that the Randwick City Council data does not contain household income information, while the IPART data does. The likely result of an inability to control for income is that estimates of energy use for households in Randwick Council (which covers a relatively affluent area of Sydney) will be higher than the Sydney-wide average, and that the income/wealth effects evident in the IPART data will 'spill over' into indirect indicators of income and wealth, such as dwelling type and dwelling size.

Both IPART datasets consisted of two parts: a random sample across Sydney (including the Blue Mountains), Wollongong, and Newcastle; and a specific low income sample. For an analysis which aims to provide insight into energy use in households generally, account needs to be taken of the non-random (low-income) sample. The approach taken in NSW Independent Pricing and Regulatory Tribunal (2004) was to retain the low-income sample data and apply weights to house-

[5]Some appliance ownership information was available, but, after experiment, it became clear that it was not possible to use this to estimate a CDA-style regression model.

holds so that the (weighted) income distribution reflected that of the general population. In the following analysis, all households in the low income sample have been removed. In addition, due to the very different climatic conditions in the Blue Mountains, only data from Sydney, Wollongong, and Newcastle was analysed. Finally, a number of households with inconsistent or missing information were removed from the analysis[6]. The resulting dataset consisted of 1427 households (2003 dataset) and 1225 households (2006 dataset). Although data on Wollongong and Newcastle households was retained, excluding these from the analysis does not substantially affect results.

The Randwick City Council dataset contained similar information to that in the IPART dataset, with the exception (already noted) that household income information was unavailable.

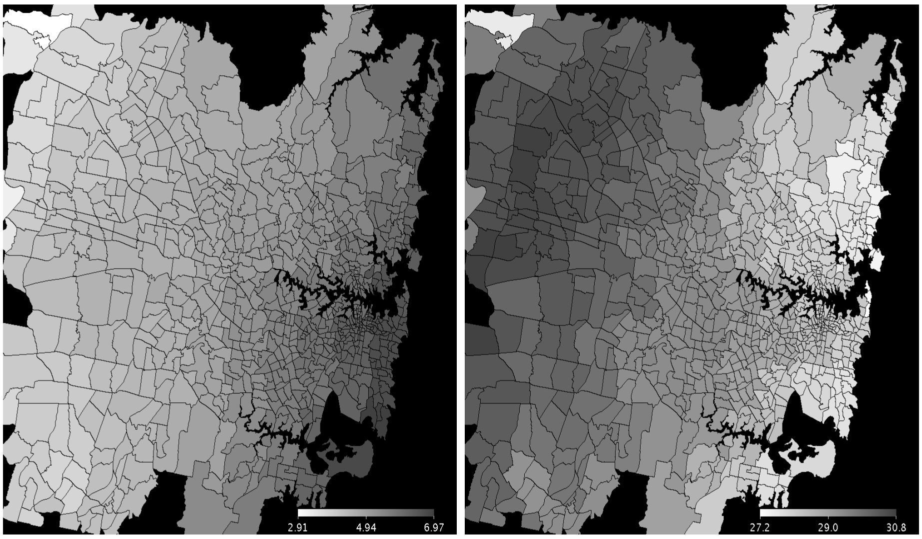
For the IPART data, the target variable was the natural log of annualized in-dwelling energy consumption. For the Randwick City Council data, the target variable was the natural log of average daily consumption. The log-transform was necessary in both cases as a simple linear regression on an untransformed target variable resulted in non-normally distributed residuals. In both cases, gas and electricity consumption was combined into a total energy use target variable for the household. The combining of gas and electricity into a single target variable does pose some problems, as energy source is known to affect energy use. This is partly because the end use efficiency of gas and electricity differs for different tasks, and partly because different energy sources are typically used for different tasks: gas for central heating and electricity for isolated room heating, for example. To capture these effects, dummy variables are used for households with gas connected, and for households that report using gas for specific purposes (cooking, hot water, etc.). Concern that the use of simple energy-source dummy variables to explain differences in end-use energy will produce distortion is allayed by the fact that performing the same analysis on houses with electricity only (i.e. no gas) produces broadly similar coefficients; compare, for example, Tables 3.2 and 3.5.

Because space heating and cooling represents a significant proportion of household energy use (Harrington and Foster, 1999; Bartels and Fiebig, 2000), and because Sydney has strong East/West climatic variation (see Figure 3.10), the dataset was augmented with fine-grained (0.05° lat/long grid) information on temperature obtained from the Australian Bureau of Meteorology. Each household record in the IPART datasets was extended with additional climatic information. Because the spatial extent of the Randwick City Council data was more limited, this was not done for that data set.

Finally, it should be noted that *only* energy billed to the electricity and gas accounts of individual households is considered. For apartments in buildings that have significant common area energy use, actual per household energy use will be underestimated. However, a re-analysis of the data from Myors et al. (2005) suggests that common area energy use is only likely to be significant for large apartment-complexes with lifts and (especially) pools/spas. Since apartments in buildings greater than 3 storeys make up less than 8% of the apartments surveyed in the IPART data, the distortions involved by excluding common area energy use are unlikely to be large[7].

[6]Households were excluded on the basis of such irregularities as having self-reported gas consumption but zero gas consumption obtained from the utility company.

[7]I confirmed this by excluding high-rise apartments from the analysis, and regression coefficients do not change substantially when this is done.



(a) Mean June Minimum (b) Mean Dec. Maximum

Figure 3.10: Figure a shows mean daily minimum temperature (in °C) in June 2000. Figure b shows mean daily maximum temperature in December 2000. Data Source: Australian Bureau of Meteorology.

3.3.5 Analysis and results

The regression analysis was conducted in a standard way, with the selection of model variables guided over numerous trials by a mixture of fit to data, common sense, and collinearity and residual analysis. Listing all available variables is impractical, but the main data sets are described in sufficient detail in NSW Independent Pricing and Regulatory Tribunal (2004) and NSW Independent Pricing and Regulatory Tribunal (2006).

Tables 3.2 and 3.3 show the regression coefficients obtained for semi-log regressions on the 2006 and 2003 IPART datasets, respectively. Given that only 3 years separate the data sets, one would expect coefficients to be broadly consistent, and this is the case for all variables apart from **usegasheating**, which is negative in 2003 and positive in 2006, and **isowner**, which is negative in 2006 and not significantly different from zero in 2003. Figure 3.11 compares the standardized regression coefficients[8] for the two separate regression analyses.

To make sure the reader is clear on the exact form of the model estimated, the model obtained for 2006 (coefficients for which are presented in Table 3.2), is:

$$\begin{aligned} ln(\text{Total In} - \text{dwelling Energy}) = \; & 9.314 + 0.114 \times \text{num\_appliances} - 0.093 \times \text{isowner} \\ & +0.067 \times \text{num\_bedrooms} + 0.093 \times \text{numpeople} \\ & +0.025 \times \text{income} + 0.024 \times \text{hasaircon} \\ & -0.17 \times \text{isflat} - 0.081 \times \text{issemi} \\ & +0.357 \times \text{hasgas} + 0.108 \times \text{usegasheating} \end{aligned}$$

[8]That is, coefficients for variables that have been transformed to have zero mean and unit variance.

	Coefficient	Standardized Coefficient	Significance
constant	9.314	NA	< 0.001
num_appliances	0.114	0.243	< 0.001
isowner	-0.093	-0.075	0.001
num_bedrooms	0.067	0.114	< 0.001
numpeople	0.093	0.255	< 0.001
income* (1-9)	0.025	0.101	< 0.001
hasaircon	0.024	0.046	0.040
isflat	-0.170	-0.082	0.001
issemi	-0.081	-0.048	0.029
hasgas	0.357	0.328	< 0.001
usegasheating	0.108	0.081	0.002
adj. r^2	0.484		

Table 3.2: Results from analysis of 2006 IPART data. * Income is measured on a 9-point scale, with brackets as in NSW Independent Pricing and Regulatory Tribunal (2006).

	Coefficient	Standardized Coefficient	Significance
constant	9.157	NA	¡ 0.001
num_appliances	0.114	0.247	¡ 0.001
isowner	0.005	0.004	0.837
num_bedrooms	0.089	0.145	¡ 0.001
numpeople	0.120	0.307	¡ 0.001
income* (1-9)	0.023	0.091	¡ 0.001
hasaircon	0.095	0.083	¡ 0.001
isflat	-0.198	-0.091	¡ 0.001
issemi	-0.075	-0.043	0.041
hasgas	0.279	0.242	¡ 0.001
usegasheating	-0.107	-0.083	0.002
adj. r^2	0.453		

Table 3.3: Results from analysis of 2003 IPART data. * Income is measured on a 9-point scale, with brackets as in NSW Independent Pricing and Regulatory Tribunal (2004).

Total in-dwelling energy is in MJ per household per annum. Tables 3.2 and 3.3 (and the above equation) report results from regressions containing only primary variables (i.e. variables collected directly in the respective surveys). Extensive experimentation with the inclusion of interaction variables indicated that a small additional improvement in the r^2 value could be achieved, but the outcome does not change substantially from the one produced by the regression results shown in Tables 3.2 and 3.3. Table 3.4 shows the standardized regression coefficients for 2003/2006 with interaction variables included. The signs of all variables are as expected, except for the disagreement over the effect of gas hot water heating (**gashw**), which is positive in 2003 and negative in 2006; and the disagreement over **usegasheating** and **isowner**, already observed in the regressions without interaction variables.

Because the use of gas is associated with higher household energy use, separate regressions using households without gas connections were performed. The results from a regression on households without gas in the 2006 IPART data-set is shown in Table 3.5, and suggest that the inclusion of the energy-source dummy variable does not greatly distort the values of the other variables.

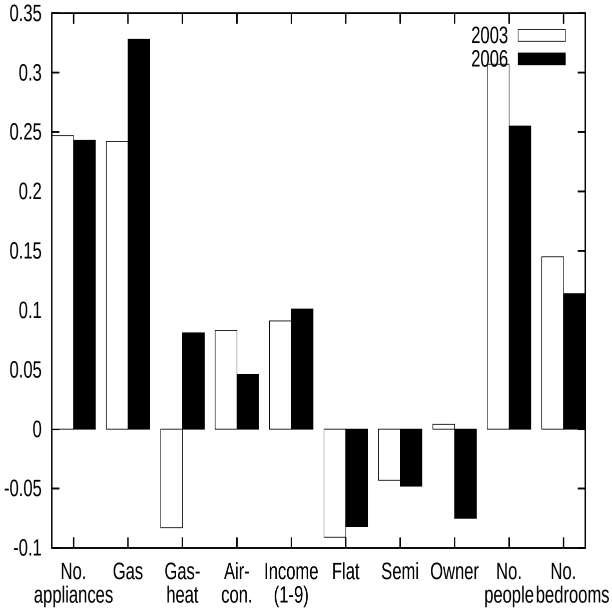


Figure 3.11: Comparison of 2003 and 2006 standardized regression coefficients.

The semi-log nature of the regression model estimated from the 2003 and 2006 IPART data sets make interpretation less than straightforward. A helpful way of viewing a semi-log model is to consider that each variable coefficient can be interpreted as the expression of how much, in percentage terms, a unit change in a given variable changes overall energy use. For example, taking the coefficient of 0.255 for the **numpeople** variable from the regression on 2006 IPART data in Table 3.4, we can see that an increase (decrease) in household size of 1 person results in an increase (decrease) in energy use of 29% (22.5%), as $e^{0.255} = 1.29$ and $e^{0.255} = 0.775$. Figure 3.12 shows the estimated percentage change in energy use resulting from a unit positive change in each explanatory variable (barring those relating to energy source) in the 2003 and 2006 IPART models without interaction terms[9] shown in Tables 3.2 and 3.3. The most interesting finding, from both a research and policy perspective, is that household energy use is around 15-20% lower in an apartment, *holding other variables constant*. That is, the regression models estimated on the IPART data suggest that moving the *same* household from a detached house to an apartment with the same number of bedrooms will result in a 15-20% reduction in in-dwelling energy use. This is at least partly (and possibly wholly) related to space heating/cooling and dwelling size – an apartment is, on average, smaller than a house with the same number of bedrooms. Such a decrease seems, at first glance, quite plausible. Given 38% of in-dwelling energy use is used for space heating/cooling (Harrington and Foster, 1999), assuming a 20% reduction in the volume of space to be heated/cooled[10], and a 30% increase in heat/cool efficiency due to shared walls and the like (Harrington and Foster assert that attached dwellings are 36% more efficient (Harrington

[9]The models without interaction terms are chosen because of the difficulty in interpreting unit changes in interacted variables.

[10]Data generally available from the ABS and other sources usually provide average floor space for detached/other dwellings, so do not allow for a direct comparison, as detached dwellings have more bedrooms on average than attached dwellings. Thus, while most would accept that a unit will be smaller than a house with the same number of bedrooms, the 20% figure quoted is based on my judgement.

	2003 Std. Coefficient	p-value	2006 Std. Coefficient	p-value
constant	9.365*	< 0.001	9.513*	< 0.001
num_appliances	0.264	< 0.001	0.244	< 0.001
isowner	0.003	0.881	-0.068	0.003
numpeople	0.332	< 0.001	0.255	< 0.001
isflat	-0.111	< 0.001	-0.101	< 0.001
issemi	-0.053	0.008	-0.056	0.009
hasgas	0.385	< 0.001	0.229	< 0.001
usegasheating	-0.054	0.013	0.09	0.001
bed×income (1-9)	0.145	< 0.001	0.161	< 0.001
aircon×rooms	0.089	< 0.001	0.048	0.041
gashw	-0.147	< 0.001	0.109	0.001
solarhw	NA**	NA**	-0.059	0.004
2003 adj. r^2	0.501		2006 adj. r^2	0.494

Table 3.4: Standardized coefficient regression results for 2003 and 2006 with interaction variables. * Unstandardized. ** Information unavailable for 2003 analysis.

	Coefficient	Standardized Coefficient	Significance
constant	9.4	NA	< 0.001
num_appliances	0.115	0.278	< 0.001
isowner	-0.076	-0.075	0.013
num_bedrooms	0.043	0.088	0.009
numpeople	0.08	0.257	< 0.001
income (1-9)	0.024	0.107	< 0.001
hasaircon	0.083	0.087	0.003
isflat	-0.141	-0.085	0.006
issemi	-0.084	-0.053	0.061
r^2	0.331		

Table 3.5: Results from analysis of 2006 IPART data (households without gas only. N=984).

and Foster, 1999), while Miller and Ambrose estimate a 33.7% efficiency increase for attached dwelling per unit area (Miller and Ambrose, 2005)), one would expect a saving in total energy use of around 17% ($0.38 - 0.38 \times 0.8 \times 0.7$), which agrees well with the results presented here.

Table 3.6 shows the regression model on the smaller ($N = 162$) dataset from an energy audit of households in Randwick City Council. The target variable was the natural logarithm of average daily household energy use, in MJ. The main factors influencing household energy use are **dwelling size**, **eveningoccupancy**: the number of people typically home on a week-night; **winterheatinghours**: the typical number of hours a heater is used in winter; **poolpump**: whether or not the household has a pool pump; and **hasclothesdrier**: a 0/1 dummy for whether the household has a clothes drier. The **poolpump** variable is perhaps partly a proxy for income, as only the wealthier households could afford a detached dwelling with a pool in Randwick. The findings that strongly relate dwelling size and evening occupancy to energy use are in broad agreement with the results from the IPART analysis. Interestingly, variables describing dwelling type were found to be insignificant once dwelling size was included. This suggests that dwelling type may be acting partly or wholly as a proxy for dwelling size in the IPART regression results, since, even though a

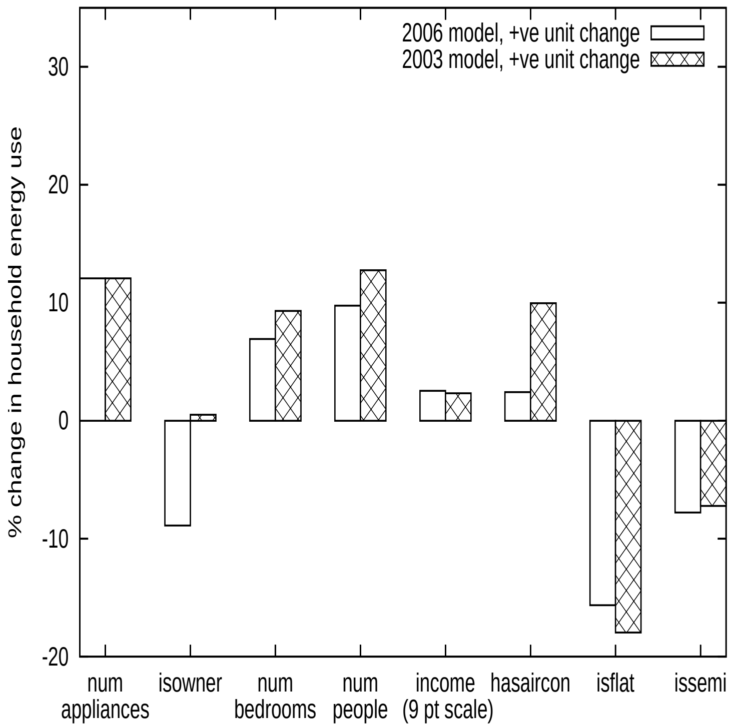


Figure 3.12: Change in energy use (MJ per household per annum of in-dwelling energy) from positive unit changes to explanatory variables, calculated from regression models detailed in Tables 3.2 and 3.3.

	Coefficient	Standardized Coefficient	Significance
constant	2.707	NA	< 0.001
winter heating hours	0.049	0.239	< 0.001
dwelling size (squares)	0.005	0.408	< 0.001
eveningoccupancy	0.164	0.325	< 0.001
pool pump	0.051	0.205	< 0.001
hasclothesdrier	0.126	0.092	0.087
r^2	0.593		

Table 3.6: Results from analysis of Randwick City Council Data (N=162).

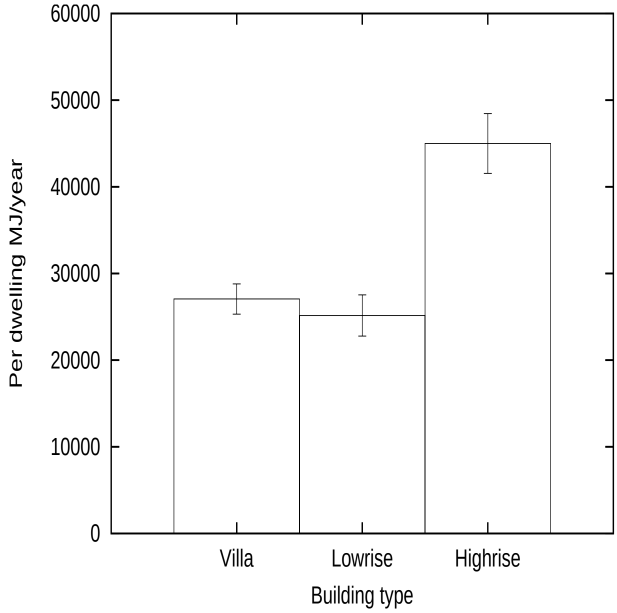
separate variable (**numbedrooms**) was included as a proxy for dwelling size in those cases, it is an imperfect proxy, as an apartment is likely to be smaller than a house with the same number of bedrooms. The inclusion of variables describing household attitudes to climate change and energy conservation, which was available in the survey data, did not produce any improvement in the model. Including the tenure status of the household (renter/owner) did not improve model fit either, as was found in the regression on 2003 IPART data.

Before further discussing the results of the preceding analyses, it is useful to revisit the data analysed in Myors et al. (2005). Although the authors themselves made no such claim, this study is now not infrequently used to suggest that apartments, and especially high-rise apartments, are more energy intense than detached dwellings. Figure 3.13 shows a re-grouping of the same data, and indicates that while there does appear to be greater energy use in high-rise apartments compared to low-rise apartments and villas/townhouses, it is possible that this is largely a result of the provision of luxury common area features (heated pools, spas, air-conditioning, etc.) rather than anything relating particularly to built form. This possibility, together with the high variance in the energy use figures for high rise apartments in Myors et al. (2005), suggest it may be unwise to draw conclusions about the energy-use implications of high-rise apartments without a more thorough analysis of energy use in high-rise dwellings. The reader should note that Figure 3.13 shows averages for different dwelling types only, and not independent effects of dwelling type, which cannot be estimated with the data from Myors et al. (2005). Figure 3.12, showing results for the analysis of IPART data, is the relevant figure to refer to for independent effects, as other effects, such as household income and structure, can be controlled for with that data.

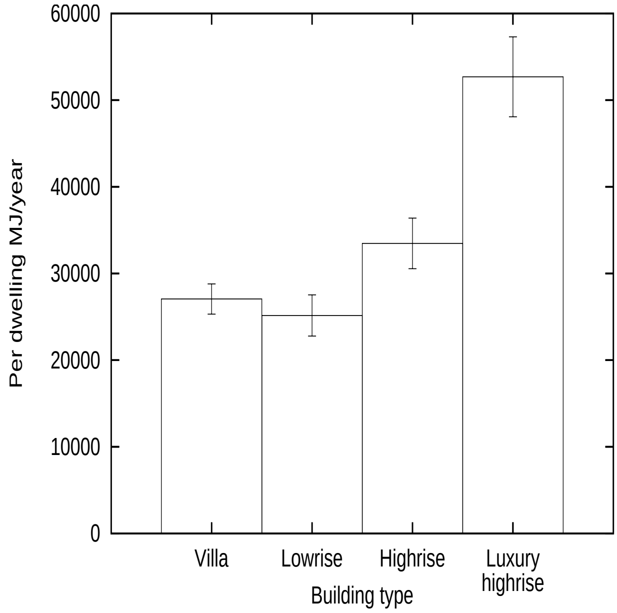
3.3.6 Discussion

The factors influencing energy use in residential dwellings are more complex than those that can be captured in a controlled regression analysis. Inhabitant behaviour, dwelling design, climate, social norms, and numerous other factors interact to determine total in-dwelling energy use, and one cannot hope to fully understand these interactions with the data available for this study. My approach is to use regression analysis on the data available to detect general trends, and discuss the potential complicating factors that cannot be accounted for due to data and/or methodological limitations.

The results presented in Section 3.3.5 provide important estimates of the independent effect of factors (such as dwelling type, household income, and household size) on household energy use.



(a) Original Groupings



(b) Alternate Groupings

Figure 3.13: Comparison of per-dwelling energy use under groupings used in Myors et al. (2005) (Fig. a) with alternate grouping that distinguishes luxury high-rise from non-luxury high-rise (Fig. b). Luxury buildings are defined as those containing a pool/spa. High-rise is defined as those buildings with a lift. Villa includes townhouses/semi-detached. Error bars show standard error of the mean, *not* sample standard error. Data Source: Same dataset as analysed in Myors et al. (2005), obtained from Paul Myors, Energy Australia.

While descriptive studies of household energy use have added to our understanding of the drivers of household energy use, there are limits to how useful descriptive studies can be in informing policy. It is not particularly helpful, for example, to know that per-capita energy use is lower in detached dwellings than in apartments, as this may be due to the fact that detached dwellings are mainly occupied by families and apartments are mostly occupied by singles and couples without children. Only a controlled analysis of independent effects can help determine whether this is the case. Informed policy requires estimates of independent effects, which answer questions like "What would be the effect of moving the same household to a different dwelling?" This is what the regression analysis in this study provides.

The regression results provide a general picture of household energy use that is, on the whole, in line with commonly held expectations. All other things equal, for example, wealthier households use more energy, larger households use more energy, and households in larger dwellings use more energy. Similarly, the finding that households with air-conditioners use more energy is not unexpected. It is unclear from the analysis whether tenure status has an independent effect on energy use or not – both possibilities remain open. From a planner's perspective, an interesting finding is that semi-detached dwellings and apartments are associated with lower energy use, all other things equal. Unfortunately, because floor-area was not available in the IPART data-set, it is not possible to determine whether this is due mainly to the smaller floor area of attached dwelling types, or due to the thermal benefit of having shared walls (demonstrated in thermal simulation models). Perhaps it is both, although the results of the regression on Randwick City Council data provide some weak evidence that the reduction in floor area is the more important factor. While thermal modelling studies of attached and detached dwellings suggest that for equivalent climate, orientation, and insulation levels, attached dwellings require less heating/cooling energy per unit area to maintain a particular level of thermal comfort than do detached dwellings (Harrington and Foster, 1999; Miller and Ambrose, 2005), it is unclear whether this translates into lower energy per m^2 in practice, and the data available for this study cannot help resolve the question. Considered together, however, the smaller per unit area energy use estimated in thermal modelling studies, along with the smaller floor areas typical of attached dwellings, add credibility to the negative parameters associated with attached dwellings in the regression analysis.

Despite the highly variable nature of household energy use, the regression results are instructive of general trends, and the r^2 values obtained (from 33.1% to 50.1%) are comparable with other regression models of household energy use: Perkins (2003b) explained 38.6% of variance; Bartels and Fiebig (2000) 66% of variance; and Larsen and Nesbakken (2004) 48%.

The finding (in the IPART regressions) that households with gas connected use more energy is unsurprising, given the typically lower end-use efficiency of gas[11]. Pears (1998), for example, used an overall end-use conversion factor of 1.5 to correct for the lower end-use efficiency of gas. The inconsistent results for the presence of gas central heating also suggest that part of the energy used in gas central heating is captured by the **hasgas** dummy variable. While the practice of relying on dummy variables to capture the effect of energy source is questionable, it does not seem possible to do much better with the available data, as the use of interaction variables (such as **numbedrooms** interacted with **mainlyusegasheating**) did not markedly improve estimated

[11] Appliances differ in their end-use efficiency, and the fuel source used is often an important factor influencing the end-use efficiency of an appliance. For example, a gas water heater usually requires more PJ of energy to keep the same volume of water hot than does an electric water heater.

models. Analysis of households that rely solely on electricity suggests that the inclusion of the energy-source related dummy variables does not distort the results (see Table 3.5).

The inability of the analysis to detect a significant effect associated with regional climate variables is surprising. Given that space heating and cooling in Australia constitute around 38% of in-dwelling energy use (Harrington and Foster, 1999), and inter-city variation in heating/cooling energy use due to differing climate is easily demonstrated, it is counter-intuitive that the climatic variation observed over the study region does not influence household energy use. The difficulty in detecting such variation is a consequence of the fact that it is not just climate that varies east/west in Sydney. Household income also varies strongly east/west, as wealthier households are more likely to live in eastern harbour and seaside suburbs. Land economic forces also dictate that the suburbs with high land values have higher dwelling densities, and so are more likely to have multi-unit dwellings. Demographic variation and housing preferences are such that the ocean and harbour-side suburbs are also less likely to be occupied by households with children (Australian Bureau of Statistics, 2006). These factors, together with the high unexplained variance in household energy use, make it difficult to detect the effect of climate, and it seems likely that some climatic effect is incorrectly attributed to household type, income or dwelling-type coefficients. Difficulties in adequately controlling for spatially correlated variables are, of course, commonplace in urban research.

Another interesting finding from the Randwick Council data is that attitudes to energy conservation and climate change are not strongly related to actual metered energy use. While that data-set was small, prior research has also suggested that attitudes are unreliable predictors of actual use (Stokes et al., 1994; Mullaly, 1999), as households are prone to overestimate their own energy conservation measures.

By far the most interesting, and also the most contentious finding, is that both semi-detached dwellings and low-rise apartments are more energy efficient than detached dwellings with the same number of bedrooms. Given this finding, it may be premature to conclude, as some have done, that increases to urban density achieved through multi-unit development will result in higher energy use. Consider Randolph and Troy (2007), for example:

> Myors et al. (2005) have shown that *per capita* greenhouse emissions from high rise flats in NSW, at 5.4 tonnes of CO_2 per year, are significantly higher than the NSW average of 3.1 tonnes of CO_2 per year. While not specifically focusing on dwelling type *per se*, research by Foran (2006) has shown household greenhouse emissions in Canberra and Perth, based upon an assessment of total household energy consumption, is higher in inner city locations compared with suburban locations .... Foran's analysis suggests strongly that urban density is positively related to total greenhouse gas emissions, with the implication that higher density areas are *less* environmentally sustainable.
>
> Randolph and Troy (2007, page 19), italics theirs.

The results of this study are at odds with such a conclusion, for they suggest that semi-detached dwellings and low-rise apartments are associated with lower energy use than detached dwellings with the same number of bedrooms, after controlling for other variables. Remember that this comparison is for households with the same number of inhabitants, and so it suggests that whether you choose to measure on a per-dwelling or per-capita basis, energy use is lower in semi-detached and low-rise apartments. High-rise apartments constitute a small portion of the sample, and little can be deduced about their energy efficiency in this study, but the re-analysis of the data from Myors et al. (2005) at least invites the possibility that it is the luxury features (such as heated pools and spas) associated with some modern high-rise apartments, and not built form, that are responsible for reported high energy use.

Looking for evidence from Input/Output studies, such as Foran (2006), or Lenzen et al. (2004), is problematic. Input/Output studies calculate the energy embodied in each dollar of expenditure, and show, unsurprisingly, that higher income is associated with higher energy use. But because per capita income is in general higher closer to the CBD[12], this results in per capita energy use being higher in the denser areas closer to the CBD. Without a controlled analysis, one cannot argue that urban density has any causal effect. In fact, the regression analysis in Lenzen et al. (2004, page 391) suggests that there is no strong statistical association between higher urban density and per-capita energy use, *if one controls for other factors.*

3.3.7 Conclusions

The main point I wish to make in this study is not that higher density housing is more energy efficient than studies such as Myors et al. (2005); Perkins et al. (2007); and Randolph and Troy (2007) suggest. Much of the existing data on both embodied and in-dwelling energy use in high-rise apartments is troubling, as it suggests that the energy savings possible in such a structure are, in practice, not achieved, due to poor design. Even worse, the theoretical savings are small compared with the increase in energy use observed when such buildings include energy-hungry luxury features.

This research suggests that medium-density dwellings (including low-rise apartments) may prove more energy efficient than detached dwellings. I fear that a conventional wisdom is developing in Australian planning circles about the energy intensity of apartments that is not (yet) supported by the available evidence, and would like to see further quantitative research in this area before such a general view forms. Furthermore, there is the potential for a division of researchers along the same old fault line that has been running through much urban analysis in Australia for decades now: density. Urban researchers who favour higher density living can find ample evidence that average per-dwelling energy use is lower in attached dwellings. Others who wish to argue against increasing density can find ample evidence that average per-capita energy use is lower in detached dwellings. By relying on summary average statistics, and selecting the basis for comparison (per capita, per unit area, per dwelling, etc), researchers can find whatever 'evidence' they need to support a particular position. The ossification that ensues makes progress difficult (Gleeson, 2007).

Stepping back a little, perhaps the base question that we should be trying to answer is: *What are the energy use implications of particular housing strategies?*, and, importantly *Which strategies are achievable?* These are metropolitan-scale questions, not dwelling or household specific ones. The second question is of prime importance because even if one could achieve a reduction in energy use by shifting family households from detached dwellings into attached ones, this is made irrelevant if such households are opposed to living in such dwellings (as suggested by Troy (1996)

[12] This trend is strongest in Sydney, where Lenzen et al. (2004)'s work was conducted, but is also true in Canberra, where Foran performed his analysis.

and Yates and Mackay (2006)). Similarly, studies that demonstrate lower per-capita energy use in detached dwellings are of limited use if significant proportions of child-free households prefer to live in apartments with better accessibility and access to services (as suggested by Vipond et al. (1998)). More thorough analysis is needed which looks at the projected household mix in our cities, and the likely housing preferences of those households. Work with such a metropolitan-scale focus has been rare in Australian planning research since the pioneering work on urban structure and energy use by Newton (1997), although some recent Australian work-in-progress (reported in Rickwood et al. (2007)) is also city-scale. Rather than asking the simple, and potentially divisive question: "What is the most sustainable dwelling type", we can instead start to think about the trade-off between future housing preferences, and the in-dwelling energy use in our cities. If, for example, substantial savings in energy use are only achievable through planning policies that essentially force people to make housing choices that they are strongly opposed to, then it may be better to concentrate on changes to energy tariffs, appliance efficiency, power generation, and building/development design.

3.4 Chapter summary

It is refreshing to find that there are some clear trends to be found in the research into dwelling-related energy use. In particular, it is pleasing that the three separate regression analyses, on separate data-sets, in Section 3.3, found that energy use in attached dwellings is less than in detached dwellings, after controlling for other factors. This is also consistent with results in Wier et al. (2001) and Perkins (2002). There is also plenty of international research indicating that energy use is lower, per capita, in attached dwellings. Figure 3.14, for example, shows per-capita energy use for different dwelling structures in Oslo, Norway, from Holden and Norland (2005), with energy use consistently lower in attached dwellings. Climatic conditions are clearly vastly different in Norway than in Sydney, but this provides more support for the claim (in Section 3.3) that energy use is 10-15% lower in attached dwellings. The energy savings observed for Norweigen households must be largely related to savings in heating/cooling (as this comprises a much larger percentage of in-dwelling energy use than in Australia), and help make it clear that different dwelling structures do reduce heating/cooling energy. Returning to consider the results in Section 3.3, it is particularly pleasing that the magnitude of the effect found is in line with what one would expect given the results of thermal simulation studies of attached/detached dwellings. In particular, given heating/cooling make up 38% of household energy use in Australia, and assuming a 30% improvement in efficiency (consistent with Harrington and Foster (1999); Newton et al. (2000); Miller and Ambrose (2005)), and a 20% reduction in floor area, we would expect $\approx$ 16% reduction in energy use, in line with the results of the empirical analysis in Section 3.3. The important caveat to note is that the sample of attached dwellings in that study included only a small number of high-rise buildings, and thus, it is possible that energy use in high-rise dwellings is higher than for low-rise ones. It is clear that *embodied* energy is higher per unit inhabitable area than for other dwelling types, but it is possible that the high in-dwelling energy use observed in the limited number of studies available is due to poor high-rise building design. Given better design, there does not seem to be any reason why in-dwelling energy consumption in high-rise apartments should be much higher than in low-rise apartments.

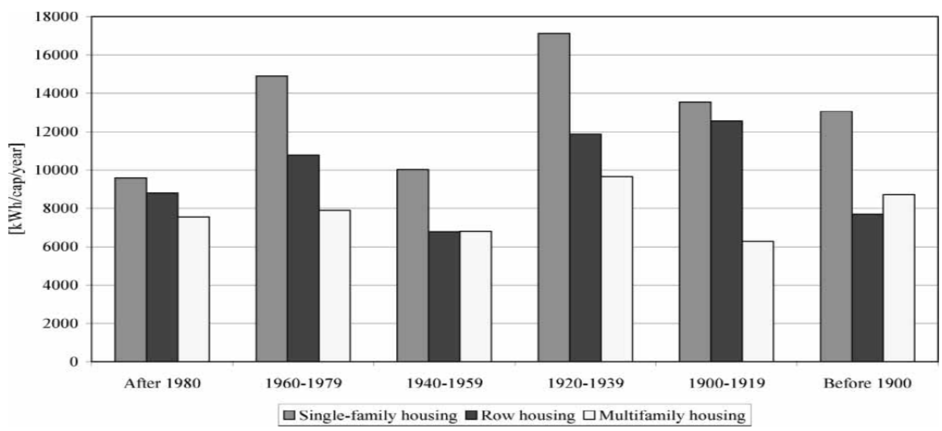


Figure 3.14: Temporal trend of in-dwelling energy consumption in Oslo. NB: ‘multifamily’ refers to apartments. Source: Holden and Norland (2005)

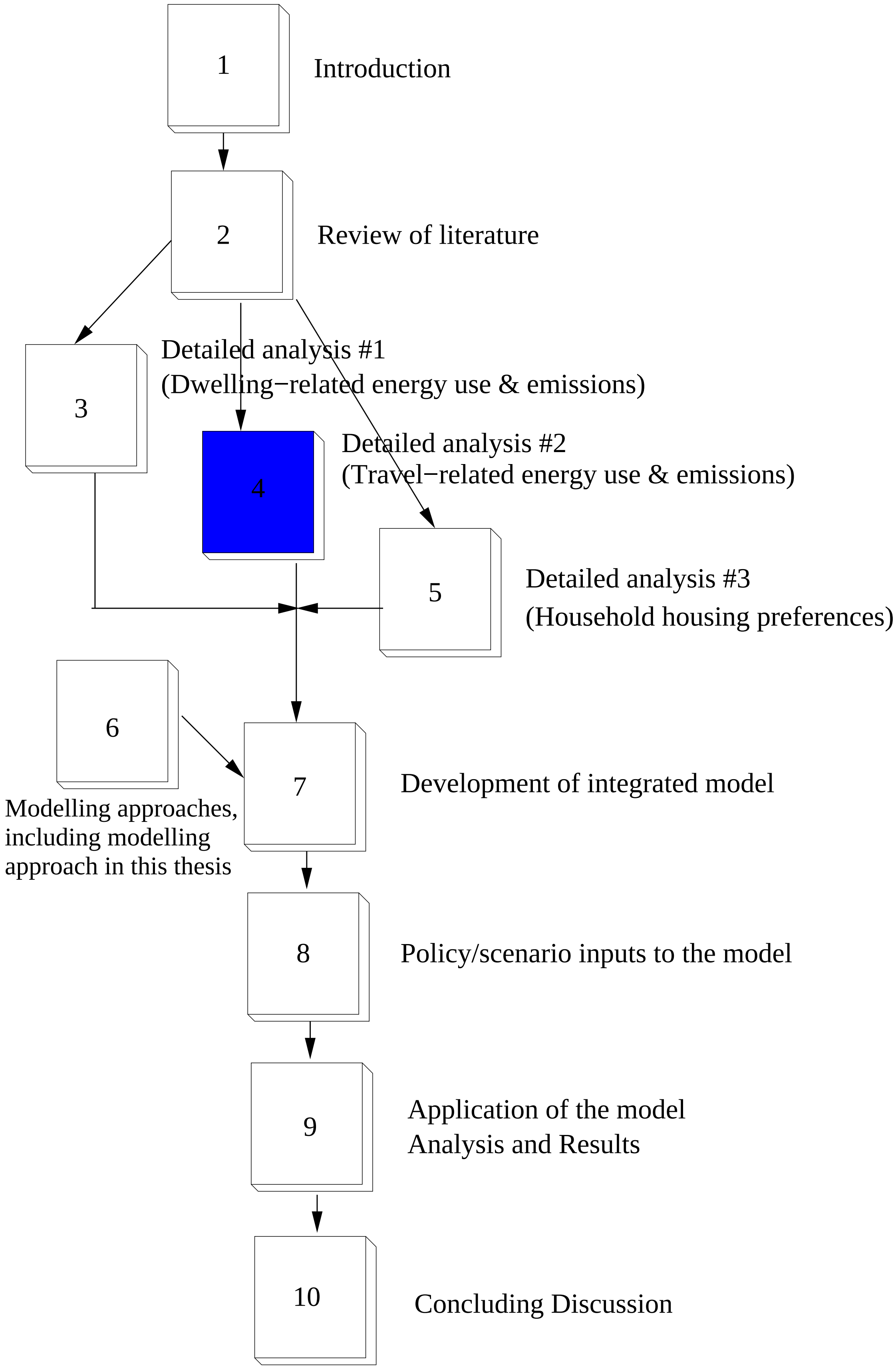
I have concentrated on the effect of dwelling type on in-dwelling energy use in this summary discussion, as this effect can be easily included in the modelling work in Chapters 7-9, after conversion to primary energy. It is worth noting, however, that this effect is small relative to other, more complex ones, relating to built form. A review by Steemers (2003), for example, concludes that energy arguments about densification will depend on infrastructure issues, rather than more marginal changes to in-dwelling heating/cooling energy. He notes, for example, that there is more capacity for co-generation[13] in higher-density areas. Energy savings from building and appliance design, and from changes to energy generation technology, are all more likely to make more of a difference than floor area and other simple built-form factors (such as dwelling type). Social, cultural, and behavioural factors are also important. The comprehensive longitudinal study of residential energy use in New Zealand, for example, found that socio-economic factors were more important in determining energy use than factors relating to dwelling age, size, or structure (Isaacs et al., 2006, page 93). This suggests that energy tariffs, energy efficiency regulations, and technological changes to energy production may be more promising strategies for reducing in-dwelling energy then any change to dwelling size and type achievable by land-use policy.

There is sometimes a tendency amongst urban researchers to ignore political realities. It is something of a moot point which of two styles of development is more energy efficient if the populace is strongly opposed to one of them. This is why it is important to understand the housing preferences of households, and a method to help do this is developed in Chapter 5.

[13]Co-generation refers to the capture of otherwise wasted heat energy in the generation of electricity. This heat, rather than being wasted, is used for domestic water or space heating.

Chapter 4

Detailed Analysis – Urban Travel and Energy


1
Introduction
2
Review of literature
3
Detailed analysis #1
(Dwelling−related energy use & emissions)
4
Detailed analysis #2
(Travel−related energy use & emissions)
5
Detailed analysis #3
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Modelling approaches,
including modelling
approach in this thesis
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Application of the model
Analysis and Results
10
Concluding Discussion

4.1 Introduction

The review in Chapter 2 has already provided an overview of some of the relevant literature on urban travel. The analyses in this chapter explore the relationship between urban form and travel behaviour. Together with the travel model developed in Chapter 7 it is through these analyses that the second thesis question ("How does transport and land-use policy influence household travel behaviour and resulting energy use?") is addressed. The detailed analysis in this chapter also provides support for many of the choices made in development of the integrated model (Chapter 7).

This chapter is arranged as follows. This remainder of the introduction provides some supplementary review material not covered in the broad review of Chapter 2. This is followed by three complementary analyses of the effect that urban structure has on travel behaviour. Section 4.2 includes an analysis of commuting behaviour in Australian cities, using aggregate census journey to work data[1]. Section 4.3 is a more detailed analysis, focusing solely on Sydney, using disaggregate travel data. Section 4.4 moves away from the empirical approach taken in Sections 4.2 and 4.3, and develops a mathematical model of the relationship between urban structure and travel behaviour. Section 4.5 concludes with a general summary and discussion of the findings in this chapter.

Brown et al. (2008) conducted a descriptive study of both U.S transport and in-dwelling energy consumption. They show that the larger U.S metropolitan areas have lower per capita greenhouse emissions than do smaller ones. The study contains important information about the variation in transport and in-dwelling energy use, and indicated that transport emissions are more variable between cities than in-dwelling energy use, even allowing for the significant climatic variation across the United States. Thus, while climate is clearly an important complicating factor for in-dwelling energy use, the inter-city comparison of transport emissions suggested that urban structure matters a good deal for transport energy use and emissions, and that economic factors, fuel costs, and other factors commonly used to deny a strong 'link' between urban structure and transport behaviour are not sufficient to explain the observed differences. Another recent comprehensive U.S. study (Glaeser and Kahn, 2008) also found lower transport energy use in larger, denser urban areas. The same study also found that within cities, more central locations were also associated with lower transport energy use. Importantly, the analysis by Glaeser and Kahn, (unlike Brown et al. (2008)) was a controlled analysis, and estimated the *independent* effect of inter and intra city location on household energy use. They estimate a 33% reduction in total energy use for a household occupying a new dwelling in a 'better' (i.e. larger/denser) urban area compared with a worse area. However, this estimate is for *combined* transport and in-dwelling energy use, and includes the effect of climate; their estimate of the difference in transport energy use alone is $\approx 17.5\%$ (Glaeser and Kahn, 2008, page 35), somewhat lower than the 25% effect estimated in both Bento et al. (2003) and Ewing et al. (2007).

In Australia, the work of Alan Perkins (Perkins, 2002, 2003b,c; Perkins and Hamnett, 2005; Perkins et al., 2007) addresses similar issues to those addressed in this PhD, although the target city was Adelaide, and the methodology is fundamentally different to that taken in this thesis. Perkins undertook detailed travel and home-energy surveys of two developments in Adelaide – one

[1]This analysis is drawn on heavily in the paper Rickwood and Glazebrook (2009).

close to the city, and another in a far-flung suburb. He surveyed 547 persons in 212 households, and found that energy use was higher in the outer-suburban development, and that the principal cause was a dramatic increase in transport energy use. In particular, the primary transport energy use of households in the inner suburb was one-third of that used by households in the outer suburb. Because Perkins' analysis is based on actual travel surveys, and is also in Adelaide, it can be used to check the estimates obtained in a separate study by Troy et al. (2003), which investigated dwelling-related and transport-related energy use in several Adelaide suburbs. Doing so, one finds that the simplifying assumption employed by Troy et al. (2003) (per-vehicle fuel consumption is constant across the Adelaide metropolitan area), introduces significant distortions into their analysis, and results in an underestimate of transport energy use for more remote houses. In particular, Troy et al. (2003) estimate inner ring houses in a suburb like Norwood use around three-quarters of the transport energy of more remote areas like Brahma Lodge and Woodcroft, but, based on Perkins' results, we would expect this to be closer to one-third. Perkins estimates that household life-cycle greenhouse emissions from transport are of a similar magnitude to those attributable to dwelling-related energy use (i.e. both in-dwelling and embodied) – see Figure 4.1. Importantly, he also finds that transport-related emissions are much more variable than dwelling-related emissions.

One of the difficulties in interpreting the results from Perkins' work is that, while the overall pattern of increasing transport energy and emissions in outer-suburban development is clear, the analysis is not properly controlled. It is possible that the households that choose to live in the inner suburb are not comparable with those that choose the outer suburb. Household size, composition, age, and income will be different in the two suburbs, and these differences may account for part of the observed difference in energy use and greenhouse emissions. This observation is part of the reason why, in this thesis, I have chosen to take a different approach, and do metropolitan-scale modelling, rather than concentrate on travel and energy use surveys.

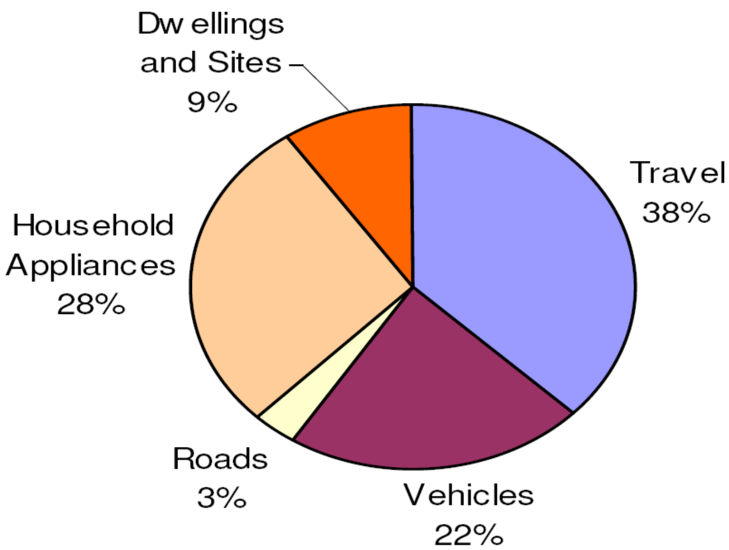


Figure 4.1: Average household greenhouse emissions for all households sampled in the survey work of Perkins (2002), reported in Perkins and Hamnett (2005).

Fuller and Treloar (2004) looked at the energy and greenhouse emission profile of a 'typical'

Melbourne resident from the 1950's until today, and concluded that the increase in household emissions over the period is mostly the result of increased transport-related emissions. Norman et al. (2006), in a case study in Toronto looking at transport and dwelling-related energy use and greenhouse emissions, find that there is much less energy use per person in inner-city high-density areas than in suburban areas, mainly because transport-related emissions are lower.

Petter Næss has conducted a number of detailed studies into the effect of urban structure on travel behaviour (Næss, 2001, 2005, 2006). Næss (2005), for example, combined travel survey data with qualitative questionnaires to determine the factors determining travel behaviour in Copenhagen. Detailed measures of urban structure were collected, and he found that changes to household location, and urban structure variables at different locations, were associated with large changes to travel behaviour. He found, for example, that the average person living in the 4th distance quartile from the CBD travels (by car) 15 times the distance of someone in the first quartile on a weekday. These are *median* values, so this multiple is very large. He found non-motorised travel was much more prevalent in inner areas, and, importantly, that weekend leisure trip distances (by car) were also greater for outer areas, casting some doubt on the 'compensatory travel' hypothesis proposed in Holden and Norland (2005) – that inner-city households undertake additional leisure travel to compensate for the lack of green-space they experience in their inner-city location.

Although the focus of my review has been on research using simpler measures such as distance from the CBD and density, there is a considerable body of research that utilizes more sophisticated measures of urban structure. The influential work of Kockelman (1996); Cervero and Kockelman (1997), for example, investigated the influence of activity density, land-use diversity, and urban design on travel behaviour. Cervero and Duncan (2006) investigated the role of jobs/housing balance, and found a large reduction in travel in those areas with better jobs/housing balance. Cervero (2002) found that including variables relating to the built environment in discrete-choice models of travel behaviour improved model accuracy, and suggested that the more traditional approach of concentrating on demographic variables and travel time/cost variables may result in biased model parameters. Kawabata and Shen (2006), in a comparison of urban structure in Boston, Los Angeles, and Tokyo, found that accessibility to employment was a good indicator of how dependent city residents were generally on automobiles for their travel. Frank and Pivo (1994) also found that mixed land-use at trip origins and destinations both had positive impacts on walking and public transport use. In short, the importance of mixed land use, accessibility, urban design, and jobs/housing balance[2] is less contested than the importance of density. The recent review by Ewing et al. (2007), for example, concluded that compact development with mixed land use, that increased the number of destinations within walking distance of residents, could play an important role in reducing transport-related emissions. Evidence emerging from studies such as these suggests that while a range of urban form parameters describing land use mix, accessibility, urban design and jobs/housing balance, are all related to transport energy use, the simple single parameter of density often serves as a useful proxy variable for more relevant, but difficult to measure, variables describing the built environment (see Kockelman (1996); Rickwood and Glazebrook (2009) for explicit expressions of this argument).

[2]Technically, jobs/housing balance is just a special case of mixed land use, but it has received so much attention that I think it warrants individual treatment.

Despite the now large body of research confirming the importance of more complex urban structure variables such as jobs-housing balance and land-use mix, some authors claim that even including these more complex measures is insufficient to capture some of the accessibility benefits arising from transport projects. Geurs et al. (2006), for example, claim that even those studies that move beyond a simple consideration of density, and use more sophisticated accessibility measures, often fail to capture the accessibility benefits of joint transport and land-use changes. Local transport improvements, they claim, have region-wide effects on the distribution of jobs, which is generally agreed to have a significant affect on travel behaviour (Kockelman, 1997; Cervero and Duncan, 2006), and yet it is not possible to capture this effect in a static regression analysis. This argument is, in effect, another way of saying that integrated land-use/transport models are required to fully understand the interaction between changes to transport infrastructure and changes to land use.

This completes the introduction and supplementary transport-specific literature review. The remainder of this chapter contains three studies of travel behaviour – the first two empirical, and the final one theoretical/mathematical.

4.2 Urban structure and commuting in Australian cities

4.2.1 Introduction

There has been much interest by urban researchers in a variety of disciplines in the relationship between urban form and travel behaviour. The quantity of research in this area is large enough to support large bodies of work investigating (and often advocating) plans and policies to influence urban travel behaviour. For example, research indicating that higher population density, mixed land use, and public transport provision result in significant shifts in travel behaviour has been the ammunition for those arguing for urban planning policies that favour higher-density development around public transport nodes (Cervero and Kockelman, 1997; Newman and Kenworthy, 1999). The motivation for such urban compaction is often environmental, although social, health, economic and aesthetic concerns are also cited (Newman and Kenworthy, 1989; Frumkin et al., 2004). Such policies, however, have not had unequivocal support, either in the research community (Troy, 1996; Levinson and Kumar, 1997; Holloway and Bunker, 2005), or amongst the general urban citizenry.

The principal aim of this study is not to advocate for or against particular planning policies, as there is an extensive literature on this already[3]. Instead, I will give a brief overview pointing to some of the major relevant publications on both sides, and then proceed with a more descriptive task – conducting an analysis of how spatial structure affects journey-to-work travel behaviour in contemporary Australian cities. I take a spatially disaggregated approach, but without adopting anything as sophisticated as the discrete choice models used in modern transport micro-simulation, as such an approach would require extensive data collection and model calibration that would preclude me covering all mainland state capitals. Despite the simpler nature of my approach, the breadth and spatial resolution of the coverage provides useful insights into how inter and intra city variations in spatial structure are associated with journey-to-work mode choice. Doing such an analysis for Australian cities, with broadly similar economic and cultural features, invites the possibility of inference not possible in international groupings due to the significant economic, political, and cultural differences inherent in comparisons of international cities.

4.2.2 Review

Most inter-city studies into the effect of urban density have used metropolitan population density, partly because this is a comparatively easy measurement to collect – an important consideration in inter-city comparisons. Intra-city research is more likely to use complex land-use measures, such as land-use mix (Cervero, 1996), jobs-housing balance (Cervero and Duncan, 2006), and regional (Rodriguez et al., 2006), or even U.S. Census Tract population density (Golob and Brownstone, 2005). Regarding the effect of density, the intra-city research is somewhat mixed, with some studies finding minimal (or no) effects of density after controlling for demographic effects (Crane and Crepeau, 1998), while others find significant effects (Geurs et al., 2006). Results from inter-city comparisons are also mixed, although the larger studies (such as Kenworthy and Laube (1999); Ewing et al. (2001); Bento et al. (2003); Baum-Snow and Kahn (2005)) generally support the notion that some measure of population distribution is important, although even here there

[3] The nature of the data I analyse, however, makes some general policy related remarks inevitable.

are exceptions, such as the review by Boarnet and Crane (2001a). It is generally understood that many other factors besides macro-scale density have an effect on travel behaviour in cities. Among them are total city population, geographic constraints on city shape and transport infrastructure, fuel and transport taxes and subsidies, populace wealth, and city cultural and economic history. There are many others besides, and some researchers have reanalysed Newman and Kenworthy's original data with a re-emphasis on the explanatory power of these other variables (Gordon and Richardson, 1989; Kirwan, 1992; Mindali et al., 2004).

Figure 4.2 shows the metro-area density and public transport energy efficiency of most of the same Australian and U.S. cities analysed in Newman and Kenworthy (1989), using the more recent dataset in Kenworthy and Laube (2001). While one can argue that this data indicates a negative link between city density and public transport energy use[4], there is still significant city and country specific variation unexplainable by macro scale density. While other factors such as those already mentioned likely explain part of this variation, it is highly likely that some significant portion of the unexplained variation is related to urban spatial structure, but at spatial scales below that of the city as a whole – neighbourhood, suburban, and city-subregion. The following analysis attempts to determine the relationship between travel behaviour and urban structure in Australian cities, by examining modal split for the journey to work.

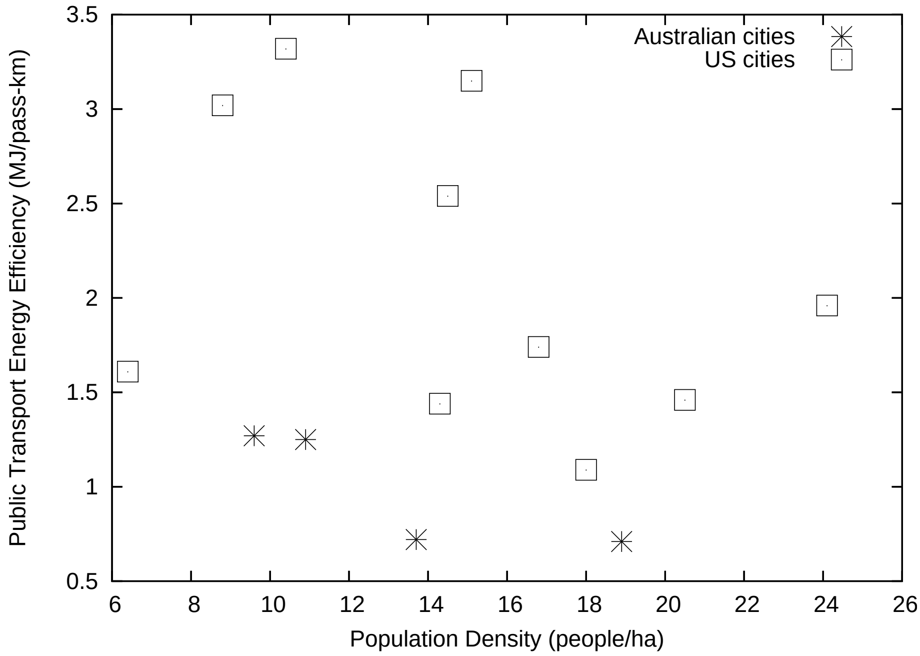


Figure 4.2: Public transport energy use per passenger-kilometre for Australian and U.S. cities of varying densities (in order of increasing density: Atlanta, Houston, Brisbane, Phoenix, Perth, Melbourne, Washington, San Diego, Denver, Chicago, New York, Sydney, San Francisco, Los Angeles). Source: Kenworthy and Laube (2001).

[4]Although not shown in the figure, the least squares fit to the Australian and U.S. cities shown (both collectively and separately) are all negative.

4.2.3 Data

For the initial analysis, Australian Bureau of Statistics (ABS) 2001 Census data is used, at the Collection District level, which is the smallest area over which data is aggregated – generally comprising around 500-1000 persons in an urban area. This can result in spatial aggregation over areas as little as 2500m^2, though 250,000m^2 is more typical. Individual unit record data is available, but without valuable spatial information, and so is not useful for spatial analysis. The ABS census data, while having the disadvantage (over travel survey data) of being spatially aggregated, does have the advantage that it has comprehensive spatial coverage, is collected at (for all practical purposes) a single point in time, and has a uniform survey/collection methodology across Australia's urban areas.

The distinct advantages of the census data make it useful as an alternative to more typical travel survey/diary methods. Travel survey methods collect richer, more detailed information about travel patterns and preferences at the household level, but suffer from problems of their own. The expense of collection means that only a very small subset of all households can be surveyed, and so the samples are usually spread thinly over a wide geographic area. Household travel behaviour is also known to be highly variable (even after controlling for important demographic variables). There are a few different approaches that can be taken in response to the high variability in individual travel behaviour, which I will not describe in detail here, except to say that one common approach is to aggregate both spatially and temporally to reduce variance[5]. Such an approach is troubling, as it is the first rule of urban economics and geography that location matters, and, given the spatial aggregation necessitated by survey size, it seems unlikely that all relevant spatial information is captured by transport surveys and models. While using Census data allows me to work at a finer spatial scale, with more reliable data, the drawback is that we are limited to working with the journey to work as the only description of actual travel behaviour[6]. Though origin-destination journey to work trip data is available from the ABS, obtaining it at the Collection District level for each mainland capital is expensive, and requires significant additional processing and analysis. In this study, I analyse only modal choice by origin, as this simplification allows me to easily compare modal choice patterns across the mainland Australian capitals[7]. I do this only as a first step; In other studies, I analyse origin-destination data (see particularly Section 4.3).

For each of the mainland state capitals, I define a broad latitude/longitude bounding box that includes the metropolitan area of the city. The top-left and bottom-right corners of the bounding boxes are shown for each city in Table 4.1. Every Collection District that has a centroid within the bounding box and a population density greater than 5 people per hectare[8] is defined as part of the residential urban area of that city. The region so defined for Sydney is shown in Figure 4.3.

This definition of residential urban area has the advantage that it avoids the need to deal with artificial boundaries, which can introduce significant distortions to measures of urban form, such

[5]Corpuz et al. (2006) aggregated 9 years worth of data at the Travel Zone level. There are approximately 7 Collection Districts to each Travel Zone in Sydney, on average. Hensher and Ton (2002) aggregated at the ABS Statistical Sub-Division level in their analysis of mode choice.

[6]Car ownership provides important indirect evidence, but I do not discuss this here, except as it relates to commute mode choice.

[7]While I do include Adelaide in this analysis, it receives less attention than the other 4 state capitals, as it rained in Adelaide on the morning of the 2001 Census, and rain is known to affect mode choice.

[8]After trial and error, I found this cutoff value the most effective in excluding urban-fringe agriculture and hobby-farmers while still including what I would consider genuinely urban development.

City	Top-left Lat/Long	Bottom-right Lat/Long
Sydney	-33.4/150.7	-34.25/151.5
Melbourne	-37.55/144.25	-38.5/145.6
Brisbane	-27.28/152.95	-27.7/153.4
Perth	-31.65/115.6	-32.6/116.05
Adelaide	-34.66/138.45	-35.2/138.75

Table 4.1: Bounding boxes that include the bulk of the metropolitan areas of the mainland Australian state capitals.

as density[9]. I do not use the well known definition of urban centre provided by the Australian Bureau of Statistics (see Australian Bureau of Statistics (2005a)), as the combination of the low population density threshold used (2 people/ha), and the general criteria for inclusion, can result in large areas of sparsely inhabited land being included. In other analyses, the ABS definition may be more appropriate, but because I use population density extensively in this thesis, and because the indicator variable used (public transport mode share) only makes sense in residential areas, my criteria for inclusion is more appropriate for this analysis. My approach, because it excludes even inner city areas with low population densities (such as parkland and industrial land), results in a higher metropolitan-area density[10] than other studies, but the general inter-city ranking is comparable with other estimates of macro-scale density (see Figure 4.4), allaying concerns that my unusual definition of an urban area produces results so radically different from traditional definitions that it will distort the analysis. The preceding discussion of how I calculate metropolitan density, and how else it might be done, highlights some of the difficulties in defining and calculating what is a commonly used indictor of urban form. For more discussion of density in an Australian context, and some of the difficulties involved in defining and measuring it, see McLoughlin (1991).

4.2.4 Analysis and results

Let us consider two hypothetical cities. Suppose these cities have the same size and population (and hence the same aggregate population density). These cities may, nonetheless, have significantly different distributions of urban population. One might be a traditional mono-centric city with population densities declining monotonically beyond an inner city employment core. The other might be poly-centric. The possibilities are of course endless. Making fairly strong assumptions about the validity of the classic urban economic model of Alonso (1964); Mills (1967); Muth (1969), one can argue, as Bertaud and Malpezzi (2003) do, that economic forces will dictate a more or less Muthian inverse exponential population density gradient, provided there is a reasonably free land market. However, the limitations of the theory, land market restrictions, and geographic constraints can all make actual observed patterns distinctly non-Muthian. Without knowledge of the finer scale structure of the cities, our ability to make sense of city-level outcomes is limited.

If our interest is in urban travel mode (private auto versus public), we can reasonably suppose

[9] It avoids, for example, the inclusion of large areas of land that are within city boundaries, but which are not developed.

[10] Calculated in this study as the sum of urban Collection District populations over the total area covered by those Collection Districts.

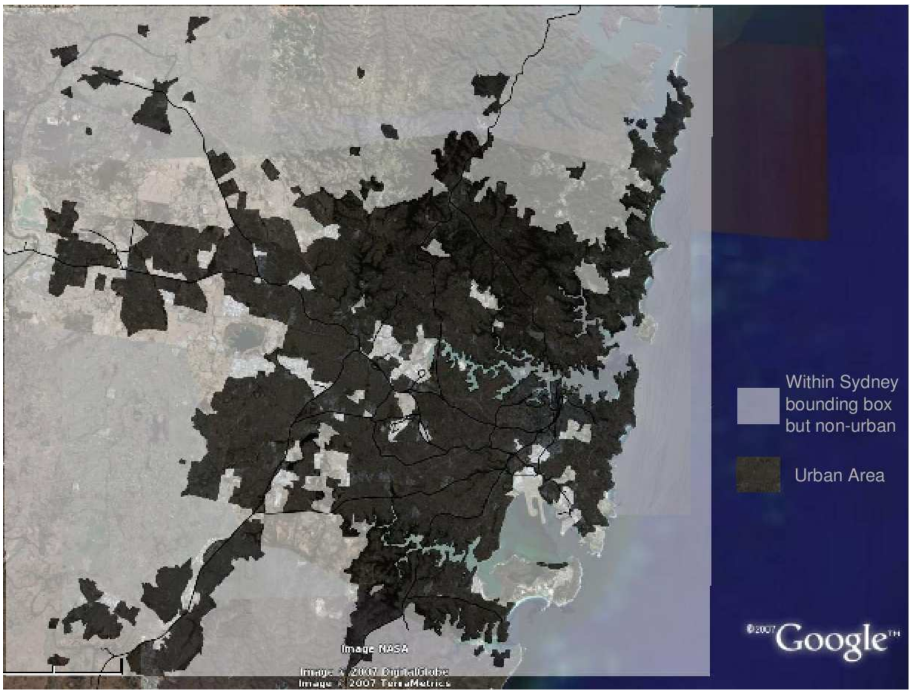


Figure 4.3: The areas of the Sydney basin defined as urban residential by our method.

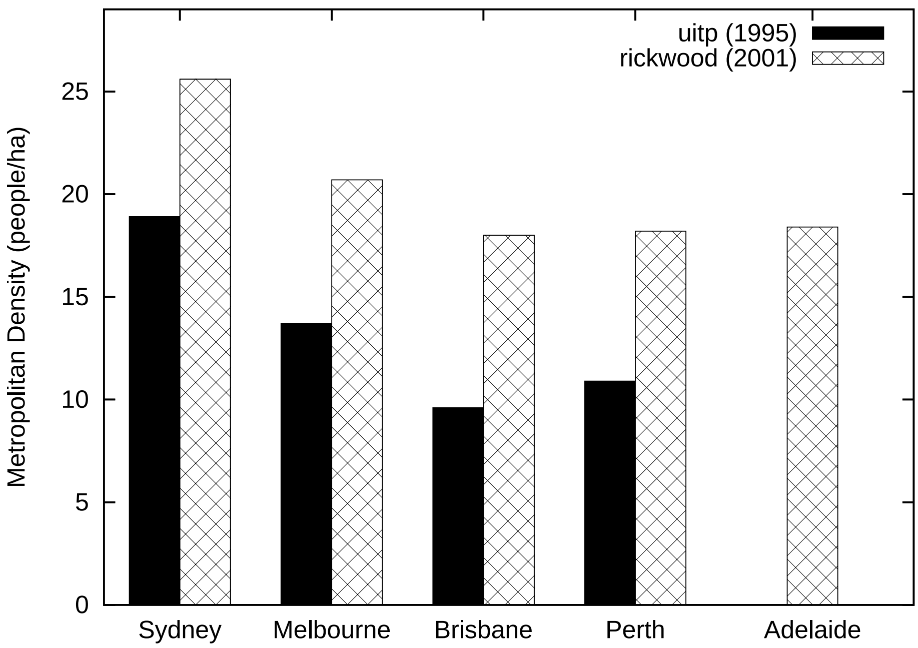


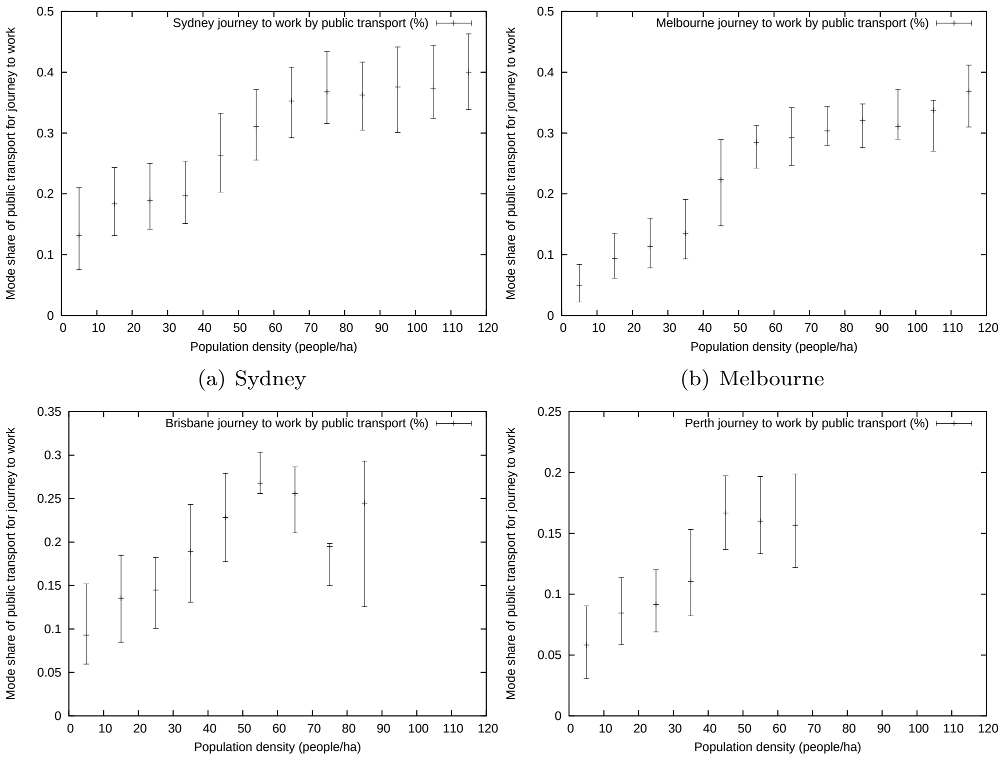
Figure 4.4: Metropolitan population density calculated 'top-down' from Kenworthy and Laube (2001) (with key uitp) for 1995, against metropolitan density calculated 'bottom-up' from ABS 2001 Census Collection District data (with key rickwood) in 2001. Note: Adelaide density for 1995 not reported, as it was not calculated in Kenworthy and Laube (2001).

that a city with a population distribution that allows for an efficient public transport system will have more efficient public transport outcomes. It is generally acknowledged that higher density development is more suitable for public transport. The actual argument is straightforward – the scale economies of mass transit are obvious, but require land use clustered around transit stops, to allow for higher patronage (transit catchment area) and better overall transit network coverage (see Small (1992) for a lengthier exposition).

If we restrict attention to commute travel, we can use the ABS census data described in section 4.2.3 to analyse how micro-scale density measures are related to commute mode choice in modern Australian cities. Modern transport modelling treats mode choice within a discrete choice framework (McFadden and Train, 2000; Koppelman and Bhat, 2006) where mode share is determined by the relative utilities of the different modes, but such an approach requires extensive data collection. For examples of Australian work in this vein, see Hensher and Ton (2002); Hensher and Rose (2007). As an alternative to the standard discrete choice model approach, census data aggregated at a fine spatial scale is sufficient to provide some useful descriptive statistics, and insights into likely individual behaviour. Figures 4.5a-d show the relationship between CD level population density and public transport commute mode share in Sydney, Melbourne, Brisbane, and Perth. Each figure shows the median and upper/lower quartiles of commute mode share for CDs within each 10 people/ha range, produced by grouping CDs into 10 people/ha ranges based on population density, sorting within each group by public transport commute mode share, and then calculating the median and upper/lower quartiles for each group. In Brisbane and Perth, higher density ranges contain few CDs, and so estimates are unreliable, as indicated by the irregular interquartile ranges.

Figures 4.5a-d are interesting, and, naïvely, one might suppose that they provide support for those arguing that higher-density living results in higher public transport mode share. The pattern of increasing mode share with density up to around 70-80 people/ha is consistent across the cities studied, so is unlikely a chance occurrence, but whether or not density is actually a determining factor, or simply masks some other underlying processes, is still far from clear. It is quite easy, for example, to mount an argument along land-economic lines that explains the patterns shown in Figures 4.5a-d. One need only point out that land prices increase closer to the city centre, which encourages substitution of capital for land (i.e. higher density), and hence it is simply *proximity* to the CBD that is the actual factor influencing public transport mode share, and that the correlation with density is a by-product of urban economic forces. It is possible to test such an argument with the ABS data available. Figure 4.6 shows public transport mode share as a function of both density and distance from the CBD. We can see that public transport mode share does indeed decline with distance from the CBD, but that it also increases with density independently of distance from CBD. However, the difference between low and medium densities is small, with the largest increase in mode share being at higher densities.

While figures 4.6a-d suggest more strongly that density is an indicator of public transport use (and presumably provision), the effects seem limited at densities below 40 people/ha. There are large increases in public transport mode share at densities above 40 people/ha, independent of distance from CBD, and this might be taken as supporting evidence for some 'critical threshold' density of around 30-40 people/ha (as suggested, for example, by Newman and Kenworthy (1989); Holtzclaw (1994)), below which public transport fails to attract sufficient riders to support frequent



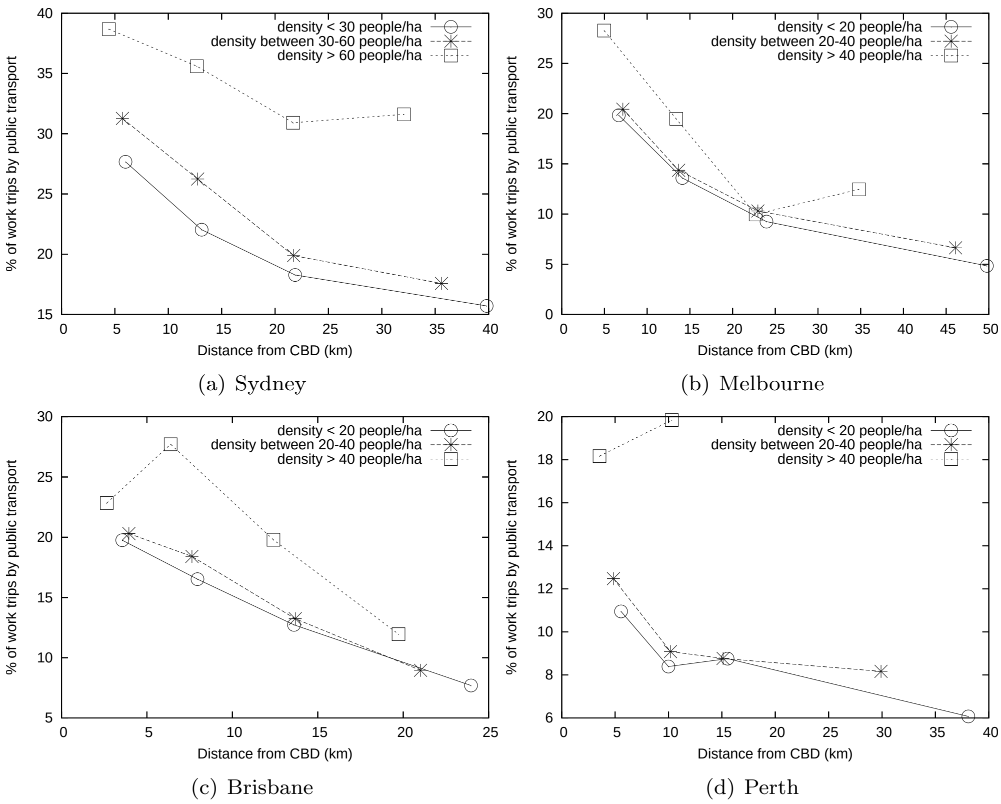
(a) Sydney

(b) Melbourne

(c) Brisbane

(d) Perth

Figure 4.5: Mode share of public transport for journey to work by origin CD density. CDs are grouped into 10 people/ha ranges, and the median and upper/lower quartiles are shown for each group. Data Source: ABS 2001 Census.

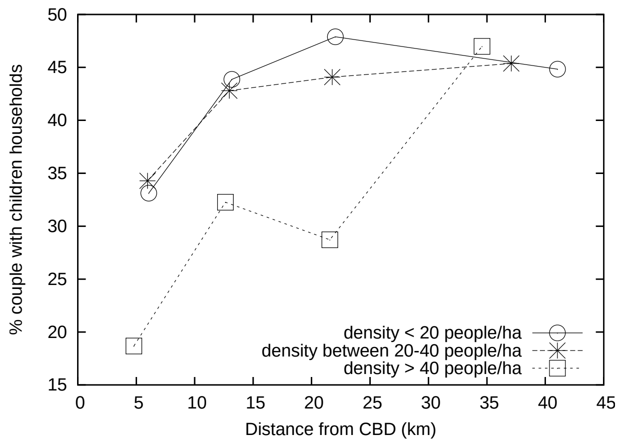


(a) Sydney (b) Melbourne

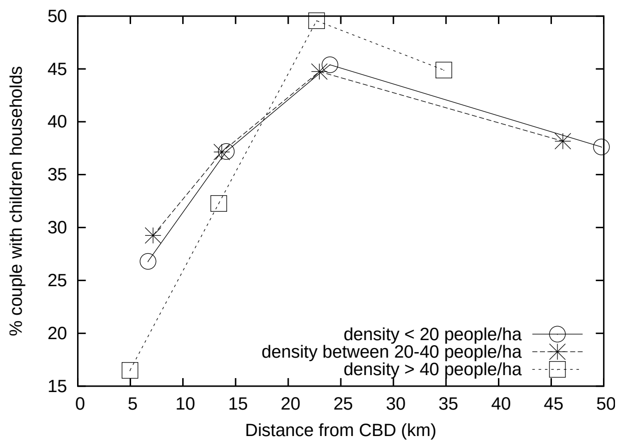
(c) Brisbane (d) Perth

Figure 4.6: Relationship between distance from CBD, residential density, and mode share of public transport for the journey to work. Data Source: ABS 2001 Census.

reliable services. However, since it is quite clear that demographic factors vary with density, it is possible that demographic factors could at least partly explain the large increase in public transport ridership in high-density areas. For an illustration, see Figure 4.7, which shows the variation (with distance and density) in the proportion of households that consist of a couple with dependent children in Sydney and Melbourne.



(a) Sydney



(b) Melbourne

Figure 4.7: Proportions of households with dependent children versus distance from the CBD and micro-scale population density in Sydney and Melbourne. Data Source: ABS 2001 Census.

Since inner-city residents are distinct from middle and outer-city residents, and since, in cities other than Sydney, almost all high density development is in the inner-city, it is difficult to tease apart demographic and income effects from location and spatial structure effects. My approach is to run two regressions: the first on Collection District data from all capitals; and the second on Collection Districts in Sydney alone, which has sufficient demographic and spatial diversity at all densities to allow for a controlled analysis. If results in Sydney are different from those for all state capitals, we should be wary of the all-capitals results. In addition, the Sydney-alone analysis serves as a base case for a more detailed Sydney-specific analysis, which I describe later. Initially including demographic variables (such as household income, proportion of households being families with children, etc.), I found significant collinearity between variables, and found that income and the proportion of households being families with children were themselves good predictors of car ownership (see Table 4.3). I chose to exclude family structure and income, and retain cars per household as an independent variable because household structure and income are generally accepted as major causal factors determining car ownership, a claim further strengthened by the regression results shown in Table 4.3. Indeed, this is why, in disaggregate discrete choice modelling with a nested logit model, mode choice is often conditioned on car ownership.

The results of the two regressions for journey to work mode split are shown in Table 4.2. In both cases, the same predictor variables were chosen. The results suggest that, in Australian cities generally, and in Sydney, that distance from the CBD, city-wide factors, and car ownership (which is itself determined by demographic factors), are important, but that local-area density seems to have a small direct effect. However, local area density also has an indirect effect, as it is associated with reduced car ownership – a major determinant of modal choice. Results based on data from Sydney alone (which has a higher proportion of higher density development), are not greatly different from results on all capital cities. For an analysis of mode choice using a small number of aggregate variables, the explanation of variance is surprisingly good, and the consistency of the results suggests that local area density is, if not a causal factor, at least a useful proxy for predicting car ownership and mode choice. A more important factor, however, seems to be the general spatial structure of the city (measured in the regression, I would argue, by city-specific dummy variables), and location within the city.

Variable	All cities	Sydney
constant	0.912	0.55
distCBD	0.004(0.333)	0.005(0.354)
localpopden	−0.021(−0.081)	−0.008(−0.035)
carsperhh	0.247(0.521)	0.281(0.647)
sydney-dummy	−0.195(−0.539)	NA
melb-dummy	−0.101(−0.278)	NA
brisbane-dummy	−0.084(−0.153)	NA
perth-dummy	−0.044(−0.087)	NA
r^2	0.746	0.753

Table 4.2: Left column shows regression results for mainland Australian state capitals (Sydney, Melbourne, Brisbane, Perth, Adelaide). Right column shows regression results for Sydney specifically. Dependent variable is mode share of automobile travel for the journey to work (arcsine-root transformed). Standardized coefficients in parentheses. All variables significant at $p = 0.001$ level.

The results are understandable if one considers that, within a given city, local area density serves as a useful proxy for relative local access to a transit stop, and a measure such as 'distance from CBD' acts as a reasonable proxy for the overall accessibility (to employment destinations) provided by a local transit stop. To substantiate these claims, I undertake a more detailed analysis of mode choice in Sydney, using more sophisticated land-use and transport variables, rather than the coarse proxies I have used so far.

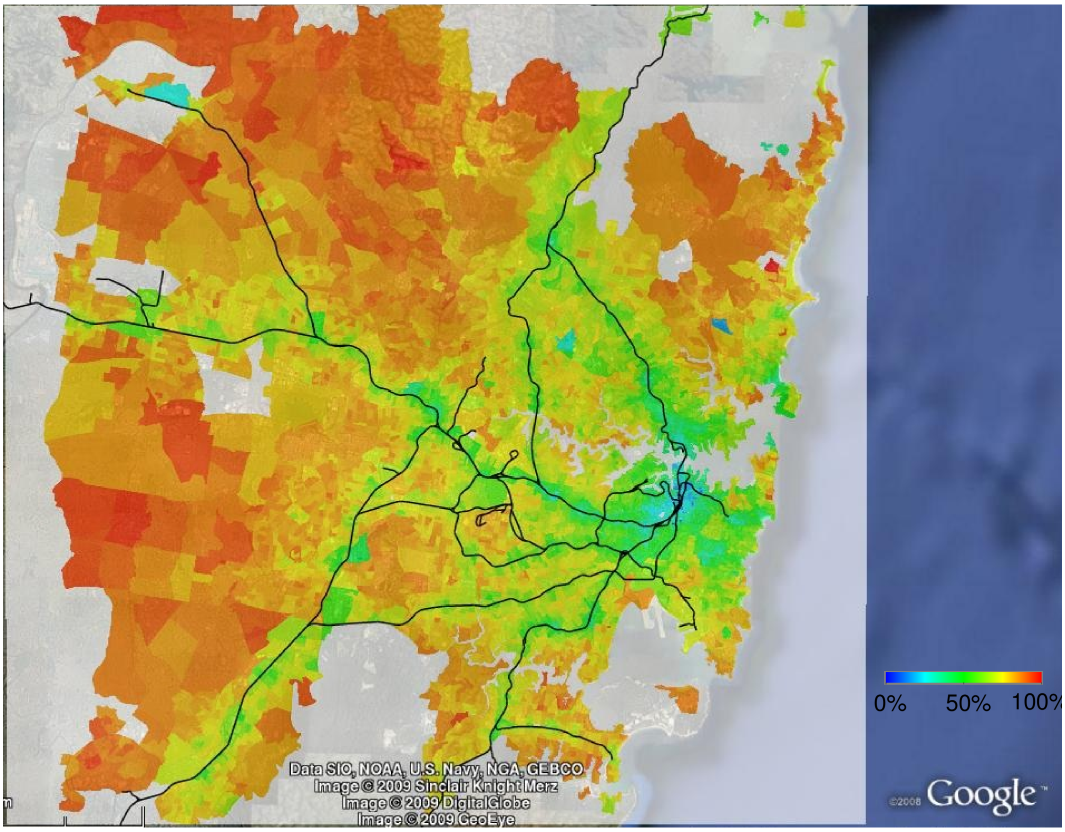


Figure 4.8: Proportion of journey to work trips made in a car in Sydney, at the ABS Census District level. Darker colours indicate higher proportions of trips by car (see embedded scale). Data Source: ABS 2001 Census.

Variable	All cities
constant	1.4924
distCBD	0.003
localpopden	−0.0971
income	0.4097
propcouplewkids	1.3572
sydney-dummy	−0.29
melb-dummy	−0.0764
brisbane-dummy	−0.0852
perth-dummy	0.0345
r^2	0.846

Table 4.3: Regression results for car ownership (dependent – cars per household) in the mainland Australian state capitals (Sydney, Melbourne, Brisbane, Perth, Adelaide). Standardized coefficients in parentheses. All variables significant at $p = 0.001$ level. Data Source: ABS 2001 Census.

Sydney specific analysis

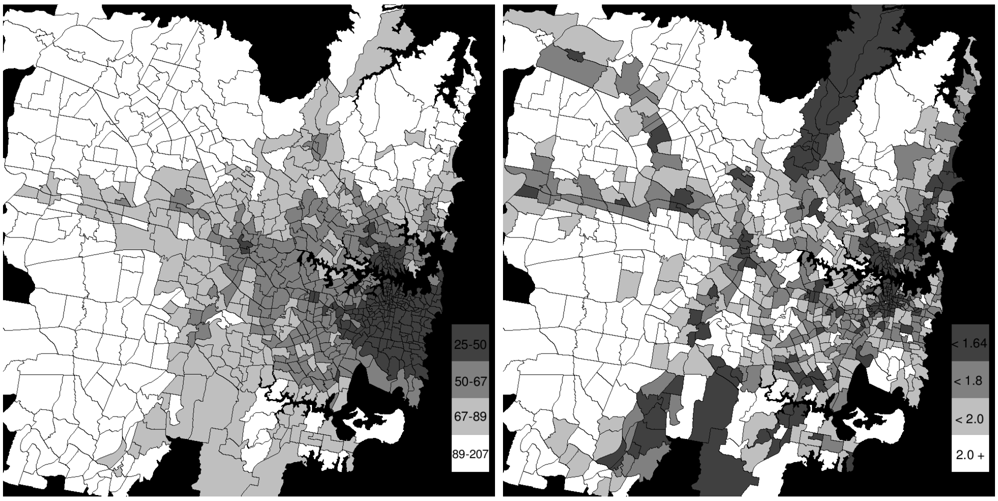
To investigate further the intuition that local area density and distance from the CBD serve as useful proxies for access to public transport, I make use of several detailed datasets of transport and land-use characteristics in Sydney. Glazebrook (2002a) developed detailed public and private transport accessibility measures for Sydney, at the Travel Zone level, of which there are around 800 in the Sydney basin (depending on how exactly one defines the extent of the basin). I include his accessibility measures in the analysis. I have also obtained, and include, the same land-use mix, employment, and transit access measures used by Corpuz et al. (2006) in their analysis of household vehicle use. Finally, I calculate and include my own measures of proximity to commercial land and walking-catchment proximity to jobs. Space limitations prevent the in-depth specification of how each measure is calculated, so I only provide more detailed descriptions for those variables that are found to be significant in the analysis that follows.

Glazebrook (2002a) describes the development of separate accessibility measures for public transport and private automobiles in Sydney, at the Travel Zone level. The measure is a complex distance weighted measure of accessibility to all destinations, from all destinations. I include the separate measures themselves, as well as their ratio (reflecting the *relative* accessibility provided by public transport compared to car). Figure 4.9a shows public transport accessibility (darker colours indicate better access), and Figure 4.9b shows the ratio of public/private accessibility (with darker colours representing relatively more competitive public transport).

To capture local area employment density, I use ABS journey to work data to calculate the number of jobs in each Travel Zone. Assuming jobs are uniformly distributed within Travel Zones[11], I then calculate the number of jobs within a 1.5km walking catchment of each Travel Zone centroid. Concretely, I calculate the following for each Travel Zone:

$$\ln(1 + \int_0^{2\pi} \int_0^{1.5} r\text{jobs}(r, \theta)\, \mathrm{d}r\, \mathrm{d}\theta)$$

[11] Of course this is not the case, but Travel Zones are generally smaller where job concentrations are large, so the distortion introduced is generally not large, and the measure is still of use, as indicated in the analysis.



(a) Accessibility provided by transit (b) Public/Private transport accessibility ratio

Figure 4.9: Left: Accessibility by public transport in Sydney (in minutes). Right: Accessibility by public transport relative to accessibility provided by car (unitless ratio). Source: Glazebrook (2002a). Source: Glazebrook (2002a) .

with each Travel Zone centroid acting as the origin, r being the distance (in km) from the centroid, θ being the direction, and jobs(r, θ) being the number of jobs at polar coordinate (r, θ) from the Travel Zone centroid. I have found the log transformation necessary, as otherwise employment in the CBD so dominates the measure that very little about employment concentration in other areas is available.

Results of the regression are shown in Table 4.4. The r^2 of the model shown is slightly lower than the best model obtained during analysis, but better models had problems with collinear variables. In particular, median household income improved model fit, but was, against expectations, negatively related to car commuting, and, as in the earlier analysis, positively related to car ownership. Somewhat surprisingly, other land-use and transport variables, such as the land-use mix and public transport access variables used by Corpuz et al. (2006), did not improve the model. Similarly, local area population density was not found to have a large effect[12].

Variable	Coefficient	Standardized Coefficient
constant	0.56	NA
distCBD	0.002	0.203
carsperhh	0.206	0.467
PubPrivRatio	0.066	0.115
logLocalJobs	−0.049	−0.278
r^2	0.886	

Table 4.4: Regression results for mode share of private automobile for the journey to work (dependent variable, arcsine-root transformed) in Sydney, at the Travel Zone level. All variables significant at $p = 0.001$ level. Data Source: ABS 2001 Census.

[12] A small, but statistically significant effect for local area population density was detected in many of the regressions, but was, against expectations, positively related to car mode share, and also suffered from collinearity problems.

Figure 4.10: Number of jobs within 1.5km of each Travel Zone centroid in Sydney. Source: Author's calculations based on ABS 2001 census data..

The regression results, again, are not surprising. As in the analysis with simpler explanatory variables, car ownership and increased distance from the CBD increase the likelihood of a car-based commute. The proportion of commuting by car also increased when local public transport provided access that was not competitive to that of the car (as measured by the PubPrivRatio variable – see Figure 4.9b). Also, as in the earlier analysis, I found that car ownership in Sydney was well explained ($r^2 = 0.899$) by household characteristics (income and proportion of households with children), and coarse urban structure/location descriptors (local area density and distance from CBD), but, as more complex measures of urban structure and location are introduced, the strength of the association with local area density and distance from the CBD either disappears (in the case of distance from CBD), or lessens considerably (in the case of local area density).

Correlations between the complex transport/land-use variables and the simpler proxies used in the earlier analysis are shown in Table 4.5. Correlations are as one would expect, with local area population density, local area employment, and measures of access to public transport all positively correlated with one another, and negatively correlated with car ownership, distance from the CBD, and use of car for the commute. From this, it is easy to see that when the more useful measures such as car ownership, local employment, and public transport access are unavailable, local area density can serve as a useful proxy, and this is why it so frequently shows up in the literature as being associated with a higher modal split for public transport. As one would expect, if one leaves car ownership out of the regression, local population density, local jobs, and distance from the CBD all have stronger effects, in line with most other research.

	carsperhh	distCBD	PPRatio	localJobs	PopDen	ptaccess	carjtw
carsperhh	1	0.6	0.66	-0.82	-0.69	-0.73	0.89
distCBD	0.6	1	0.47	-0.68	-0.61	-0.69	0.72
PPRatio	0.66	0.47	1	-0.61	-0.59	-0.65	0.68
localJobs	-0.82	-0.68	-0.61	1	0.64	0.68	-0.86
localPopDen	-0.69	-0.61	-0.59	0.64	1	0.75	-0.63
ptaccess	-0.73	-0.69	-0.65	0.68	0.75	1	-0.68
carjtw	0.89	0.72	0.68	-0.86	-0.63	-0.68	1

Table 4.5: Correlations between variables describing urban structure and location in Sydney. All correlations significantly different from 0, at a 0.001 confidence level. Data Source: ABS 2001 Census.

4.2.5 Discussion

On a purely descriptive front, the picture painted from the analysis of Australian cities is fairly clear. Within a city, there is a consistent increase in public transport mode share with increasing local density, independent of other factors. There is also a consistent reduction in public transport mode share with distance from the CBD, independent of other factors. The strength of these relationships lessen as more complex measures of urban form and access to public transport are introduced into the analysis, suggesting that local area density and distance from the CBD are useful proxies for transit-based accessibility. Having restricted myself, thus far, primarily to description and narrow analysis I now allow myself a few more general comments, and a speculative one or two. A particular note of caution about what follows: to make any inferences about future travel behaviour from the analysis already presented requires that one accept that relationships "discovered" in the analysis of cross-sectional data will continue to hold in the future.

Between cities, public transport mode share is generally higher in cities with higher metropolitan density. I do not find these results surprising, but the weakness of local area density as a direct determinant of mode choice may surprise some. The more detailed analysis of Sydney suggests that local area density is correlated with both better access to, and better access provided by, public transport, and hence ceases to provide much explanatory power after more sophisticated measures of transit access are introduced. Even serving as a proxy, without complex land-use/transport measures, the effect of local area density is small relative to distance from the CBD and car ownership. However, the indirect link between local area density and car ownership increases its usefulness in situations where car ownership information is unavailable. Given these results, it is not surprising that other studies that include car ownership and complex land use and transport variables find no (or small) effects of density (Crane and Crepeau, 1998; Boarnet and Crane, 2001a). Similarly, it is unsurprising that studies relying heavily on density as a measure of urban structure (such as Newman and Kenworthy (2006)) find a strong link between density and transport outcomes such as car ownership, car use, or mode split.

The regression results for Sydney and the Australian mainland capitals suggest a simple formulation of the relationship between transit use and city structure. Within a given city, there is a function relating better access *to* local public transport and higher public transport use. However, this effect is relatively small, which explains the difficultly in detecting marginal effects of small scale improvements to local transit infrastructure. Access *provided by* local transit, on the other hand, is a much better predictor of transit use. Accessibility by public transport is related to local access to a transport stop, but is more strongly related to general city wide factors, such as transport network structure and activity distribution. Changes to travel behaviour as a result of improved local transit provision do not occur only at the local scale. A new rail line will increase public transport use along that rail line, but also, will result in increased patronage across the urban area because of the overall improvement in transit network coverage. That this metropolitan scale effect will be small in any given area, makes its effect difficult to detect on anything but on a city-scale. Large scale inter-city comparisons consistently show a relationship between transit network kilometres and transit mode share (Kenworthy and Laube, 1999; Badoe and Miller, 2000).

While many studies note that self selection effects are important in transport studies, and difficult to control for (Levinson and Kumar, 1997; Cervero, 2002), the consistent patterns found in the inter-city analysis suggest that independent effects of urban structure are still significant, because while it is plausible that people select residential location based on transit availability, it seems less likely that people will select cities based on transit availability. Given that there is a uniform trend to higher transit mode share with increasing macro-scale density, it seems likely that self selection is only part of the explanation. This assessment fits with general inter-city review studies (Kenworthy and Laube, 1999; Bento et al., 2003; Baum-Snow and Kahn, 2005).

If the simplifying assumptions inherent in my analysis are not too distorting, then it suggests that moderate increases in local area densities, without changes to transport infrastructure, will result in no change in transit use. Even the improved transit provision typically associated with increases in local area density will produce relatively modest increases in transit use, *all other things equal*. However, to consider these marginal effects alone is misleading, as systematically increasing local area densities allows not only for better provision of, and access to, transit at the local scale, but also for a more extensive overall public transport network in the longer term.

My results indicate that planning strategies developed based on correlation analysis that indicates a link between local area density and transport behaviour are likely to disappoint those hoping for large short term increases in public transport use. In the short term, it is residential development in locations that are proximate to transit stops with good urban-area coverage that will have substantially higher mode share. This is hardly a surprising finding. For most Australian cities this implies either residential development key nodes on the public-transport network (which almost certainly means redevelopment at higher densities), or vastly improved metropolitan public transport networks. In an Australian context, Mees (2000) has argued that the initial focus should be on the latter, with a redesign and restructure of public transport ahead of longer-term city-wide land-use change. Even if the focus instead on redevelopment near existing transport nodes (as in Sydney's Metro Strategy), significant development is still likely to take place on the urban fringe in Australian cities, and my analysis suggests that developing these areas at densities sufficient to allow for the efficient provision of transit will have a small to moderate short to medium term effect on car ownership and modal choice. It would be a mistake to conclude, however, that the type of residential development on the fringe is relatively unimportant in the longer term. To make such a conclusion is to ensure that, without some radical redesign or reinvestment, the overall public transport network degrades over time, as the additional jobs and housing in new release areas become cut-off from the public transport network. Provision of jobs and housing within access to public transport, or expansion of current transport networks, on the other hand, will result in increased mode share not just locally, but over the entire urban area.

4.3 A disaggregate analysis of commuter mode choice in Sydney

The preceding analysis in Section 4.2 raises some interesting questions. However, it does suffer from the deficiency that mode choice is only analyzed in aggregate, and only characteristics of the trip origin are taken into account. In such an aggregate analysis, common factors known to affect mode choice, such as the relative travel time of public/private transport, can only be approximated, through the use of Glazebrook's accessibility metric (Glazebrook, 2002a) (for Sydney), or other proxies such as local area population density and distance from the CBD (for the other mainland state capitals). The benefit of the simple approach taken was that all mainland state capitals could be easily analyzed, and this was useful for the purposes of comparison. However, notwithstanding the Sydney-specific analysis already performed in Section 4.2.4, I felt that to obtain a better understanding of how urban structure affects mode choice, a more detailed analysis was required. This section contains such an analysis. Whilst ideally, I would have liked to take the usual approach to disaggregate analysis of mode choice, and adopted a discrete choice framework, data availability did not allow this, and a logistic regression is used to explain commuter mode choice, based on trip characteristics and characteristics or trip origin and destination. The accuracy of this disaggregate model is much greater than the aggregate model of mode choice already developed in Section 4.2.4 (as shown in Section 4.3.3).

4.3.1 Data

Australian Bureau of Statistics journey to work trip tables from the 2001 census are used. The particular data table used for this analysis is a count of Origin Zone by Destination Zone by Mode, where the zones are Sydney Travel Zones as defined at the time of the 2001 census by the NSW Transport and Population Data Centre. Mode is one of [Train, Bus, Car-Driver, Car-Passenger, Other, No Trip], where multi-leg trips are assigned a 'principal mode' as described in Australian Bureau of Statistics (2001). Only a subset of all defined travel zones are used in this analysis, comprised of 655 of the 905 travel zones defined by the NSW Transport Data Centre. As in the analysis already presented in Section 4.2, only those zones comprising the metropolitan area of Sydney within the Sydney basin are analyzed. For the purposes of this analysis, 'No Trip' journeys are discarded, and all other modes are collapsed into a binary variable with values of either [Car-driver, Other].

The Journey to Work trip table used in the analysis does not provide any information about the characteristics of the commuters themselves. Consequently, I am limited to analyzing mode choice based on characteristics of the trip only. In much analysis of travel behaviour, characteristics of the trip itself, and particularly characteristics of the trip endpoints, is limited (Cervero, 2002, page 266). This analysis, on the other hand, focuses on quite detailed small-area measures describing the urban environment. Because of the lack of commuter characteristics, parameter estimates in the analysis that follows should be treated with caution, as there is the potential for biased parameter estimates. This potential exists, however, in all mode choice analyses. Despite the limitations, there is still much to be gained from such an analysis, given the size of the data set used (560,487 trips), and the spatial resolution (655 zones covering the Sydney basin).

To keep this section to a reasonable length, only those variables that appear in the final regression model are described in detail.

Variables describing trip and trip endpoints

The variables used in the regression are displayed in Table 4.6; more detailed descriptions follow in the remainder of this section.

Name	Regression Variable Name
Median household income at trip origin	ORIG_medincome
Origin zone proximity to employment	ORIG_logworkers
Destination zone proximity to employment	DEST_logworkers
Measure of commercial land at destination	DEST_comproxinvsqlogscale
Relative accessibility provided by transit (compared to car) at trip destination	DEST_ettratio
Origin zone population density	ORIG_logpopden
Destination zone population density	DEST_logpopden
Trip travel time at peak by transit	pubtime
Trip travel time at peak by car	privtime
Ratio of trip travel time by transit compared to trip travel time by car	pubprivratio

Table 4.6: Regression variables used in the logistic regression on commuter mode choice.

Median household income for each origin travel zone was calculated for each zone from the 2001 census.

The natural logarithm of the population density (people per square kilometre) was calculated for each zone by using population count data from the 2001 census. Figure 4.11 shows the values calculated for each zone.

A measure of proximity to employment was calculated for each zone. Specifically, the natural logarithm of the number of jobs within a 1.5km radius of each Travel Zone centroid is calculated. This measure has already been described in more detail in Section 4.2.4 (Figure 4.10), but that Figure is reproduced here (as Figure 4.12) for the reader's convenience.

The ratio of the public-transport/private-vehicle accessibility measures calculated in Glazebrook (2002a) is calculated for each zone. This measure has already been described in Section 4.2.4, but again, the relevant figure is reproduced here for convenience (as Figure 4.13)

A measure of the proximity of commercially zoned land is calculated and included in the analysis. Specifically, the following measure is calculated for each Travel Zone:

$$\int_0^{2\pi}\int_0^{1.5} \frac{C(r,\theta)}{r}\,\mathrm{d}r\,\mathrm{d}\theta \tag{4.1}$$

where $C(r,\theta)$ is 1 if and only if the land at polar coordinates (r,θ) from the zone centroid is zoned as commercial. This measure is similar to the measure of employment already discussed, but is weighted by commercial land area, rather than jobs.

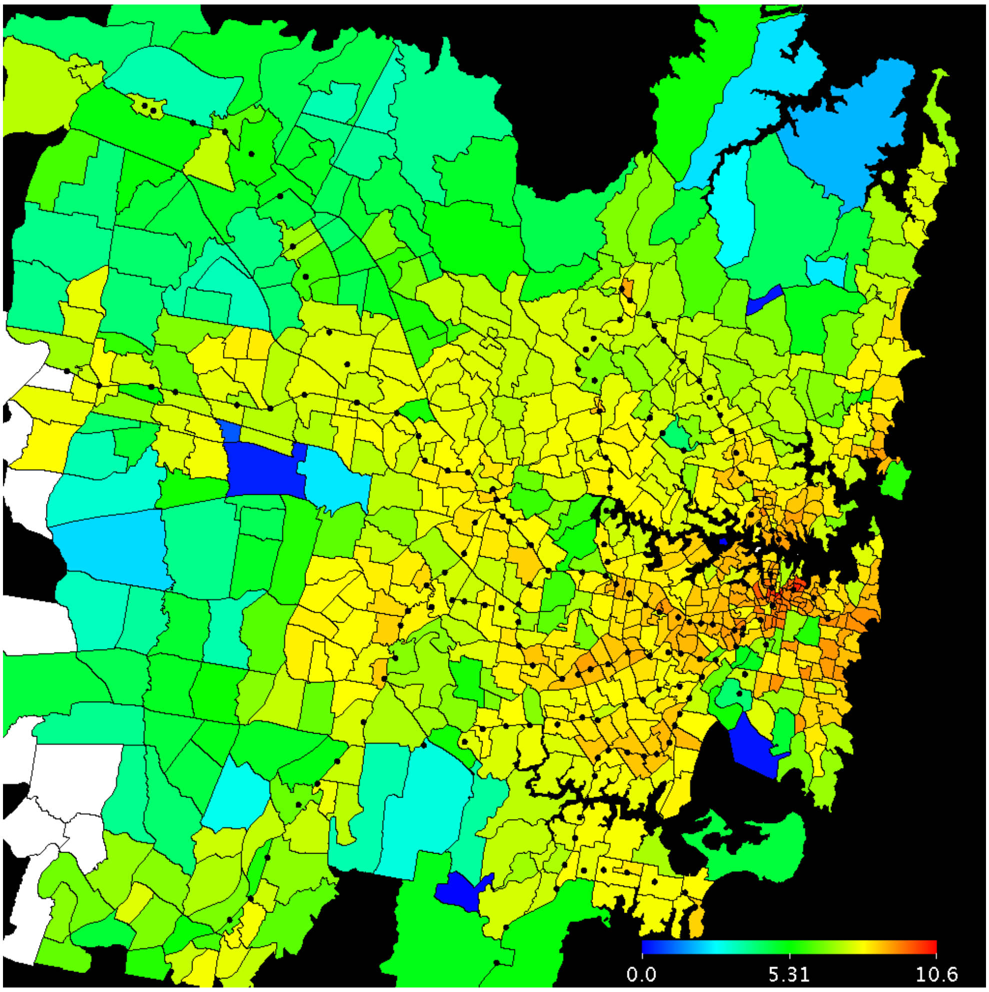


Figure 4.11: Natural logarithm of population density (measured as people per square kilometre) in metropolitan Sydney, by Travel Zone. Source: Author's calculations from 2001 census.

Figure 4.12: Number of jobs within 1.5km of each Travel Zone centroid in Sydney. Source: Author's calculations based on ABS 2001 census data.

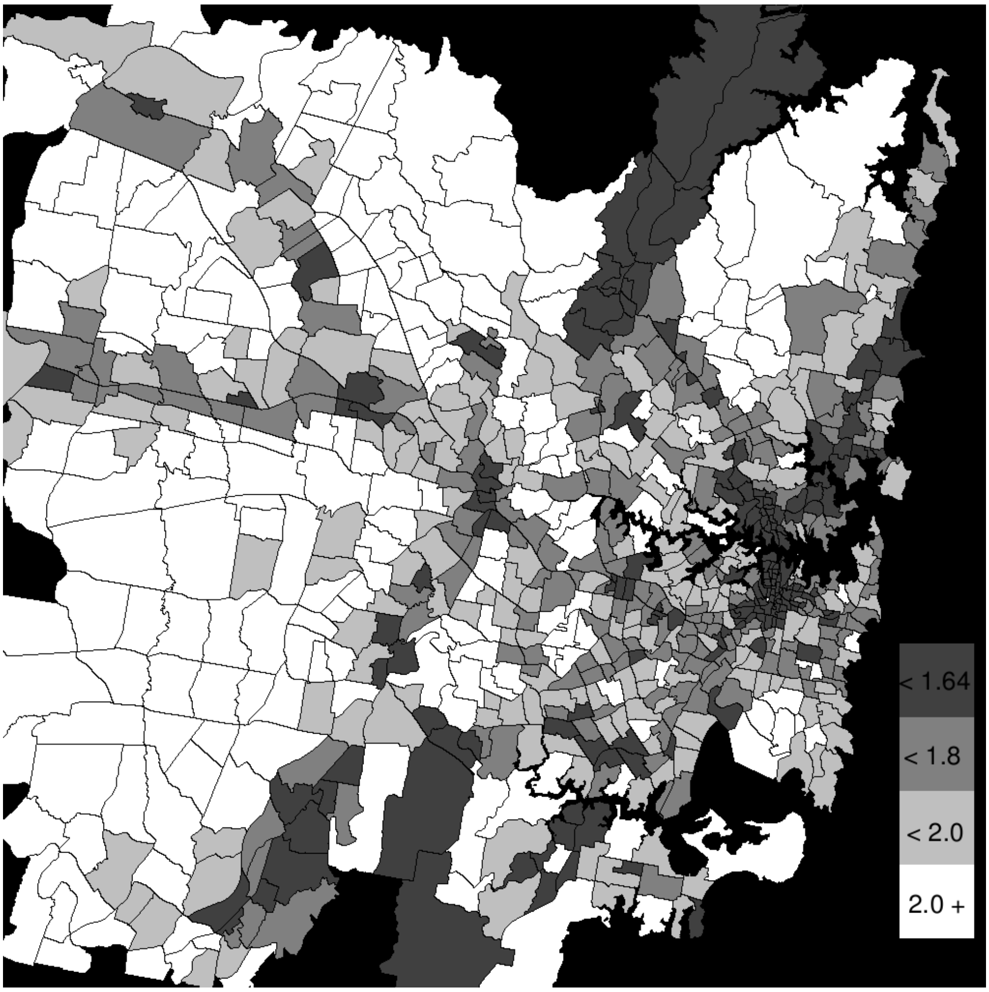


Figure 4.13: Accessibility by public transport relative to accessibility provided by car (unitless ratio). Source: Glazebrook (2002a).

The final variables included are travel time matrices giving peak travel time (in minutes) between all zones by both transit and car, and a matrix with the ratio of these measures (i.e. indicating the competitiveness of travel by transit). Figure 4.14 shows travel time ratios by cumulative proportion of all commute trips, with only a small number of trips being faster by transit, and $\approx$ 95% of trips being between 1 and 3 times the travel time by transit as by private auto-commute, with a median trip ratio of 1.7.

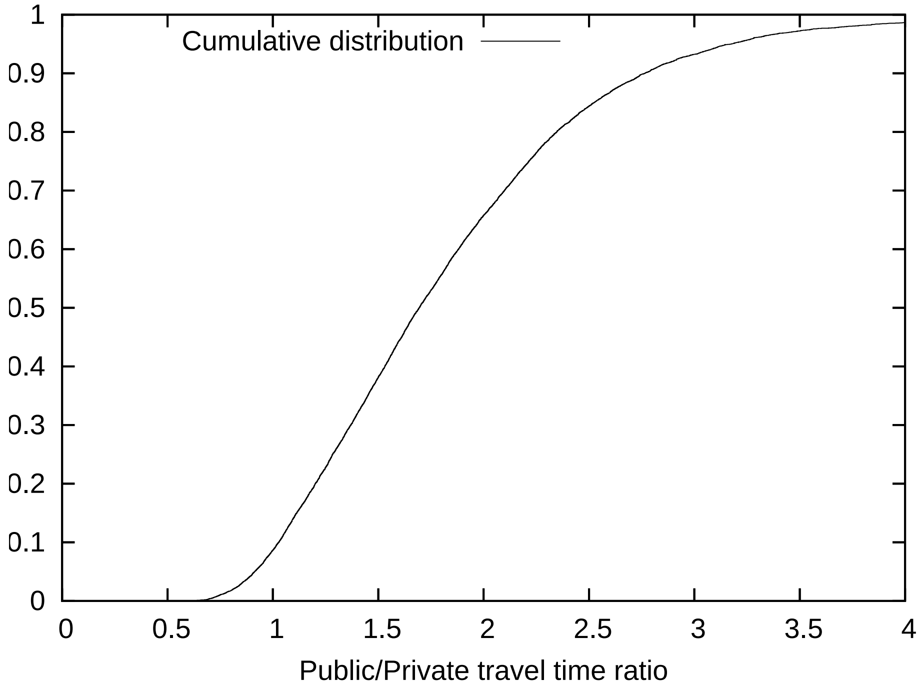


Figure 4.14: Public/private trip time ratio by cumulative proportion of trips in Sydney. We can see that only a very small number of origin→destination trips are faster by public transport, with the bulk ($\approx$ 95%) of all trips having a public/private travel time ratio between 1 and 3.

Other variables

Other variables that were tried, but did not improve the model, are listed below.

Zone centroid distance from the CBD Self-explanatory

Cars per household The mean number of cars per household, from Sydney Household Travel Survey data, as described in Corpuz et al. (2006).

Zone ratio of couples with children The ratio of households residing in each zone that were classified as 'Households with children' at the 2001 census.

4.3.2 Method

Each of the 560487 commute trips can be described by a vector of the form $[x_1, \ldots, x_I, y_1, \ldots, y_J, z_1, \ldots, z_K, M]$, where the x_i's are variables describing the trip origin, the

y_j's are variables describing the trip destination, the z_k's are variables describing the trip itself (such as travel time by different modes), and M is 1 if the trip was made by car, and 0 otherwise.

Given this data, parameters for a logistic regression of the following form are estimated:

$$\frac{1}{1+e^{-z}} \quad \text{where} \quad z = C + \beta_1 x_1 \ldots + \beta_I x_I + \beta_{I+1} y_1 + \beta_{I+J} y_J + \beta_{I+J+1} z_1 + \gamma_{I+J+K} z_K$$

This function, which ranges from 0 to 1, can be interpreted as the probability of a trip being made by car. The software package SPSS was used to estimate the optimal coefficients (the β's) for the 560487 commute trips in the data set. It is more common, in analysis of mode choice, to estimate coefficients for some random-utility discrete choice model (see Cervero (2002), for example). I did attempt to use the discrete choice program Biogeme (Bierlaire, 2003), but the data could not be analyzed, apparently because the data set contains identical data vectors with different mode choices. Biogeme did not seem able to handle this unusual situation[13]. A logistic regression, while somewhat simpler, and not the norm in mode choice analysis, serves my purposes.

Comparison of models

In order to gauge the accuracy of the model, the results are compared against the results obtainable by:

1. The aggregate model of mode choice obtained in Section 4.2 (published as Rickwood and Glazebrook (2009)), with parameters re-calibrated for this data set[14];
2. A naïve model that predicts a 70.7% probability of car as the mode choice for all trips; and
3. An 'Optimal' model that predicts the majority mode for each zone→zone commute.

Rather than compare the log-likelihoods of each model, or likelihood ratio's, which are difficult to interpret, I prefer to compare models using two alternate measures. Firstly, and most simply, I report the percentage of trips for which the model predicts the correct mode[15]. Secondly, the geometric mean likelihood for the trip data, given each model, is reported. If P_i is the predicted probability of trip i being made by car, δ_i is 1 if and only if trip i was made by car (0 otherwise), and $\bar{\delta}_i$ is 1 if and only if trip i was not made by car (0 otherwise), the likelihood of all I trips[16] is $\prod_{i=1}^{I} P_i\delta_i + (1-P(i))\bar{\delta}_i$, and the geometric mean likelihood is $(\sqrt[I]{\prod_{i=1}^{I} P_i\delta_i + (1-P(i))\bar{\delta}_i})$. As can be seen, this measure is closely related to the likelihood, but is much easier to interpret – values lie between 0 and 1, with higher values representing a model that more accurately describes the available trip data.

4.3.3 Analysis and results

A logistic regression was performed using SPSS, and the results are shown in Table 4.7. Because all listed variables are significant at the 0.001 level, the Wald test statistic (Agresti, 2002, page

[13] I spent some time investigating why Biogeme was not able to converge to a solution. It is possible the data set was simply too large, but this seems unlikely.

[14] The original model cannot be used exactly, as the data set on which it was calibrated differed slightly from the one used here. So, to allow a fair comparison, the model coefficients must be re-estimated.

[15] The mode 'predicted' by the model is simply the mode estimated as most probable for that trip.

[16] Remember, I in this case is 560487.

232) is given for each variable as a better indication of the relative influence of each variable (higher values indicates a stronger influence).

Variable	β	Wald test statistic	sig	e^{β}
ORIG_medincome	1.586	3063.853	$< .001$	4.882
ORIG_logworkers	-.249	981.157	$< .001$	.779
DEST_comproxinvsqlogscale	-.005	1195.342	$< .001$	.995
DEST_ettratio	1.227	2235.584	$< .001$	3.410
DEST_logworkers	-.461	6663.262	$< .001$	.631
pubtime	.011	2972.908	$< .001$	1.011
privtime	-.026	6276.737	$< .001$	.975
ORIG_logpopden	-.131	268.635	$< .001$	.877
DEST_logpopden	-.200	1673.202	$< .001$	.819
Constant (C)	2.314	695.340	$< .001$	10.112
Proportion correct	83.6%			
Geometric mean likelihood	66.8%			

Table 4.7: Logistic regression coefficients for disaggregate model of mode choice.

The coefficients produced by a logistic regression are shown in Table 4.7. As expected, an increase in travel time by transit is associated with lower transit mode share, all other things equal, and an increase in travel time by private automobile is associated with higher transit mode share, all other things equal[17]. More interesting than this is the influence of characteristics of urban form at trip end-points. Trips with destinations that are centres with high employment (DEST_logworkers) or population (DEST_logpopden) densities are much less likely to be made by private automobile. Similarly, destinations with large amounts of commercially zoned land (DEST_comproxinvsqlogscale) and destinations that are well linked in with the transit network (DEST_ettratio) have higher transit mode shares. Regarding variables describing built form at the trip origin, density of workers (ORIG_logworkers) and population (ORIG_logpopden) are both associated with higher transit mode share. This is perhaps because there are lower levels of car ownership in higher density areas. As expected, areas with wealthier households (ORIG_medincome) tend to have lower transit mode shares, due in part to higher automobile ownership rates in those areas[18]. All these results seem reasonable enough if one considers that most of the built-form variables shown to have an impact (ORIG/DEST_logworkers, ORIG/DEST_logpopden, DEST_ettratio, DEST_comproxinvsqlogscale) are higher in more developed city centres/nodes. It is highly likely that these variables are serving as proxies for other relevant, but difficult to measure variables. For example, centres tend to have limited and/or expensive parking, and more frequent transit services.

Table 4.8 shows that the accuracy of the model in Table 4.7 is very close to the accuracy of the 'Optimal' model[19], and much better than both the aggregate mode choice model in Rickwood and

[17]Repeating the 'all other things equal' caveat for results quickly becomes tedious, and I will dispense with it for this reason. The reader should understand it is implicit in the discussion from this point.

[18]An alternate model with ORIG_carsperhousehold instead of ORIG_medincome produced results similar to those shown in Table 4.7.

[19]Remember, the 'Optimal' model is the best possible model achievable with the available data. If $p_{A,B}$ % of trips from zone A to zone B are made by car, the 'Optimal' model is one that gives a $p_{A,B}$ % probability of trips between A and B. It is not possible to do better than this because the variables used in the regression only relate to the trip itself; trip origin; and destination. Hence, multiple trips between A and B are indistinguishable (i.e. have identical parameter vectors).

Glazebrook (2009) (described in Section 4.2), and the best 'Naïve' model that predicts a 70.7% chance of private vehicle commute for all trips[20].

Model	Proportion correct	Geometric mean likelihood
Optimal	84.8%	71.0%
Disaggregate	83.6%	66.8%
Aggregate	72.3%	56.9%
Naïve	70.7%	54.6%

Table 4.8: Comparison of different mode choice models.

The most surprising thing about the model comparison in Table 4.8 is that the aggregate model performs quite poorly when its performance is measured on disaggregated data. In fact, it does only a little better than the 'Naïve' model that always predicts the city-wide average 70.7%/29.3% car/transit mode split. While the aggregate model does pick up important spatial variation (as indicated by the high r^2 for that model, reported in Rickwood and Glazebrook (2009)), the fact that the aggregate model is *not* weighted by the number of observations in each zone counts heavily against it when its performance is measured using disaggregated trip data. The disaggregate model, on the other hand, comes quite close to the maximum achievable accuracy on this data set (shown by the 'Optimal' model in Table 4.8). The lesson to be learned here is that, although aggregate analysis can provide useful information, such an aggregate model is much less useful in modelling household behaviour than a disaggregated model which is calibrated on household level data. To give you some idea of the size of the difference, Table 4.9 shows a model that still gets the mode right for 81.8% of trips (only 1.8% less than the full model) , even though it contains only a single demographic variable (ORIG_medincome), a single trip-related variable (pubprivratio), and two variables related to built form at the trip end-points (ORIG_logpopden, DEST_logpopden). This reduced model also shows the usefulness of population density as a proxy for more complex measures of urban form and transit service.

Variable	β	Wald test statistic	sig	e^{β}
ORIG_medincome	.835	1057.833	< 0.001	2.305
ORIG_logpopden	-.486	7122.574	< 0.001	.615
DEST_logpopden	-.853	37623.278	< 0.001	.426
pubprivratio	.423	31005.080	< 0.001	1.527
Constant	9.606	30013.746	< 0.001	14852.235
Proportion correct	81.8%			

Table 4.9: Logistic regression coefficients for very simple disaggregate model of mode choice.

4.3.4 Discussion

There are two important findings from the disaggregate study of mode choice in Sydney conducted in this section. The first is confirmation of the fact that disaggregate models of travel behaviour are

[20]Note that the 70.7% mode share for commuting by car is lower than that reported by other sources for commuting in Sydney (such as the ABS census, or Transport Data Centre (2007)), because in this analysis I have excluded a number of outlying regions (not considered part of the Sydney metropolitan area) and trips with mode 'Other'.

more accurate that aggregate models. This additional accuracy does come with more onerous data requirements, but can come without significant additional model complexity. The second main finding is that it is possible to develop an accurate disaggregate travel model even in the absence of information about actual trip-makers, by instead relying on variables describing both trips and trip end-points. In other words, characteristics of the trip itself, and of trip endpoints, appear to provide sufficient information to explain travel behaviour. The first of these findings suggests that a disaggregate travel model should be developed for the metropolitan-scale micro-simulation modelling in Chapter 7, and this is done.

The mode share regression results shown in Table 4.7 show that travel time, together with measures of activity density at the trip *destination*, are the most important determinants of mode choice. That travel time of each mode affects mode choice is unsurprising. However, the strong influence of variables describing the built environment at the trip destination suggests that other variables are equally important, even if they are only serving as proxies. Cervero, in his analysis of mode choice (Cervero, 2002), comes to a similar conclusion:

> [M]ode choice models used by regional planning organisations across the United States to forecast future travel demand are also often under-specified .... [R]arely, however, do equations account for the influence of points A (origins) and points B (destinations) themselves in explaining mode choice. That is, the potential effects of densities, land-use mixtures, and urban designs in and around trip origins and destinations are left unsaid. This compromises the ability to test the possible transportation benefits of land-use initiatives, be they transit-oriented development, infill housing, neo-traditional towns, or clustered developments that promote efficient automobile circulation. ... [T]o the degree that bus and rail services to dense urban settings are more frequent, thus shortening transit travel times, omitting a density variable from mode choice utility function can produce biased estimates of included variables that are related to density. This might be the case when factors that routinely accompany density (e.g. passenger amenities like protective shelters) and that are not explicitly captured in models have a bearing on mode choice. In such instances, omitting a density variable (even if it functions only as a proxy) from the utility expression could lead to a misstatement of the effects of travel time on mode of travel.

Cervero (2002, page 266)

4.4 A computational study of activity distribution and travel behaviour

The focus of Sections 4.2 and 4.3 has been on empirical analysis of the relationships between observed travel behaviour and other variables. Sometimes, however, a more theoretical approach allows for a clearer understanding of the underlying issues. In reality, the decision processes which govern personal travel behaviour are very complex, and, consequently, the empirical models used to describe observed travel behaviour require a large number of variables. Because these variables will be different (or unavailable) in different cities, it can be difficult to produce results with any generality from detailed empirical studies. An alternative approach is to develop simple (but plausible) mathematical models of travel behaviour, and use these to investigate the link between urban structure and travel behaviour. While such an approach has the obvious limitation that it is not well constrained by observable data, it has the advantage that it is completely amenable to researcher manipulation, and thus allows for a properly controlled analysis. It allows us, for example, to imagine two cities that are identical in every regard bar one, and apply our model of travel behaviour to individuals in each city, to see what effect that single difference has. This is perhaps the best way to view the purely mathematical/computational approach in this section – as a method of facilitating various thought experiments on the importance of urban structure on travel behaviour.

4.4.1 Synthetic analysis of a circular city

My approach to presenting the analysis will be to start simple, and gradually build up a more complex (and realistic) model. Because my interest is specifically on the effect that urban structure has on travel behaviour, I make no attempt to model economic and social variables which influence travel behaviour.

The approach I will take throughout this analysis will be to simulate the changes that occur to city-wide travel when key variables describing urban structure are varied. In particular, I will concentrate on investigating how average trip length varies as the intra-city distribution of trip end-points changes.

Preliminaries

Assuming a homogenous set of households inhabiting a circular city, I will investigate the impact of different distributions of trip origins/locations on city-wide (aggregate) travel behaviour. For example, I will investigate the effect of more compact city-forms (i.e. those with trip origins and destinations tightly concentrated near the city centre) versus those with uniform distributions of trip origins and destinations.

A *trip* is defined, for the purposes of this analysis, by an (origin, destination) pair. For simplicity, I assume that straight-line travel is always possible from every possible origin to every possible destination. Also for simplicity, I assume a single mode of travel (car).

Since trips are (origin,destination) pairs, and since the approach taken will be to simulate a large number of trips, a method of generating trips is required. For simplicity, I will assume in all the following analysis that trip origins and trip destinations are identically distributed. To generate an (origin,destination) trip pair then simply requires the specification of a single spatial distribution from which origin and destination points are drawn.

The following assumptions are made initially to simplify the analysis, though some of these assumptions are relaxed later.

1. Each household makes a fixed number of trips per week (i.e. all trips are non-discretionary).
2. Households (i.e. trip origins) are distributed throughout the circular city according to the function $D(r)^{21}$.
3. Trip destinations are also distributed randomly throughout the city according to the same function $D(r)$.

There is some support in the literature for the assumption that trip rates are largely independent of land use and location (Ewing et al., 1996; Boarnet and Crane, 2001a), which instead exert a stronger influence on trip distance and mode. Figures 4.15 and 4.16 also add some support to such a claim. Figure 4.15 shows the number of trips made by Sydney households as a function of the accessibility of the origin travel zone (as measured by the accessibility measure developed in Glazebrook (2002a)), showing no clear trend. Figure 4.16 shows trip rates for Sydney households as a function of origin zone distance from the CBD, again with no clear trend evident.

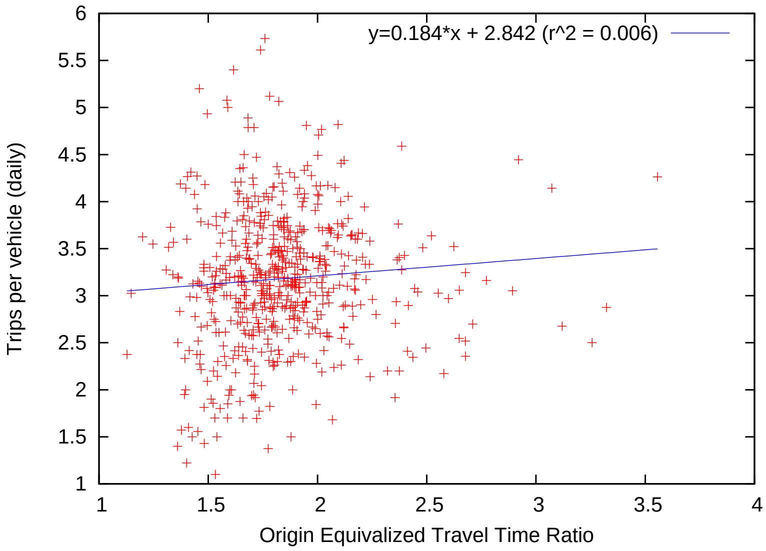


Figure 4.15: Number of trips (daily) and trip-origin equivalized travel time in Sydney (see Glazebrook (2002a)). Source: Author's analysis from various data sources.

Although the majority of the following analysis will be purely mathematical in nature, and so could be performed on a mathematically convenient city with radius 1, I believe the results will be easier to interpret, and hence more meaningful, if they are presented on a scale that is comparable with empirical data, and this is done in the following analysis.

[21] Given a circular city, D should be a function of both r (distance from the city centre) and θ, but since I assume the city is perfectly symmetric, θ can be dropped.

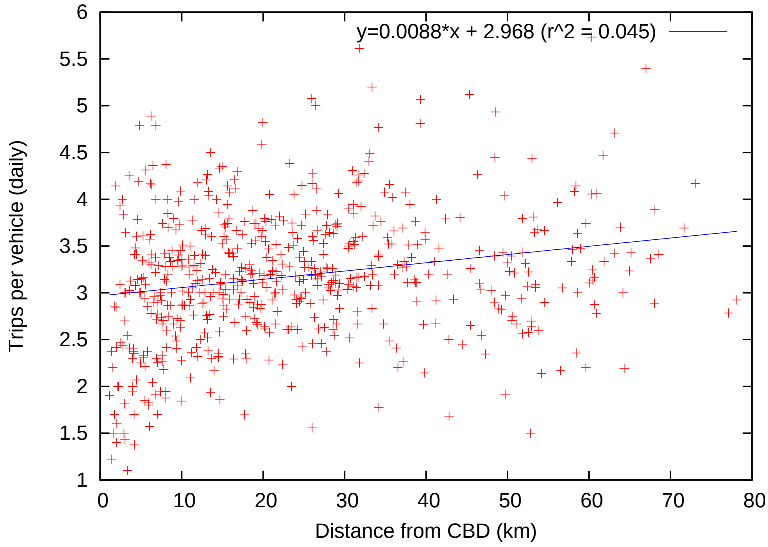


Figure 4.16: Number of trips (daily) and trip-origin distance from the CBD in Sydney. Source: Author's analysis from various data sources.

So that the reader is clear on how trips are generated given the specification of a particular origin/destination density function $D(r)$, let us consider the function shown in Figure 4.17. The function indicates that trip origins/destinations are five times denser at the city centre than at the city fringe. Drawing a value from the range $[0, 20]$, weighted according to the function shown in Figure 4.17 (i.e. with the chance of drawing a value near 0 being 5 times the chance of drawing a value near 20) gives us the distance from the CBD of our trip origin. Let us call the value generated in this manner r_1. Because our hypothetical city is perfectly symmetric, an angle (call it θ_1) can be drawn uniformly from the range $[0, 2\pi]$. (r_1, θ_1) is one trip endpoint, and repeating the process (getting (r_2, θ_2)) then allows us to define a trip from (r_1, θ_1) to (r_2, θ_2). Repeating this process a large number of times (i.e. generating a large number of trips) allows us to calculate average trip-length statistics. This is what is done (for various origin/destination distribution functions) in the following simulations. Several other refinements are also introduced, but those will be described later.

Synthetic case 1: Uniform activity distribution

To begin, let us start with the simplest possible case – a circular city with a perfectly uniform distribution of trip origins and destinations. Let the radius of the city be R, and assume that trip origins and trip destinations are distributed evenly (i.e. uniformly by area) throughout the city. Assuming such a distribution of end points, what is the average trip length? For a trip with origin (r_1, θ_1) and destination (r_2, θ_2), the trip length is $\sqrt{r_1^2 + r_2^2 - 2r_1 r_2 \cos(\theta_2 - \theta_1)}$. Calculating the average trip length by drawing trip origin/destination points at random from a circle of radius R gives an average trip length of $\approx 0.9R$. This implies that, for a population with fixed driving behaviour (i.e. a fixed number of trips per week), where trip endpoints are distributed uniformly over a circular city with radius R, the average distance travelled will be $\approx 0.9R$. This case serves as a useful comparison for the following cases, where the distribution of trip end points becomes

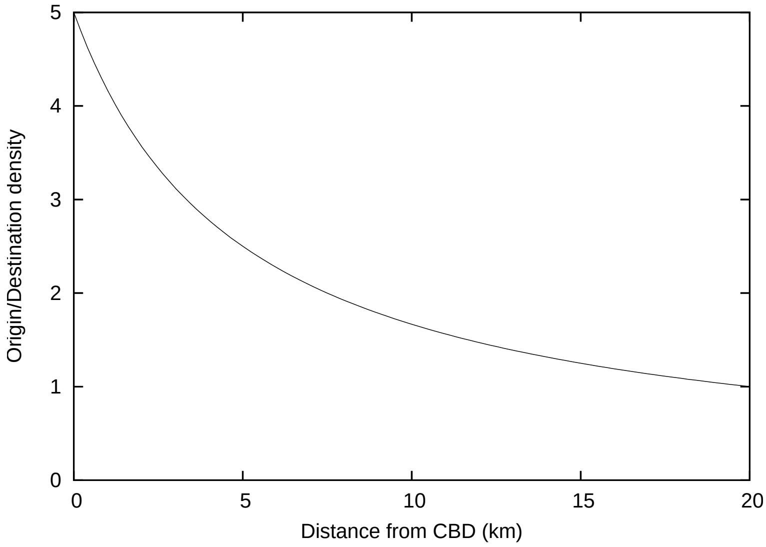


Figure 4.17: A sample trip origin/destination distribution.

a little more realistic.

Synthetic case 2: Varying centralization of activity distribution

Most cities with free land markets exhibit some centralization of population, employment, and other activities. In short, activity typically becomes more concentrated towards the 'centre' of the city. This is the reason for the continuing relevance of the mono-centric city model, despite the fact that many cities exhibit more complex structures, such as having multiple centres. Bertaud and Malpezzi (2003), in their study of the spatial distribution of population in 48 world cities, conclude that the general centralization of population and economic activity predicted by the mono-centric model is observable in many cases:

> The first important finding is that in many cities ... the standard urban model fits the data quite well.
>
> Bertaud and Malpezzi (2003, page 5), ellipsis mine.

While the general concentration of population and activity are generally accepted (see Mills (2000); Glaeser and Kahn (2004)) the mono-centric city model, and extensions (Wheaton, 1977; Cheshire and Sheppard, 1995; Henderson and Mitra, 1996), are less useful for empirical work that strives to go beyond general indications of concentration and dispersion. It is still a debatable empirical point, for example, whether a negative exponential model produces a better fit to actual data than, say, an inverse power function (Batty and Kim, 1992). Wishing to leave such empirical distractions largely aside in this synthetic analysis, I will use a function of the form $\frac{C}{r+a}$ to describe the relationship between distance r from the city centre, and the density of trip origins/destinations[22]. C is a constant and a an adjustable parameter, as described below. I

[22]I talk of the distribution of trip-end points without reference to the direction of the destination (θ), because, as already mentioned, the city is symmetric, and so θ is always drawn uniformly from the range $[0, 2\pi]$.

choose this particular functional form simply because it allows sufficiently flexibility in modelling activity distribution in a circular city, and because a function of this form produces a reasonable fit to observed data for those cities with which I am most familiar: the Australian state capitals. Consider, for example, Figure 4.18, which shows the population density profiles of Australia's two largest cities, along with some curves of the specified form. It should be clear from inspection that the functional form chosen is a plausible one with which to model the distribution of activities in a city. To be precise about the function used to model activity distribution in our circular city, let $D(r) = \frac{C}{\frac{r}{R}+a}$ $(0 \leq r \leq R)$, and $D(r) = 0$ otherwise, where a is a scale parameter and C a constant. $D(r)$ describes the distribution of origins/destinations in a city covering a circle of radius R. A trip end-point (r, θ) can be generated by drawing r from D and θ from the continuous uniform distribution over the interval $[0 - 2\pi]$, as already explained in the section entitled 'Preliminaries'. Two such trip end-points so generated form a trip.

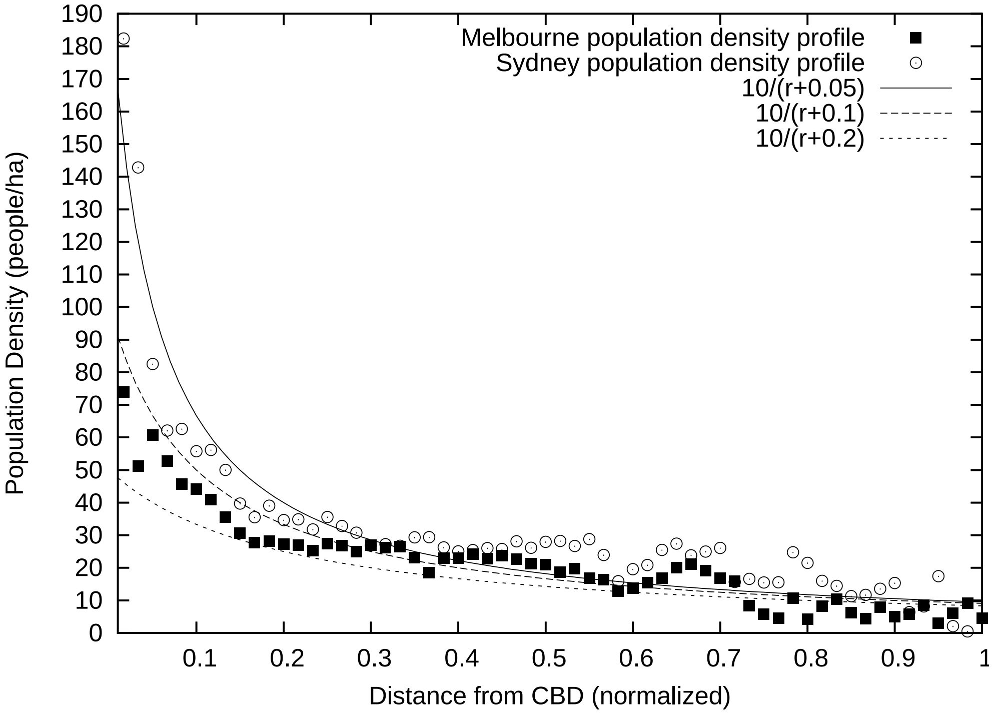


Figure 4.18: Population density profiles of Sydney and Melbourne with various inverse distance functions. Note distance from the CBD has been normalized to lie within the range 0 (at the CBD) to 1 (at the city fringe).

Figure 4.19 shows the resulting average trip length for various values of a, calculated in each case by calculating the mean trip distance from 20,000 trips. It is important to note that, thus far, I have *only* varied the distribution of activities (i.e. trip end points). The trip end point function I use (D), says nothing about the *absolute* density of trip origins/destinations, only *relative* densities. For example, with D of the form $\frac{C}{\frac{r}{R}+a}$, when $a = 1$, this implies that the trip end-point density at the urban core ($r = 0$) is twice that at the urban boundary ($r = R$), but it says nothing about the absolute densities at either point. Thus, the simulations thus far suggest that, aggregate city density aside, increasing the *relative* concentration of, say, population

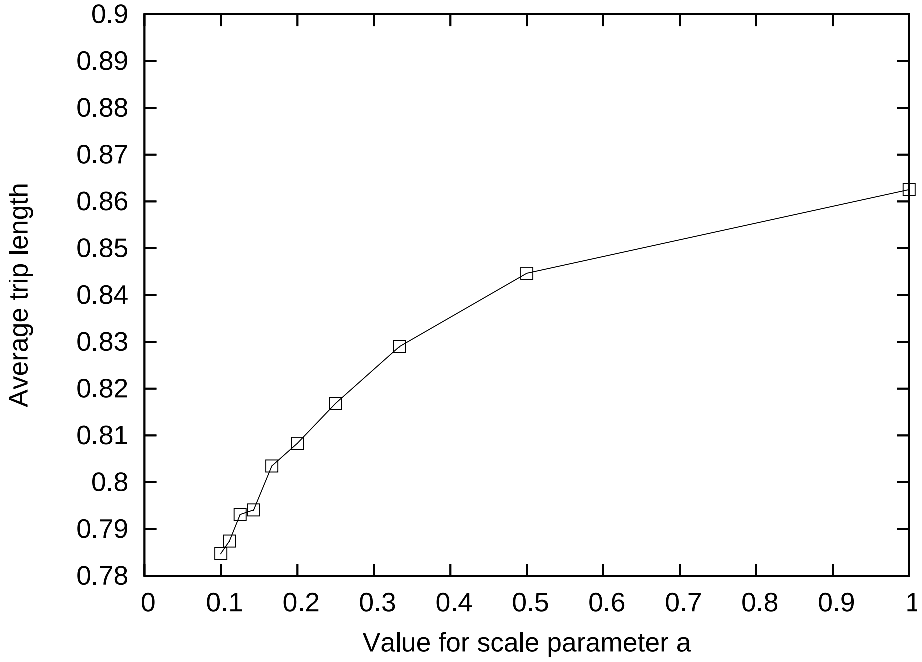


Figure 4.19: Simulated effect of activity distribution on trip length.

and jobs, will decrease average trip length. This is assuming all trips are non-discretionary and non-substitutable, and that all activities are equally likely as trip end points. Over the values of the scale parameter a used here, the reduction in average trip length, compared to a uniform distribution of trip end points, ranges from approximately 5% to 13%. This is not insubstantial, but takes place over quite a range of values for a. For $a = 0.1$, for example, trip end-point density is 11 times greater at the city core than at the fringe, while at $a = 1$, it is only twice as great at the core than at the fringe. And yet the the difference in average trip length between the two (a 13% reduction versus a 5% reduction) would be difficult to detect in an empirical study, where one has to contend with all the difficulties that ensue in studying the behaviour of capricious individuals in urban areas with complex geography and irregular transport networks.

Thus far, I have engaged in some very unrealistic assumptions, for while the function describing the intra-city distribution of activities is plausible, and it does not seem too far-fetched to generate trips by drawing trip end points from an activity distribution function, the assumption that all travel is non-discretionary and non-substitutable is very unrealistic, and needs to be relaxed. This is done in the next simulation.

Synthetic case 3: Introducing trip substitution

In the cases simulated thus far, I have used a very restrictive model of travel behaviour. It has been assumed that the number of trips per person is fixed, and that all trips are non-discretionary and non-substitutable. That is, trips origin and destination points are generated by draws from D, with no discretion or acceptance criteria applied by the traveller. This is clearly unrealistic, as people are clearly less inclined to travel longer distances, especially in the case where there are alternative trips of shorter duration that are full or partial substitutes. Let us retain the assumption that all trips are non-discretionary. Concretely, I retain the assumption that each household makes a fixed number of trips per time period. The grounds for retaining the non-discretionary nature of trips is that, while distance may deter people from making some trips altogether, this reduced travel comes at some cost to that person's engagement in activities. For this synthetic study, I wish to hold this constant. Although trips remain non-discretionary, in the sense that there is no choice for the traveller to *not* make the trip, I will introduce trip substitutability in the following way. Let $D(r)$ be the function describing the distribution of trip end-points, as defined in the previous synthetic case. Assume that trip *origins* are non-substitutable, and are drawn from D. However, let us assume that, rather than a single trip destination, that K *possible* trip destinations are drawn (also from D) for every trip origin, all of which are equivalent. Let us further assume that, since all destinations are equivalent apart from their location, the traveller selects the closest of these K destinations in all cases. Assuming destinations are identical, and that households choose the closest, is equivalent to assuming non-identical destinations, but some 'satisficing' decision process by households regarding destinations, as found, for example, in Næss (2005).

Although the purpose of this synthetic analysis is to avoid some of the difficulties encountered with empirical data, it is still preferable that assumptions be plausible, or broadly consistent with empirical data. To help convince the reader that the 'shortest of K-alternatives' trip destination model used in the synthetic analysis is consistent with empirical data, Figure 4.20 shows the actual frequency distribution of journey-to-work trip distances in Sydney (for auto-commuters) with that implied by various K-alternatives model, where trip origins and destination points were drawn from the set of Travel-Zone centroids[23]. We can see that for Sydney, using a 'K-alternatives' model with a value for K of around 6 produces a frequency distribution of commute travel distances that is similar to the actual frequency distribution obtained from journey-to-work census data.

Applying the simple, but plausible, trip-substitution model specified, Figure 4.21 shows average trip lengths for various values of the scale parameter a (determining intra-city activity concentration), and the parameter K (describing the number of substitute destinations for each trip). We can see that, unsurprisingly, the presence of destination substitutes makes a great difference on average trip length, and that more centralized cities have consistently shorter trip distances for all values of K. Trip distances in centralized cities are between 6-10% shorter, for all values of K, over the range of a simulated here.

Synthetic case 4: A growing city with a strict urban boundary

To this point, I've been simulating the effect of different spatial distributions of activities, and these distributions have been posed in relative terms, rather than absolute terms. Thus, I have looked only at how difference in the *relative* concentration of activities might affect travel behaviour. Much of the empirical work on travel behaviour, however, has been concerned with absolute activity or population densities (e.g. Newman and Kenworthy (1989)). It is also difficult to interpret results expressed in terms of the scale-parameter a, and so it is instructive to consider a more concrete example. This will be done in the following way:

1. An initial city, of radius 20km, 500,000 'activities' (i.e. trip end-points), and uniform end-

[23]The New South Wales Ministry of Transport define around 1000 Travel Zones for the purposes of Travel and Traffic analysis in the Greater Sydney Region. A subset of ≈ 700 of these is used that excludes areas generally not regarded as part of the urban area of Sydney.

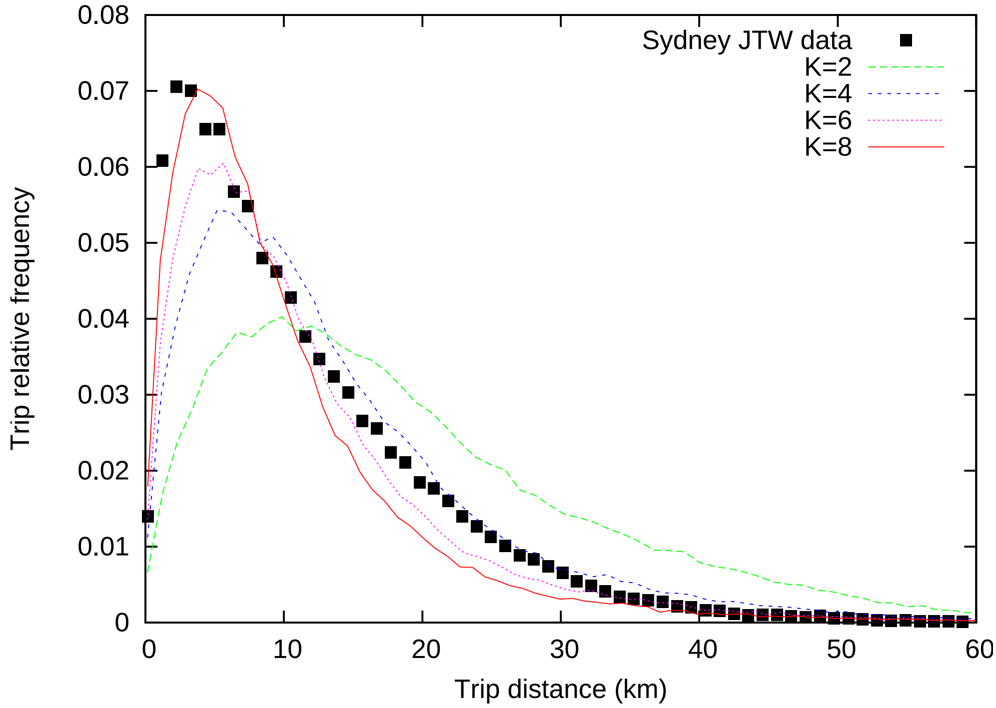


Figure 4.20: Trip frequency distributions using K-alternatives trip destination model, for varying K. Also shown is the actual frequency distribution for journey to work trips in Sydney in 2001 (Data Source: ABS 2001 Census).

point distribution is assumed.

2. This city grows by 500,000 'activities' per iteration, for 9 iterations, with the spatial distribution of new activities described by $\frac{C}{\frac{r}{20}+0.2} \qquad (0 \leq r \leq 20)$ (i.e. the ratio of new activities added at the city centre is ≈ 6 times that on the fringe).

Thus, from an initial city of 500,000 activities, the city will grow, and its activity distribution will change, becoming more centralized. The city's overall density will also increase by ten-fold as all activity growth occurs within the original urban area (defined as a circle with radius 20km). Thus, we have both a changing relative distribution of trip end points, and a change in absolute origin/destination densities.

In addition, the nature of trip substitution is also refined for the results presented in Figure 4.23. It seems that larger cities, with more employment, shopping, cultural, and recreational activities, will have larger values of K than smaller cities. For non-exclusionary activities, such as shopping and recreation, it seems reasonable to assume that the number of substitutable trip destinations increases proportionally with the city-wide number of activities. However, for an exclusionary activity like employment, both the number of vacancies and the number of competitors for vacancies will increase. The relationship between the number of job vacancies and the effective number of choices is unclear. To investigate this, a separate simulation is performed to determine the average commute distance for a situation where W workers are competing for W jobs. Values of W between 1 and 60 are simulated. The simulation is performed as follows:

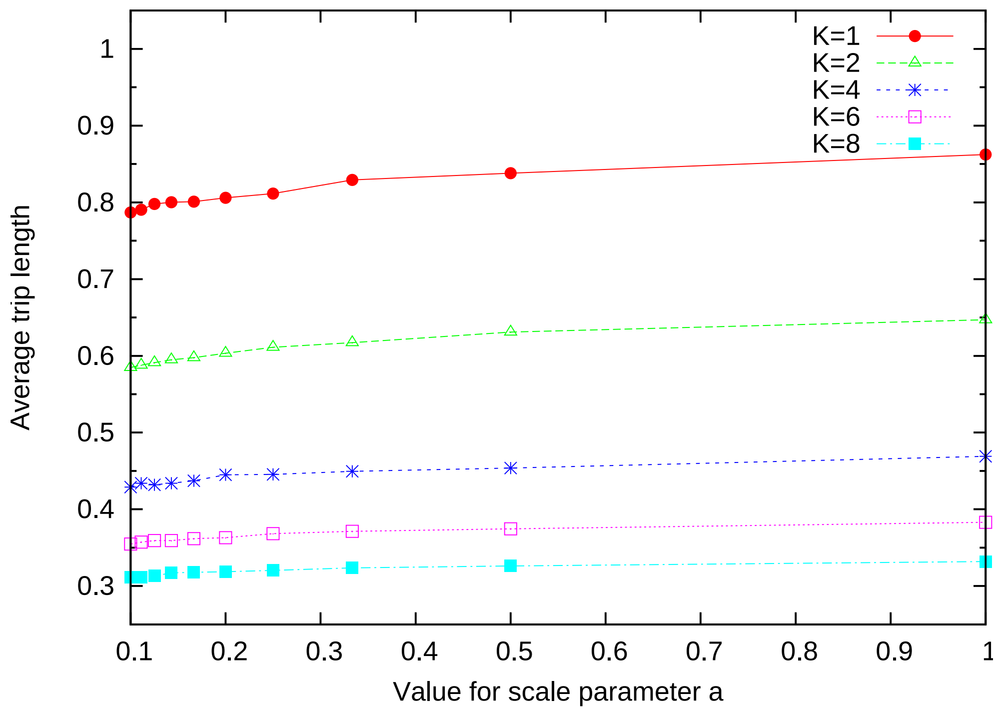


Figure 4.21: Mean trip distance for varying values of the scale parameter a and varying values of K – the number of substitutable destinations. Note that trip length reported here is for a city of radius one.

1. W jobs are drawn from the activity distribution D to make a pool of available jobs.

2. W workers are drawn from D. Call these workers $p_1 \ldots p_W$.

3. Starting with p_1, through to p_W, match each worker with the job closest to them, and remove that job from the pool of jobs available.

4. When all workers are paired with jobs, calculate the average commute distance for all job/worker pairs.

This procedure is repeated 100 times for each W in the range $[1 \ldots 60]$, for two different activity distribution functions: constant activity density; and activity density over a city with unit radius given by $D(r) = \frac{C}{r+0.1}$. The results, in Figure 4.22, show how average trip length decreases as W increases. Figure 4.22 also shows that the distribution of trip distances can be approximated using a 'K alternatives' technique with $K = A^{0.54}$, where A is the number of activities in the city. In other words, the effective K value for commute travel grows approximately with the square root of the number of activities in a city. As already noted, for most other activities, the effective K value should grow proportionally with the number of activities in the city. Thus, overall, it seems reasonable to expect K to increase proportionally with city activities, as the linear trend will dominate. For the simulations that follow, however, a number of different possibilities are investigated: linear proportionality ($K \alpha A$); square-root proportionality ($K \alpha \sqrt{A}$); and an intermediate case ($K \alpha A^{\frac{2}{3}}$). In all cases, the constant of proportionality is set such that in the first iteration, the the value for K is 1.

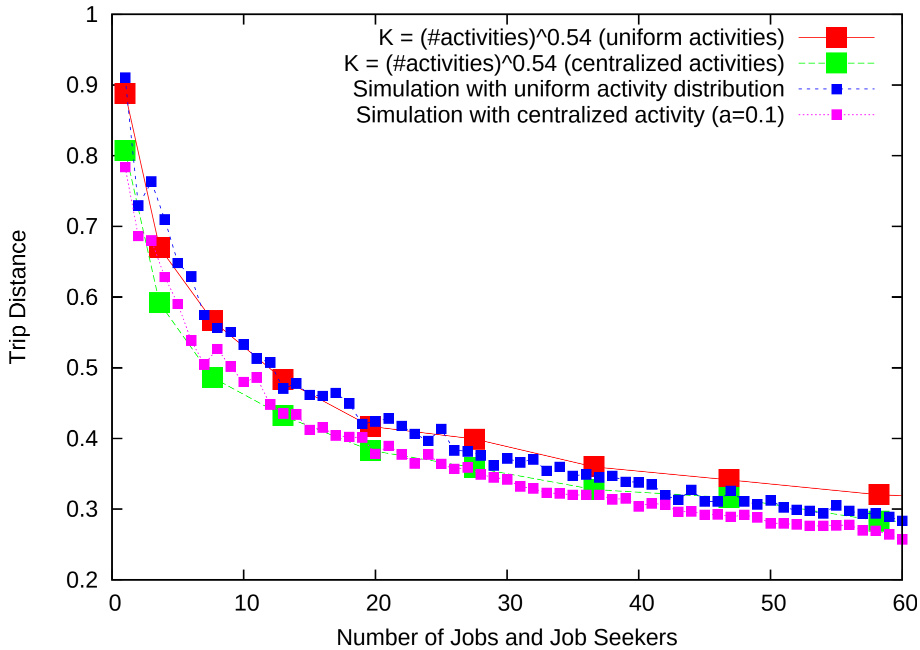


Figure 4.22: Expected commute trip-length for two cities of the same size, one with uniform distribution of population and jobs, and another with centralized distribution of population and jobs. Small box-points show the results of the commute trip-length simulation, with large box-points showing how well a 'K-alternatives' approach can approximate the distribution from the more detailed simulation.

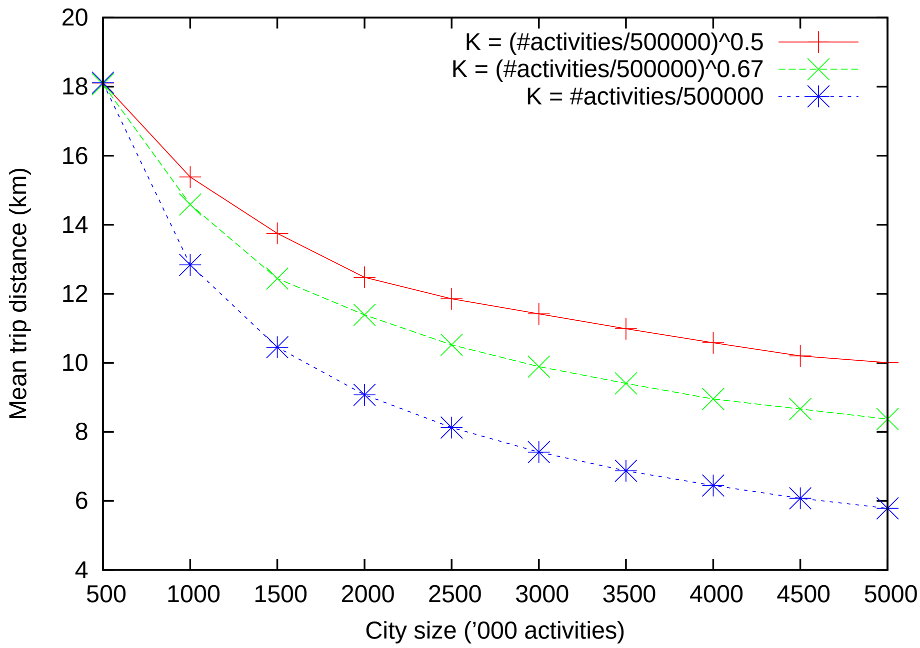


Figure 4.23: Shows changes to average trip length with changing city size, for different functions relating K – the number of trip alternatives – to the number of activities in the city.

A note on the effect of density

Before proceeding to the final synthetic study, it is worthwhile considering what the simulation results thus far have to say about the link between observable city-wide density and average trip length. Figure 4.24 shows the mean trip length for cities with the same population and intra-city distribution of activities[24], but differing density. For a range of plausible choices of K (the parameter governing trip-substitution), mean trip length is strictly decreasing with increasing density. The general shape of the graphs is similar to those in the empirical work of Newman and Kenworthy (Newman and Kenworthy, 1989, 1999). This is a striking result, and shows that it is possible to derive a negative relationship between density and trip length even for a city with *no* public transport. Thus, even if trip *rates* are unaffected by city density, and even if trip *modes* are unaffected, a negative relationship between density and trip length is still evident. This is an important result.

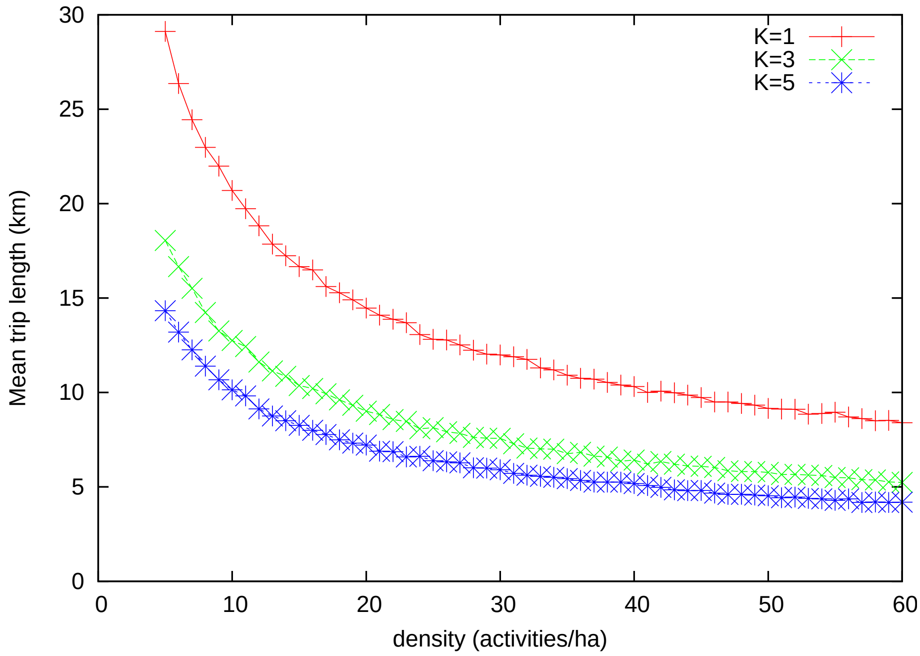


Figure 4.24: Mean trip length for cities with the same population and intra-city activity distributions, but varying densities.

Synthetic case 5: Study of fringe vs. consolidation

A final extension to the model will allow for a more realistic final synthetic simulation. This far, the urban boundary has been fixed, and all additional growth has been accommodated within this boundary. More realistically, as the city grows, a proportion of new growth would occur at the city fringe (expanding the city radius), with the remainder occurring through consolidation and increased activity density within the 'old' urban boundary. I shall call the proportion of

[24]The value of a used is 0.25 for all cases, which gives an activity density near the CBD a little over three times that on the fringe.

growth that takes place on the fringe (i.e. beyond the old urban boundary) ρ, with the remaining proportion $(1-\rho)$ being accommodated through consolidation.

A growing urban boundary and a steepening activity density gradient are modelled in the following way over 10 growth iterations; In iteration 1, an initial city, with 500,000 trip end-points, radius 15km, and pre-defined activity density function[25] $D(r) = \frac{957.5}{\frac{r}{15}+0.915}$, is modelled. In each subsequent iteration, the radius of the city is expanded, and 500,000 additional trip end-points are added to the city. The radius is expanded by an amount sufficient to accommodate $\rho \times 500000$ of these additional end-points on the city fringe at a fringe density equal to $\frac{500000}{\pi \times 15^2}$ (i.e. the same as the density for the city as a whole in iteration 1). Call the function describing the spatial distribution of activities in iteration i (for a city of $500000 \times i$ activities and radius R_i) D_i, of the same form as in prior simulations (i.e. $D_i(r) = \frac{C_i}{\frac{r}{R_i}+a_i}$). In iteration $i \quad (2 \leq i \leq 10)$, D_i is chosen such that:

1. Activity density at the city fringe (i.e. $r = R_i$) is 500 across all iterations: $D_i(R_i) = 500$.
2. The activity density function D_i integrates to the number of activities within the city.

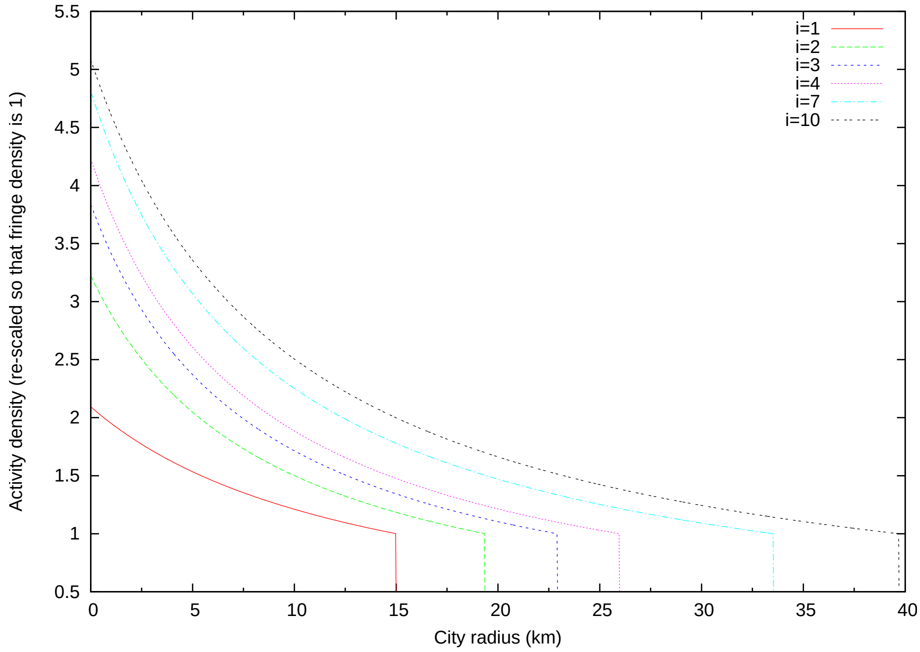


Figure 4.25: Activity density gradients for selected iterations in the 10-iteration simulation performed in this section. Note that this (and subsequent) figures have been re-scaled so that the fringe activity density is 1, for ease of interpretation. They would all need to be multiplied by the fringe density constant (500) for them to satisfy the integration constraint, specified in point 2 of the in-text discussion.

These constraints define exactly the activity density function for each subsequent iteration[26]. Figure 4.25 shows the activity density functions for selected iterations in the case where $\rho = \frac{2}{3}$.

[25] The constants in the function are chosen simply to make the fringe density equal to 500, with a fairly 'flat' initial density gradient.

[26] The values of C_i and a_i are determined numerically, to within a tolerance of 0.0025, as no analytical solution for their values could be obtained.

We can see that, for a city where two thirds of new growth occurs through fringe expansion (i.e. $\rho = \frac{2}{3}$), an initial city with radius 15km, 500,000 activities, and a 2:1 core/fringe activity density ratio grows to one with 5,000,000 activities, a radius of $\approx$ 40km, and an inner city activity density over five times that on the fringe. Higher values for ρ will result in a physically larger city, with a less steep activity density gradient. Conversely, lower values for ρ will result in a smaller city with a steeper density gradient. Thus, by varying ρ, we can determine the effect of different urban growth policies. Figure 4.26 shows the effect of different urban growth policies, ranging from one focused on consolidation ($\rho = \frac{1}{3}$), to one where all growth occurs through fringe expansion ($\rho = 1$). For the simulation results shown in Figure 4.26, a K-alternatives trip substitution model was used, with K proportional to $A^{\frac{2}{3}}$ (where A is the number of activities), and the constant of proportionality chosen such that $K = 1$ in the initial iteration[27].

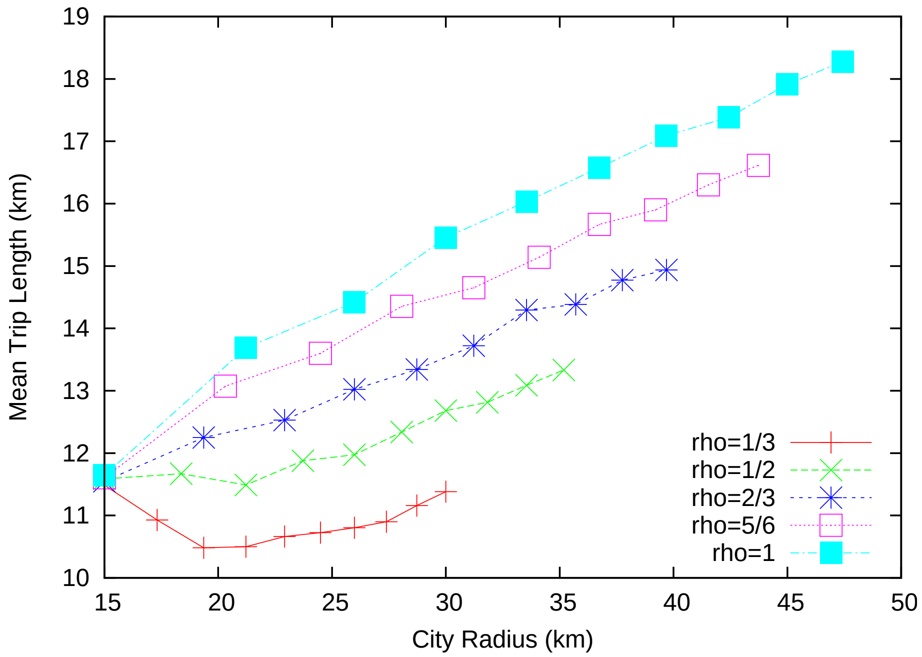


Figure 4.26: City radius and mean trip length for cities with varying values of ρ – the parameter determining the proportion of development that occurs at the city fringe.

Figures 4.26 and 4.27 show that cities with consolidation policies (those with lower values of ρ) have consistently lower trip lengths than do cities with expansion strategies (those with higher values of ρ). Also worth noting is that, despite the simplicity of the trip simulation model adopted, a turning point is evident in the graph. Mean trip length initially decreases for the growth trajectories of cities with $\rho = \frac{1}{3}$ and $\rho = \frac{1}{2}$, but then plateaus and starts to increase as the city continues to grow. Thus, there is no simple relationship between mean trip length and city radius. Nor is there any simple relationship between mean trip length and city density. The relationship between city-size and the number of trip alternatives, as well as physical city size and intra-city activity distribution, are all important.

[27] K thus reaches ≈ 4.6 in the final iteration.

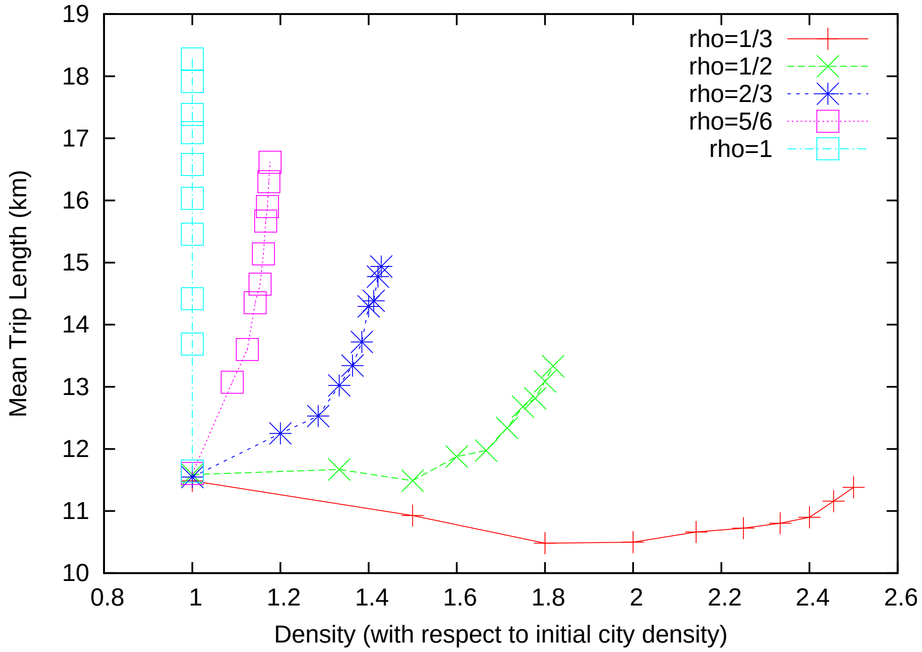


Figure 4.27: City activity density (expressed relative to base initial reference density of 1), and mean trip length for cities with varying values of ρ – the parameter determining the proportion of development that occurs at the city fringe.

4.4.2 Discussion

As already noted in the final simulation study on the effect of different fringe/core growth strategies, there are no relationships between city density, or city radius, that always dominate over other factors. Referring to Figure 4.27, we can see that increasing density *is* associated with shorter trips for the city where two-thirds of growth occurs through consolidation ($\rho = \frac{1}{3}$). However, the same is not true for other cases. Indeed, for the majority of cases simulated, average trip length is strictly increasing with city density. This is clearly because the expanding physical size of the city is the dominating factor in those cases. As other results have demonstrated, this does not indicate that there is some fixed density 'sweet spot'[28] beyond which increases in density act to increase trip lengths. To the contrary, the simulation results in Section 4.4.1 indicate that, for a fixed population, increased density causes a reduction in trip length, with the primary cause being the reduction in physical city size associated with higher density.

The explanation for the turning point evident in Figure 4.27 is complex. Initially, increasing activities causes the number of trip substitutes (K) to increase, and this, combined with the more marginal dampening effect of increasing density, causes trip lengths to decline in initial iterations. However, because the effect of K in decreasing trip lengths *decreases* as K grows (i.e. there is a decreasing marginal effect), the increased physical size of the city causes trip lengths to increase. From the simulations so far, the following conclusions present themselves:

1. The effect of activity centralization alone is relatively minor. Thus, the difference between two cities with identical aggregate activity density, but differing intra-city activity distribu-

[28] Or fixed city-size sweet spot, or any other kind of sweet spot, for that matter.

tions, is relatively small, reaching around 15% only for vastly different intra-urban configurations (i.e. uniform versus highly centralized), and generally being less than 10% for most non-extreme comparisons. See Figure 4.19.

2. The effect of urban consolidation policies in reducing trip lengths (Figures 4.26 and 4.27) comes about because such policies act to centralize activities *and* limit the increase in physical city size. It is the combination that is important, with the decrease in physical city size being the more important factor.

3. The extent to which some trips are substitutable is very important in influencing trip length. Figure 4.28, for example, is a reproduction of Figure 4.26 in the last simulation, but with the assumption that the number of trip destination alternatives grows proportionally with city size. The simulations in this study suggest that the number of trip alternatives should grow less than proportionally with city size for commute trips, but it seems possible that the number of substitutable trip destinations for other trip purposes, such as shopping, would grow more or less proportionally with city size. Further research into this would be interesting.

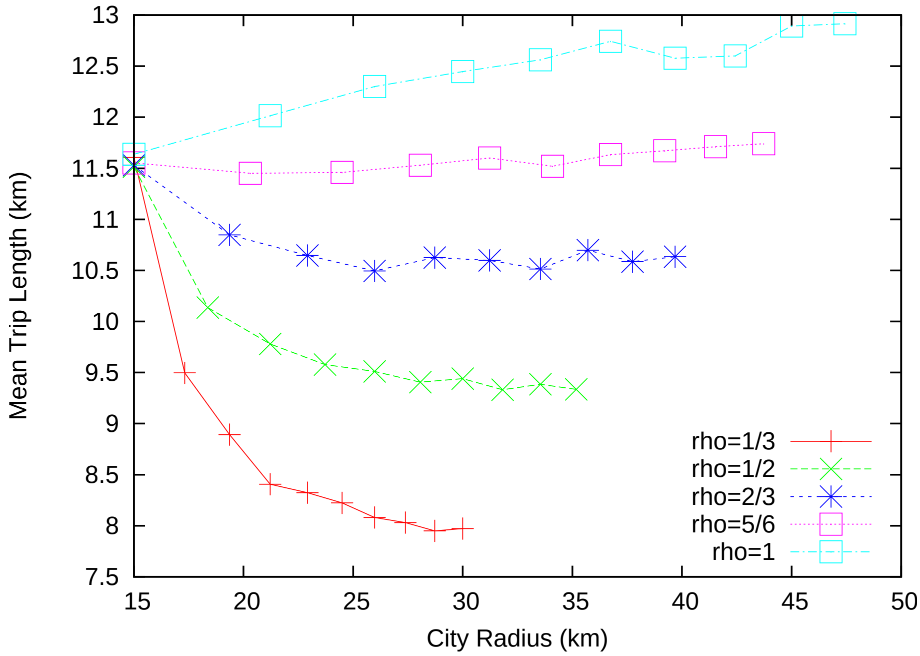


Figure 4.28: City radius and mean trip length for cities with varying values of ρ – the parameter determining the proportion of development that occurs at the city fringe – when K is proportional to city size (as measured by number of activities).

The results presented in these simulations provide a simple mathematical argument for why it is that cities with centralized distributions of population and employment should have shorter trip-lengths than more dispersed cities, but estimates the size of the effect of distribution alone to be relatively minor ($\approx$ 10% for quite a wide range of activity density distribution functions). However, when city-radius and activity distribution are both taken into account, it becomes clearer that the reduction in city-radius associated with a consolidation policy is at least as important as the inter-city distribution of activities. Furthermore, because the benefits of centralized activities become marginal beyond a certain point (i.e. average trip distance declines at a decreasing rate with increasing centralization), it seems plausible that, for cities such as Sydney, that already exhibit significant centralization of population and employment, it may be better to focus on limiting growth of the urban boundary, rather than focusing on the intra-city distribution of jobs. These are, however, only tentative suggestions, for the analysis here is exploratory in nature. There is enough, however, to provoke some interesting thoughts for further research. The three main findings of the simulations are that, all other things equal:

1. As city radius expands, average trip length increases.

2. As city activities become more centralized, trip lengths decrease.

3. As the number of activities increases, trip length decreases.

The simulations suggest, however, that the interplay between these factors is complex, and sensitive to parameters governing the relative strength of each effect. For example, it is important to know how quickly trip destination substitutions grow with city size. The same simple model shows that while it is possible for average trip length to *increase* as a city grows and becomes denser (due to the dominating effect of an expanding city boundary), that comparing cities with the same number of activities always shows that the smaller (in radius terms), and that a more centralized city always has a shorter mean trip length than a larger, less centralized one. This provides some support for policies of urban consolidation.

The simulation model of travel behaviour developed in this study could be further developed to take account of congestion, and of different travel modes. This is a potentially fruitful area for future research.

4.5 Chapter summary

The main finding, both from the analyses in this chapter, and from my reading of the available literature, is that urban structure and household location matter a great deal in influencing travel behaviour. While there are still a number of dissenters wishing to emphasise the importance of economic factors, the weight of evidence is that there are strong independent effects relating to urban structure. This is not to say that economic factors (or other factors) are unimportant, just that concentrating on these *to the exclusion of factors relating to urban structure* is a dangerous practice, likely to bias research results. This is true even when variables relating to built form are only likely to be acting as proxy variables.

The simulation study in Section 4.4 shows very clearly that the empirically observed relationship between per-capita energy use and city density found in such studies as (Newman and Kenworthy, 1989; Brown et al., 2008) is explainable on mathematical grounds alone, as all other factors were held constant in that study. In fact, the strength of the relationship is likely understated by the study in Section 4.4, as neither public transport, nor congestion, were considered. This study, together with the mode-share studies in Sections 4.2 and 4.3, suggest strongly that it is not possible to 'explain away' the empirical correlation between measures of urban form and transport energy use by focusing on economic and/or demographic variables, as some have attempted to do (Kirwan, 1992).

An example of the case where concentrating on economic variables (at the expense of those relating to the built environment), is provided in Gargett and Gafney (2004). Figure 4.29, taken from this report (by an Australian Government body), if viewed uncritically, might lead one to conclude that vehicle use is determined by economic growth rate. This observation, combined with research indicating a link between between personal (individual) income and vehicle ownership and travel Dargay and Gately (1999); De Jong et al. (2004)[29], may lead one to conclude that aggregate and individual income are the principal determinants of travel behaviour, but this would be a mistake. Neither of the two observations (i.e. that traffic increases with both national and personal income) contradict the claim that urban form has a strong independent effect on travel behaviour. For example, while aggregate Australian VKT can be 'explained' simply from GDP (see Figure 4.29), the relationship breaks down at almost any level of disaggregation. For example, Gargett and Gafney (2004) shows that per-city VKT does not follow the same trend – cities with higher per capita product do *not* have higher per-capita VKT. In fact, the relationship between income and vehicle travel tends to run in the *opposite* direction at the city level, whether the comparison is between Australian cities (Rickwood and Glazebrook, 2009), or a range of international cities (Kenworthy and Laube, 1999).

The analysis in Sections 4.2 and 4.3 of this chapter suggest that location has a strong effect on car ownership and car mode share. The aggregate study in Section 4.2 finds that the relative accessibility provided by private and public transport is an important factor affecting mode choice, but that when such information is not available, coarser measures such as distance from the CBD and both local and metro-area density can act as useful proxies, a finding matched in other studies (Newman et al., 1985; Kockelman, 1996; Glaeser and Kahn, 2008). The disaggregate study in Section 4.3 also suggests that measures of population and employment densities at both trip

[29]The travel model for Sydney households developed for the modelling component of this thesis also finds a strong link between household income and vehicle travel, see Table 7.6.

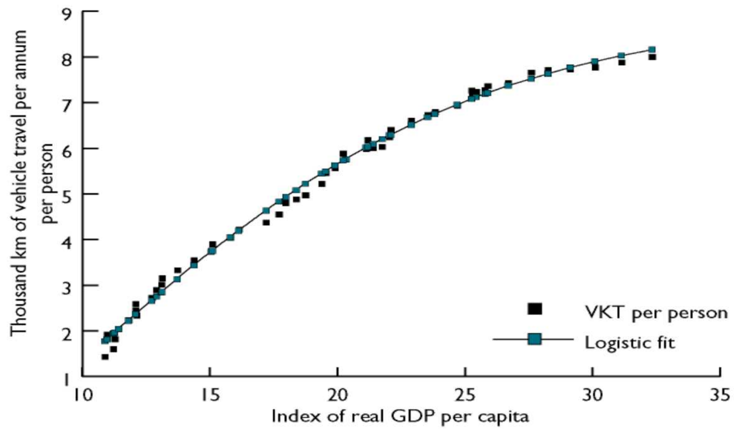


Figure 4.29: Australian vehicle kilometres travelled against per capita GDP. Data Source: Bureau of Transport and Regional Economics (2002).

origins and trip destinations are associated with higher public transport mode share. While these two studies focus on commute mode share, the results are almost certainly indicative of general travel patterns. The two empirical studies concentrate on travel behaviour, rather than resulting energy use, but it is well established that the per-kilometre energy costs of public transport are far lower than for private auto travel. To quantify the energy consequences of particular travel behaviours, all that is required is the use of particular conversion factors. This is done later, in Chapters 7 and 8.

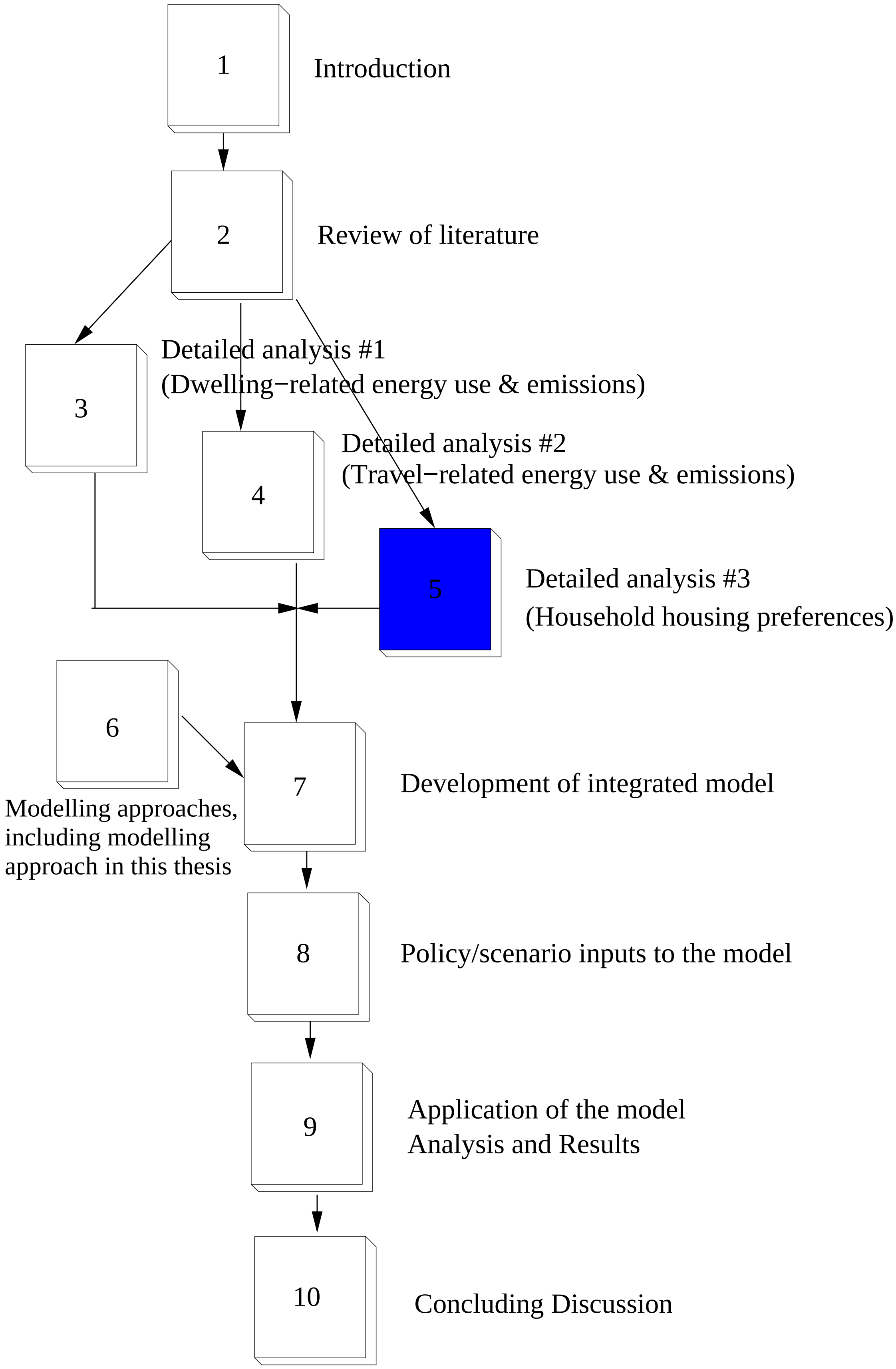
The analysis in Sections 4.2 and 4.3 also confirm that population density can, at the very least, act as a useful proxy in the analysis of travel behaviour. In Section 4.2, for example, together with distance from the CBD, it captured much of the spatial variation in accessibility measured by the much more complex analysis in Glazebrook (2002a). It is worth noting that a number of other researchers have also come to the conclusion that density acts as a useful proxy in many instances. Consider, for example, Kockelman (1996)'s comments on density:

> Its statistical significance in many models may be almost entirely due to its strengths as a *proxy* variable for many difficult-to-observe variables that affect travel behaviour.
>
> Kockelman (1996, page 12)

The studies in this chapter provide a platform, and justification for, a more detailed analysis, which takes place in Chapters 7-9. In particular, they confirm the importance of household location in influencing travel behaviour, and provide a justification for the use of density and distance from the CBD as useful proxy variables. These two measures are used extensively in the detailed household travel model developed in Chapter 7.

Chapter 5

Detailed analysis – Housing Choice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Concluding Discussion

Introduction

This chapter consists primarily of the development of a novel technique for estimating a residential choice model. The model developed in Chapter 7 requires a residential choice model. If we wish to assess the impact of land-use policies on residents, we must know how residents will respond to those land use policies. For housing policy, this requires a residential choice model. Without a model of residential choice, we have no reasonable way of knowing, for example, what households are likely to inhabit newly developed apartment complexes in the city-centre. We also have no way of knowing how well certain housing policies cater to the tastes of households, and knowing this is even more important, as housing policies aimed at reducing energy use, but which are politically unpopular, are bound to fail, as argued in Chapter 3, Section 3.3.7:

> Stepping back a little, perhaps the base question that we should be trying to answer is: *What are the energy use implications of particular housing strategies?*, and, importantly *Which strategies are achievable?* These are metropolitan scale questions, not dwelling or household specific ones. The second question is of prime importance because even if one could achieve a reduction in energy use by shifting family households from detached dwellings into attached ones, this is made irrelevant if such households are opposed to such living conditions (as suggested by Troy (1996); Yates and Mackay (2006)). Similarly, studies that demonstrate lower per-capita energy use in detached dwellings are of limited use if significant proportions of child-free households prefer to live in apartments with better accessibility and access to services (as suggested by Vipond et al. (1998)). More thorough analysis is needed which looks at the projected household mix in our cities, and the likely housing preferences of those households.

The approach I take is to adopt a random-utility discrete choice framework (Quigley, 1976; McFadden, 1977) to model the housing preferences of households. Other approaches are possible, but are not pursued in this thesis. Readers are referred to Oskamp (1994); Waddell (1998); Phillips and Kelly (2006) for details of some other quantitative approaches. More qualitative approaches, based on household questionnaires and/or interviews, are also possible, such as in Winstanley et al. (2002). It is clear, from such studies, that the process whereby households arrive at their choice of suburb/dwelling is vastly more complicated than can be captured by a quantitative model (including the one developed in this Chapter). However, I do not see this as a good argument against such quantitative models, for reasons better put by others:

> I have no sympathy for those people who criticize the unrealistic simplifications of model-builders, and imagine that they achieve greater sophistication by avoiding stating their assumptions clearly.

Paul Krugman, in "How I Work"

> Any attempt to predict the future behavior of a system requires a model of that system, whether it's explicit or implicit, complex or simple.

John Quiggin "Bad Models or Bad Modellers"

Residential Choice Modelling without Price Information

This section details a technique for estimating a residential choice model which does not require the use of house price or rent data. Instead, estimates of residential choice-probabilities can be obtained using only small-area aggregate dwelling occupancy data, such as is usually available through a city and/or national census. Heterogeneity of household preferences is captured by dividing households into groups and assuming only within-group preference homogeneity. Multinomial choice models for groups are jointly estimated by adopting a vertical sorting model, together with the explicit accounting of housing supply. While suffering from problems stemming from the lack of prices or specific household panel data, there are also several distinct benefits of the approach. In particular, the model can be estimated using widely available aggregate census data, and the spatial resolution achievable is excellent. Results obtained on both synthetic and real data (for households in Sydney) are presented.

5.1 Introduction

Since the pioneering work of Quigley (1976) and McFadden (1977), there have been many studies that have adopted a random-utility discrete choice approach to modelling the residential location choices of households. However, despite technological advances that have made possible the collation and analysis of detailed spatial data sets, modern studies into residential choice are still hampered in their ability to detect small-scale variation in household location preferences. This is troubling, as the importance of neighbourhood and even street level effects is generally accepted.

In a housing choice context, one of the major difficulties in adopting a discrete choice model is that house prices/rents must be available for each housing choice. In most other studies, a household's capacity to afford a particular dwelling is included through the use of interacted income/price variables (Yates and Mackay, 2006; de Palma et al., 2007), or simply through independent measures of income and house prices (Skaburskis, 1999; Bhat and Guo, 2007; Garciá and Hernández, 2007). Prices are assumed to adjust to clear the market, which obviates the need to explicitly model supply constraints (although de Palma et al. (2007) do look for, and find, non-price choice constraints).

The limited availability of house price data often forces choice modellers to resort to coarse partitioning of the region/city under study into a small number of sub-regions. A price index, a hedonic price model, or something similar, is then estimated for each sub-region. The coarse partitioning results in valuable locational information being lost, that can be only partly mitigated through the use of locational attributes (crime rates, local school performance, etc.), which capture some of the within sub-region variation in prices and choice utility (see Bhat and Guo (2004) for a good example of this approach). The alternative approach I take is to partition the region under study into zones of small enough size such that local area effects are effectively incorporated into the constant dummy variable for that region. This approach is not common, due, in part, to the difficulty in obtaining reliable house price estimates at a fine scale (but see de Palma et al. (2005)). The technique I devise, however, can adopt this approach, as it avoids the need to use housing price data.

The alternative approach developed in this chapter can still be interpreted using a standard random-utility backed discrete choice framework, but it has less onerous data collection requirements. The basic idea is that, in the absence of price information, one can still estimate preferences from observed choices by adopting a vertical sorting model and taking account of supply constraints. In other words, by explicitly modelling the choice process (i.e. the sorting of households into dwellings), I show it is possible to avoid the need to know prices, provided one can specify the order in which households get to choose[1].

The technique I propose makes it practical to estimate spatially fine-grained choice models for an entire metropolitan region in the presence of heterogenous household preferences, using only widely available census-style data. The technique thus has tremendous potential to enable the widespread estimation of residential choice models. It can be used in isolation, in those instances where data unsuitable for a more traditional analysis is available, or in conjuction with more traditional methods involving partial cross-sectional or longitudinal data together with price information, to provide a better overall understanding of not only the housing decisions of households, but also the potential distortions and biases associated with the adoption of either technique alone. I begin, in Section 5.2, with a brief review of some existing work on residential choice, before proceeding to develop my new technique in Section 5.3.

5.2 Existing work

In spite of the valuable information available in longitudinal data sets, the difficulties in obtaining and analysing longitudinal panel data, and the spatial sparseness of such data, mean that there have been relatively few residential choice studies based on such data (but see Ioannides and Kan (1996), and Kan (2000)). Instead, most researchers have used cross-sectional data. The risks in doing so are well known, but there is often no more palatable alternative, and while it would be a brave soul who put a great deal of faith in the model coefficients obtained from such data, the consensus nevertheless seems to be that there are often valuable general insights to be gained, and so such analyses remain common. There are, for example, a large number of studies into residential location, dwelling, and tenure choice using multinomial logit discrete choice models[2] estimated on cross-sectional data. Examples include: Tu and Goldfinch (1996) in Lothian, U.K; Cho (1997) in Chongju, South Korea; Ben-Akiva and Bowman (1998) in Boston, U.S.A; Yates and Mackay (2006) in Sydney, Australia; Garciá and Hernández (2007) in Spain; and de Palma et al. (2007) in Paris, France. Residential choice models are also part of larger land-use/transport models, which are covered separately in the next chapter.

Regardless of whether longitudinal data or cross-sectional data are used to calibrate a model of housing choice or housing career, the spatial scale at which the analysis can occur is usually quite coarse. Fine-grained information on house prices/rents is often unavailable, or unreliable without significant spatial aggregation. The cross-sectional Canada-wide study by Skaburskis (1999), for example, used city-wide dwelling price estimates. Ben-Akiva and Bowman (1998) used zonal median prices for eight zones in a cross-sectional study of households in Boston. Yates and Mackay (2006) used median prices and rents in a two-location (inner/outer city) model for Sydney. Cho (1997) used a low-quality/high-quality criterion for a binary spatial partition of location in

[1] In fact, I show that even a partial ordering will do, but more on this later.
[2] By far the most common model structure employed in such studies.

Chongju, South Korea. Analysis at such coarse spatial scales is questionable when location, down to the neighbourhood level, can have a very large effect on house prices. While improvements in spatial data availability are already resulting in more disaggregated studies (see, for example, recent work by Clark et al. (2006); Bhat and Guo (2007); de Palma et al. (2007)), data availability continues to be a major constraint on the development of spatially disaggregated discrete choice models.

For studies interested in general inter-city or inter-regional household location decisions (such as Skaburskis (1999); Duncombe et al. (2001)), the use of spatially coarse rent/price measures seems to be the only practical option, and it is at least plausible that the use of such measures will not distort analyses of general inter-city trends too much. Within cities, however, it is difficult to accept that the location decision is adequately characterised by the subdivision of the city into only a small number of regions. Certainly, studies that include detailed dwelling specific variables, such as number of bathrooms, but resort to coarse spatial subdivisions, will likely suffer from significant contamination of non-locational parameter estimates due to the inadequate treatment of location.

5.3 Heterogenous preferences without prices

The conventional approach to analysis of housing choice is to adopt a random utility discrete choice framework. Under such an approach, there are a fixed number (say J) of distinct housing choices, each of which has an associated utility value U_j. The probability $P(j)$ of making choice j is taken to be the probability that $U_j > U_k \quad (\forall k \in [1 \ldots J], k \neq j)$. The utility values of each choice are themselves determined by variables describing the chooser and the choice, as well as a random error term. (This is a necessarily terse description; a fuller treatment can be found in a number of standard references, such as Koppelman and Bhat (2006).) In the following description, I adopt the same basic framework, but find it easier to talk of estimating choice probabilities, rather than (as is more usual) choice utilities. In the common multinomial logit model with a Gumbel-distributed error term, the probability of choice j is, in any case, directly related to choice j's utility (i.e. $P(j)\ \alpha\ e^{U_j}$).

The simple basis to all that follows is that, provided a likelihood function can be defined for observed housing choices, given a particular choice model, parameters can be estimated by maximizing the likelihood function. Thus, the following sections (5.3.1-5.3.4) concentrate solely with the specification of such likelihood functions. I begin the exposition by specifying the likelihood function in the case of homogenous preferences and completely observable choices. These unrealistic assumptions are progressively relaxed until we reach the point where a likelihood function is available that can be evaluated with commonly available data. Choice models are then estimated using both synthetic and real data (Sections 5.4 and 5.5), to demonstrate the applicability of the technique.

5.3.1 Homogenous preferences, completely observable choices

Households are viewed as having a fixed housing budget, within which they pay for the most desirable house they can afford. Assume that there are N households ordered by housing budget (i.e. the jth household can outbid the kth household if $j < k$). In practice, the simplest way to do this is to order households by income. More sophisticated orderings are possible, taking into account household structure, age, or wealth, but these details are unimportant here – I require only that some such ordering is possible.

Assume there are N dwellings (I ignore vacant dwellings), and let P_i be the probability that any household would choose the ith dwelling in the absence of competition, i.e. if all dwellings were available to them for selection. This is actually only the case for the first household ($j = 1$), but for each household it represents a 'free choice' probability. Given a free choice each household would select a dwelling and so we have

$$\sum_{i=1}^{N} P_i = 1. \tag{5.1}$$

In practice however the ordering between households does not allow free choice and so these probabilities are modified by the distribution of available dwellings at the time the choice is made. If we let the function $c(j)$ represent the dwelling actually chosen by household j, then the probability that the jth household chooses the $c(j)$th dwelling for the constrained case, $P'_{c(j)}$, is given by

$$P'_{c(j)} = \frac{P_{c(j)}}{1 - \sum_{l=1}^{j-1} P_{c(l)}} \tag{5.2}$$

The denominator in this expression takes into account the gradual removal of dwellings from potential selection by lower order households. Since the choices of each household, $c(j), (j = 1, \ldots, N)$ are assumed known then the likelihood function for all selections is simply the product of the constrained choices of each household,

$$L(P_1, P_2, \ldots, P_N) = \prod_{j=1}^{N} P'_{c(j)} = \prod_{j=1}^{N} \frac{P_{c(j)}}{1 - \sum_{l=1}^{j-1} P_{c(l)}} \tag{5.3}$$

Here the likelihood is a function of the N variables P_i $(i = 1, \ldots, N)$. It is important to note that because the choice of each individual household changes the choice set for subsequent households, it is not possible to calculate choice probabilities for an individual household without taking into account the choices of all households with a greater housing budget. Figure 5.1 gives a simple illustration of the basic model, where the choice set consists of a complete enumeration of all choices, and households are sorted by housing budget.

5.3.2 Heterogeneity of preferences

Housing preferences vary between households. This variation is usually modelled through variables describing a household's age, income, education, and so on. My approach is instead to segment the population (i.e. the choosers) into disjoint subgroups, within which preferences are assumed to be homogeneous. Heterogeneity of tastes is modelled by dividing households into $M << N$ subgroups. As before I define 'free choice' probabilities for each class of household and dwelling. Specifically let $P_{k,i}$ be the probability that the kth household group would choose the ith dwelling in the absence of any competition, i.e. if all dwellings were available to them for selection. Given

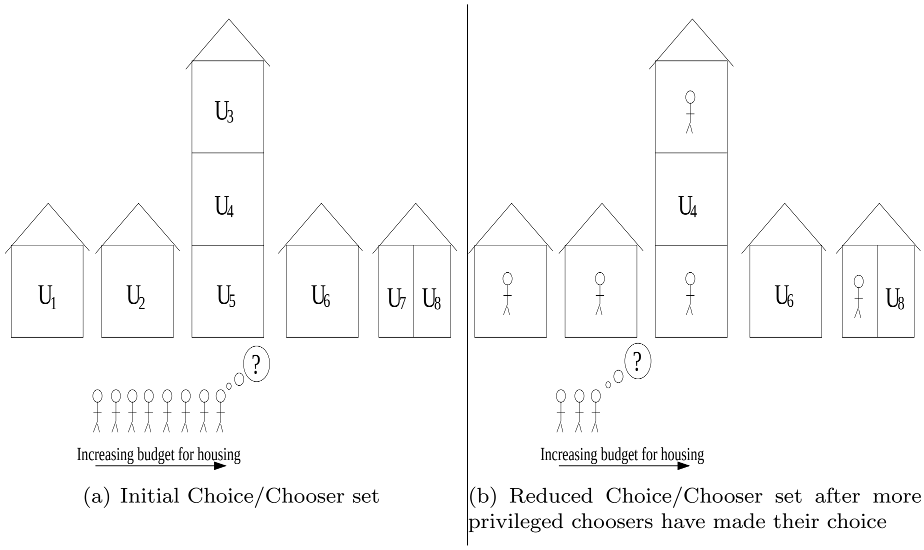


Figure 5.1: A simplified illustration of an alternate choice modelling approach, where supply and budget constraints obviate the need for house price data. Figure a shows 8 households 'queuing' to select houses, Figure b shows the remaining choices for the poorest 3 households after the first 5 households have made their choice.

a free choice each household group selects a dwelling and so we have

$$\sum_{i=1}^{N} P_{k,i} = 1, \quad (k = 1, \ldots, M). \tag{5.4}$$

Again the ordering of households limits the choices available. If we define the function $g(j)$ to represent the household group containing the jth household then the probability that the jth household choose the $c(j)$th dwelling becomes

$$P'_{j,c(j)} = \frac{P_{g(j),c(j)}}{1 - \sum_{q=1}^{j-1} P_{g(q),c(q)}} \tag{5.5}$$

In this case the likelihood function becomes

$$L = \prod_{j=1}^{N} \frac{P_{g(j),c(j)}}{1 - \sum_{q=1}^{j-1} P_{g(q),c(q)}} \tag{5.6}$$

5.3.3 Partially observed choices

Thus far, I have assumed that each household's specific choice is observable. In particular, I have assumed that $c(j)$ is known, and this defines precisely the individual dwelling chosen by that household (i.e. $c(j)$ takes values in the range $[1 - N]$). While this may be the case for panel and survey data, it is not the usual case for aggregated census data, which is the type of data most readily available, and which many researchers would like to be able to use.

Suppose that we know, instead, only which of D *classes* of dwelling each household chooses (with $D << N$). I define the function $d(j)$ as the dwelling type selected by the jth household[3]. (Note that $(1 \leq d(j) \leq D)$ for $(j = 1, \ldots, N)$.)

To continue let the total number of dwellings of type i be n_i. We have then

$$\sum_{i=1}^{D} n_i = N. \tag{5.7}$$

Since both households and dwellings are now grouped it is convenient to recast probabilities in terms of groups. Let $P_{k,i}$ now represent the 'free choice' probability of a household in group k selecting a dwelling in group i. We have then

$$\sum_{i=1}^{D} P_{k,i} = 1, \quad (k = 1, \ldots, M). \tag{5.8}$$

Note that there are now $D \times M$ free probability variables. As usual, when individual households make selections, the number of dwellings reduces. If we let $n'_{i,j}$ represent the number of dwellings in group i after j individual households have made their selections, then we have

$$n'_{i,j} = n_i - \sum_{l=1}^{j-1} \delta_{d(l),i} \quad (i = 1, \ldots, D) \tag{5.9}$$

where δ_{ij} is the Kronecker delta. If the jth household belongs to the kth group $(k = g(j))$ and selects a dwelling in the ith dwelling group $(i = d(j))$,then the probability of this occurring is

$$P'_{k,i} = \frac{P_{k,i} n'_{i,j}}{\sum_{l=1}^{D} P_{k,l} n'_{l,j}}. \tag{5.10}$$

As before, each selection is made independently and so the combined likelihood as a function of all $M \times D$ probabilities is

$$L(P_{1,1} \ldots P_{1,M} \ldots P_{D,M}) = \prod_{j=1}^{N} \frac{P_{k,i} n'_{i,j}}{\sum_{l=1}^{D} P_{k,l} n'_{l,j}}. \tag{5.11}$$

where it is understood that both house (k) and dwelling group indices (i) inside the product are functions of the household index j, $(k = g(j), i = d(j))$. This likelihood function represents the probability that the actual observed data $d(j)$ would have occurred by chance given the free choice probability variables, $P_{k,i}, (k = 1, \ldots, M; i = 1 \ldots, D)$. It is worth further examining the dependence of L on the probability variables, as some simplifications can be made. First examine the numerator in (5.11) which can be written as the product of two terms

$$\prod_{j=1}^{N} P_{k,i} n'_{i,j} = \prod_{j=1}^{N} P_{k,i} \prod_{j=1}^{N} n'_{i,j}. \tag{5.12}$$

[3]Dwelling type is meant loosely here. Dwellings types may be defined by actual dwelling form (apartment, detached house), location (i.e. suburb), or other features. Provided that dwellings can be usefully grouped into $D << N$ categories, the nature of the subdivision does not matter for the purposes of defining a likelihood function.

For the second term we can combine with (5.9) and show that

$$\prod_{j=1}^{N} n'_{i,j} = \prod_{i=1}^{D} n_i! \tag{5.13}$$

This expression follows because as every individual household, j, makes a selection, say a dwelling in group i, then the number left in that group reduces by one. After all N selections, all n_i dwellings are taken and so the product over j in the left hand side of (5.13) must be proportional to $n_i!$. The same argument holds for each group ($i = 1, \ldots, N$) and so the product over j is equal to a product of factorials over the dwelling groups. Note that this term is independent of both the selections of individual households and the free choice probabilities, $P_{k,i}$ and does not influence the maximum likelihood solution.

The first term in (5.12) can be simplified by introducing the term $m_{k,i}$ to represent the number of households in group k that select a dwelling in group i. (Note $\sum_{k=1}^{M} m_{k,i} = n_i$.) Again the product over households can be broken down into a product over household and dwelling groups. Specifically we have

$$\prod_{j=1}^{N} P_{k,i} = \prod_{k=1}^{M} \prod_{i=1}^{D} P_{k,i}^{m_{k,i}}. \tag{5.14}$$

Combining (5.14), (5.13) with (5.12) the numerator of the likelihood function in (5.11) becomes

$$\prod_{j=1}^{N} P_{k,i} n'_{i,j} = \left(\prod_{k=1}^{M} \prod_{i=1}^{D} P_{k,i}^{m_{k,i}} \right) \left(\prod_{i=1}^{D} n_i! \right) \tag{5.15}$$

This expression is useful as an explicit dependence on individual selections, (i.e. product over j), is removed. It shows that the numerator in the likelihood expression only depends on the total number of selections of each household-dwelling group pair, through the variables $m_{k,i}$ which are measurable from the data. This expression for example can easily be differentiated with respect to variables, $P_{k,i}$, for use, say in a gradient optimisation algorithm. The combined expression for the likelihood can then be written

$$L(P_{1,1} \ldots P_{1,M} \ldots P_{D,M}) = \frac{\prod_{k=1}^{M} \prod_{i=1}^{D} P_{k,i}^{m_{k,i}} \prod_{i=1}^{D} n_i!}{\prod_{j=1}^{N} \sum_{l=1}^{D} P_{k,l} n'_{l,j}}. \tag{5.16}$$

In the denominator of the likelihood expression the product over individual selections j can also be rewritten using similar arguments, but in this case I have found no useful simplification. Indeed, unlike with the numerator, the denominator's value will always depend on particular selections of individual households.

5.3.4 A practical approximate likelihood maximiser

There are now only two remaining obstacles that appear to prevent us from evaluating the likelihood function in equation 5.11 on readily available data sets. These apparent obstacles are:

1. I assume that the complete ordering of households (by housing budget) is known. That is, the precise order in which households get to choose dwellings is known.

2. I assume that the dwelling-type choice $d(j)$ is known for each household.

Census-style cross-sectional data-sets are, however, only likely to provide us with aggregate count information, not information on individual households. The difficulties are better explained by example, so let us assume, for simplicity, that household income is our sorting variable[4], that dwellings are divided into different types based solely on suburb (i.e. all dwellings in one suburb make up a single dwelling-class), and heterogeneity of housing tastes are allowed for by dividing households into just two household groupings – those with children and those without children. Now, because of privacy concerns, in most countries, a census-style cross-sectional data set will not be able to tell us the exact income of the richest household with children, and the suburb in which they live. Instead, what *would* be typically available is the number of households with children in each suburb, within a particular income range. So, for example, we may know that there are 20 households with children earning between \$80,000 and \$120,000 living in suburb X, and 27 households with children earning between \$40,000 and \$60,000 living in suburb Y, and so on. More formally, we know the values in a table $H_{d,k,\$}$ $(1 \le d \le D; 1 \le k \le M; 1 \le \$ \le B)$, with the $(d, k, \$)$th entry giving the number of dwellings of type d chosen by households in group k with household income falling within income bracket \$. The first of the obstacles listed above comes about because we only know the income bracket of each household, and not its exact income. This only allows a partial ordering of households – we know, for example, that households in higher income brackets get to 'choose' dwellings before those in lower brackets, but we do not know the choice order for those households within the same income bracket. Furthermore, we do not observe the actual dwelling type chosen by any single household (the second of the difficulties listed above).

It turns out that the first of these two difficulties is less of a problem than the second. Given that we can still impose a partial ordering of households, we could in theory, evaluate a likelihood function for all possible full-orderings consistent with the observed partial ordering. In practice, this will not be possible due to the number of permutations, but it ends up being unimportant, because the method for minimizing the likelihood function now presented is very insensitive to different within-bracket orderings. The second difficulty (we do not know the dwelling-type choice $d(j)$ for the jth household) is more problematic, and requires some further refinement of the likelihood function.

For the moment, let us take on faith the claim that accounting for the different possible household orderings is unimportant, provided the partial ordering constraint imposed by the table $H_{d,k,\$}$ is satisfied[5]. So let us then, for convenience, fix the order of households. And further, let us assume that within a particular bracket, households in group k_1 choose before those in group k_2 if and only if $k_1 < k_2$. As before, let $g(j)$ be the 'group' of the jth household. The likelihood

[4] As already mentioned, sorting by income is only one possibility. I assume income as the sorting variable just to simplify the exposition.

[5] It may not be clear to some readers how H partially constrains choice order. We can calculate that there are $\sum_{d=1}^{D}\sum_{k=1}^{M} H_{d,k,\$}$ households in bracket \$, and we can calculate the number of these belonging to each household group by evaluating $\sum_{d=1}^{D}\sum_{\$=1}^{B} H_{d,k,\$}$ for each of the M possible groups. Thus, we know the number of households in each household group in each bracket, and this imposes constraints on the allowable orderings of households.

function can then be well approximated by

$$L \approx \prod_{d=1}^{D}\prod_{k=1}^{M}\prod_{\$=1}^{B}\beta(H_{d,k,\$}\ ;\ \sum_{d'=1}^{D}\sum_{k'=1}^{M}\sum_{\$'=1}^{\$-1}H_{d',k',\$'}\ ,\ P'_{k,d,\$}) \tag{5.17}$$

where $\beta(x;n,p)$ is the (binomial) probability of observing x successes from n trials, given a trial probability of p; and where

$$P'_{k,d,\$} = \frac{P_{k,d}}{1-\sum_{q=1}^{\$-1}P_{k,d}H_{d,k,q}} \tag{5.18}$$

Now the likelihood function in eqn. 5.17 *can* be evaluated given the available data, and, moreover, it can be evaluated efficiently enough to allow the use of standard numerical optimisation techniques to find a minima. Returning now to my claim that that value of the likelihood function in eqn. 5.17 is not sensitive to different possible orderings of households, it should be clear that the sensitivity to within-bracket ordering of households matters more where there are only a small number of income brackets. To see this, consider first the case where the number of brackets is equal to half the number of households (i.e. $B = \frac{N}{2}$, with only two households are within each bracket). This imposes a very strict partial ordering, and, within each bracket, the choice probabilities for the second of the two households needs to be corrected only for the loss of a single dwelling resulting from the choice of the other household within that bracket. Reversing the within-bracket ordering will not, then, make a significant different to the likelihood, because this correction will be small provided choice probabilities for each household group are sufficiently spread amongst the available dwelling types. In the more realistic case where the number of brackets is small relative to the number of households (i.e. $B << N$), we can usefully introduce some additional artificial ordering by splitting ordering brackets into a number of different *tranches*. Let the number of *tranches* so defined be T. We can define, then, the augmented table H' by defining $H'_{d,k,\$,t} = \frac{H_{d,k,\$}}{T}$. Given that we can artificially boost the number of sorting brackets in this manner, and given that the sensitivity of the likelihood function decreases with an increasing number of brackets, I hope it strikes the reader as plausible that the likelihood function can be made sufficiently insensitive to within-bracket orderings for it to serve as a useful likelihood function in practice. Some may find the argument unsatisfactory, but for such readers, the synthetic results presented in the next section should help alleviate any lingering concerns.

5.4 Applying the technique – synthetic data

I conducted numerous synthetic experiments to determine how well underlying parameter values could be re-captured by maximizing the likelihood function outlined in the previous section. Due to length constraints, I report on just one such synthetic experiment here, the results of which are consistent with other unreported synthetic experiments.

A synthetic data-set was generated in the following way:

1. The number of dwellings of each of 121 different dwelling types was determined by drawing a value uniformly from the range $[30, 1000]$. There are 59292 dwellings in total.

2. There are three household groups of equal size, making $\frac{59292}{3} = 19764$ households in each group.

3. Households within each group are divided evenly into three 'housing budget' brackets, with equal numbers of households in each bracket[6].

4. 'True' choice probabilities for each of these 121 dwelling types were randomly generated[7], for each of 3 different household groups. Figures 5.2a-5.2c show the true unconstrained 'free-choice' probabilities for each of the three household groups.

5. Households of all types are arranged according to their 'housing budget' bracket, with the ordering of households within each bracket being randomly determined.

6. Each household is assigned (one at a time) to a particular dwelling group, by calculating the constrained choice probability of each dwelling group, and then drawing a dwelling choice from this distribution. Once this choice is determined, the choice probabilities for subsequent households are adjusted accordingly (to reflect the fact that a particular dwelling is no longer available).

It is important to note that while in these synthetic examples, dwelling groups are defined purely by location (i.e. all dwellings in each 'zone' form a single dwelling group), this is done purely for ease of illustration. In practice, dwelling groups could be defined based on location and dwelling characteristics. This is the case for the non-synthetic example in the following section, for example.

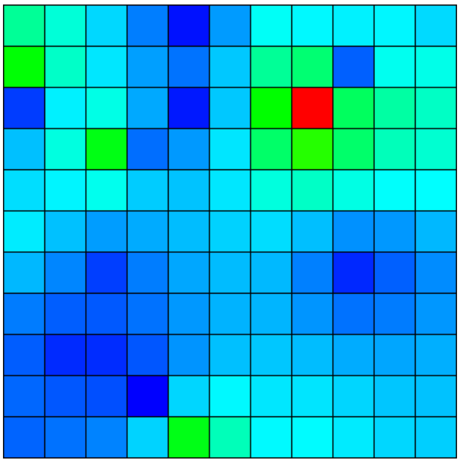
Following the above steps allows us to determine the values in the table $H_{d,k,\$}$. (For this particular case, note that $1 \leq d \leq 121$, $1 \leq k \leq 3$, and $1 \leq \$ \leq 3$.) Once the synthetic data set is generated (producing H), estimates of choice probabilities can be obtained by maximizing the likelihood function[8] specified in eqn. 5.17. This is done by initially setting all choice probabilities equal, and then using a standard numeric optimisation algorithm to maximize the likelihood[9]. The dwelling type choice probability estimates for each household group are shown in Figures 5.3-5.5, along-side the 'true' values. We can see that while the exact values are not recaptured, they are recaptured at least well enough to closely approximate the true preference order. This is especially impressive given that the data used to obtain the estimates is itself only one possible outcome from the stochastic process whereby households are allocated to households. That is, because synthetic households are allocated not deterministically, but according to draws from a probability distribution over possible choices, re-running the allocation procedure in step 6 of the list, above, with the exact same choice probabilities, would result in different allocations, and, hence, different values in the table $H_{d,k,\$}$. That the underlying estimates are not overly sensitive to this stochasticity is further evidence for my claim that the likelihood function is not sensitive to within-bracket ordering.

[6] This is not exactly right. As the total number of households in each group (19764) is not exactly divisible by three, one group must have an additional member.

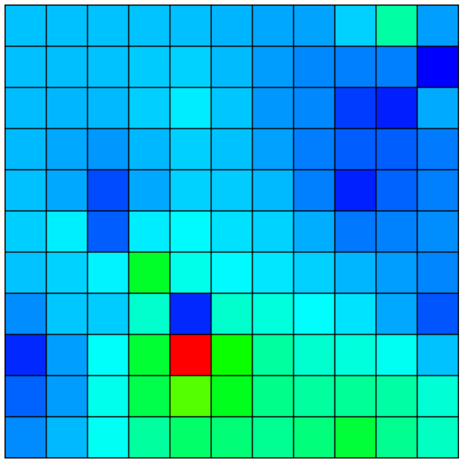
[7] The exact scheme for doing this is a little involved, and in any case not important here, as Figures 5.2a-5.2c provide all the necessary information.

[8] Actually, of course, by minimizing the log-likelihood.

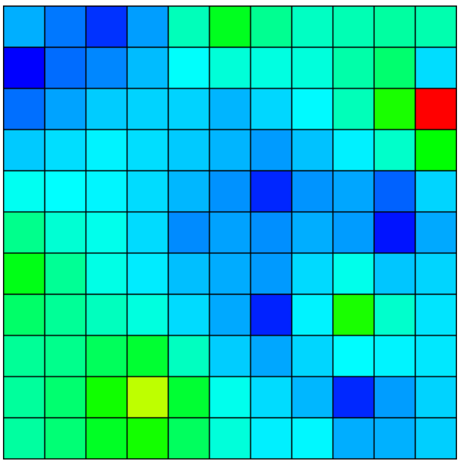
[9] I use a simple gradient-free optimization algorithm. More sophisticated methods would doubtless result in faster convergence, but these proved unnecessary due to the acceptable convergence speed of the simpler method.



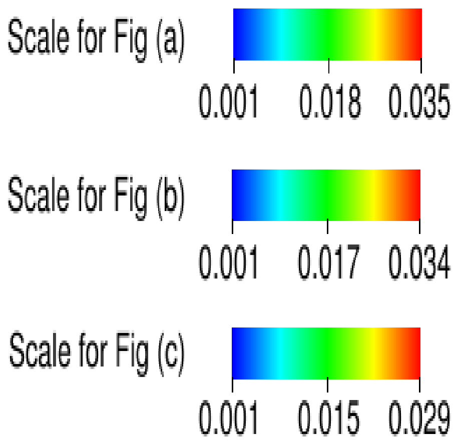
(a) Household group 1



(b) Household group 2

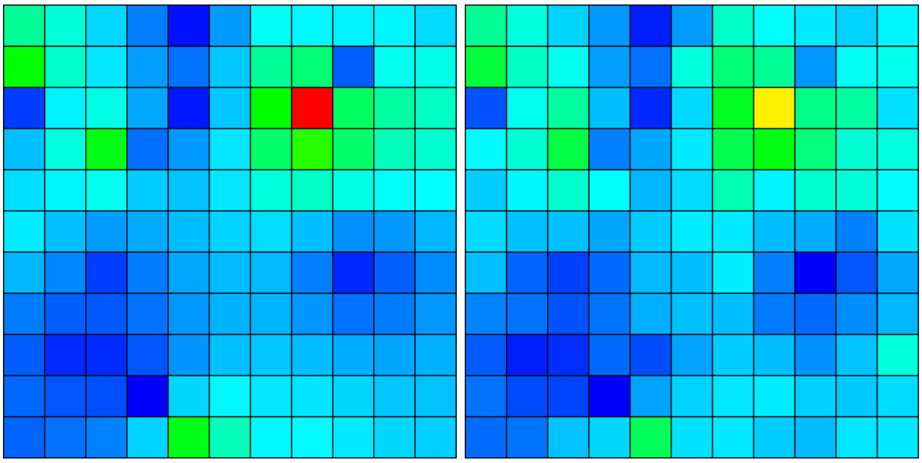


(c) Household group 3



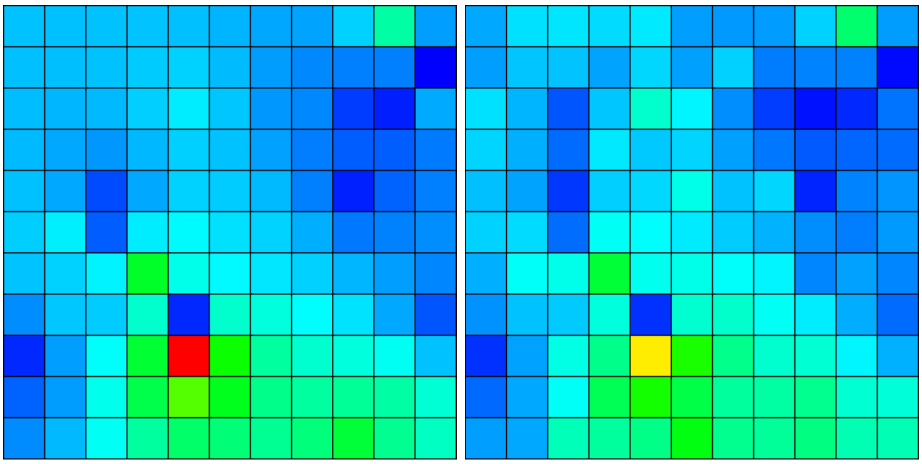
(d) Scales

Figure 5.2: True 'free-choice' dwelling choice probabilities for three household groups, for each of 121 different dwelling groups. Values shown are actually proportional to choice probabilities, having been multiplied by the number of households of each type (19764) to avoid reporting numbers in scientific notation.



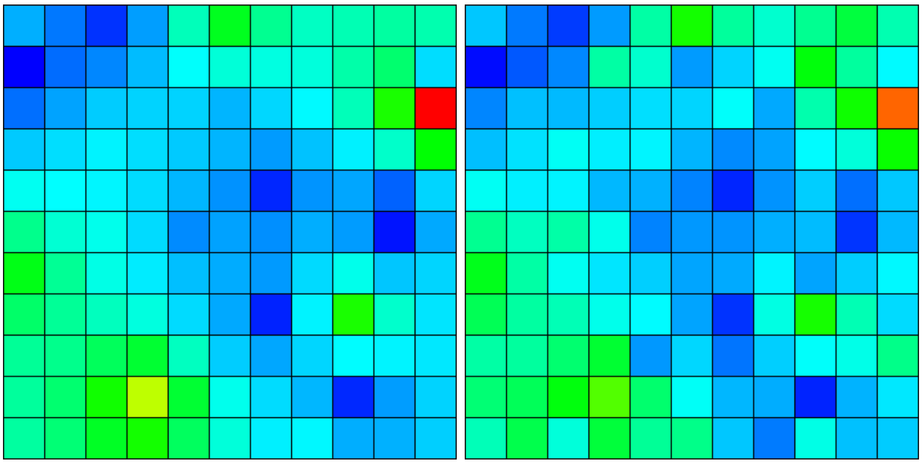
(a) True probabilities (b) Estimated probabilities

Figure 5.3: True and estimated 'free-choice' dwelling choice probabilities for household group 1, for each of 121 different dwelling groups. Note: scale is identical to that in Figure 5.2a.



(a) True probabilities (b) Estimated probabilities

Figure 5.4: True and estimated 'free-choice' dwelling choice probabilities for household group 2, for each of 121 different dwelling groups. Note: scale is identical to that in Figure 5.2b.



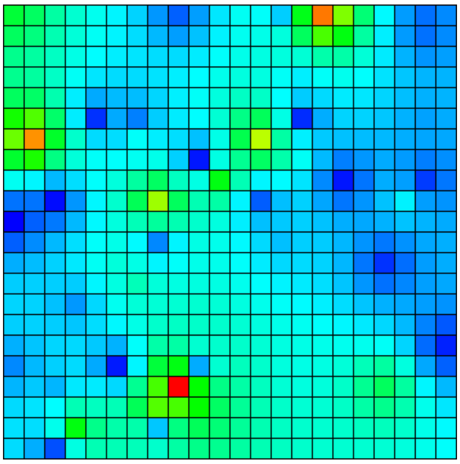
(a) True probabilities (b) Estimated probabilities

Figure 5.5: True and estimated 'free-choice' dwelling choice probabilities for household group 3, for each of 121 different dwelling groups. Note: scale is identical to that in Figure 5.2c.

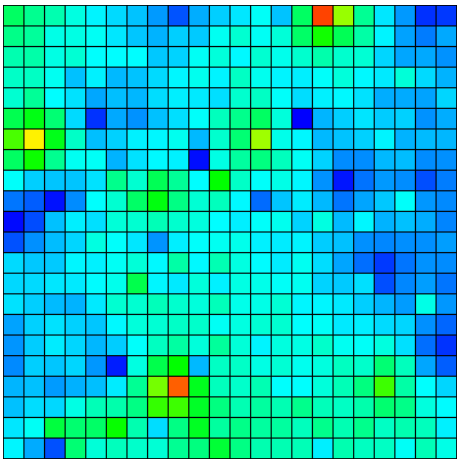
While the synthetic example presented in this Section is not as complex as we would expect in the case where real data was used, it is far from a trivial example. It requires, for example, the joint estimation of 363 choice probabilities (121 dwelling-type probabilities for each of the three household groups). More complex synthetic experiments were conducted (i.e. with more dwelling types, household groups, and sorting brackets), but presenting results for these more complex experiments would require a large number of figures, and for this reason, I opted to present a simpler example. I should note though, that in the synthetic experiments, the technique was always able to approximately recover the 'true' underlying choice probabilities provided that: the number of dwellings of each dwelling type was not too small; the number of households in each household group was not too small; and the choice probabilities for each household group were not too heavily concentrated on a small number of dwelling types. In other words, the ability to recover the 'true' underlying choice probabilities is dependent not on the total number of parameters to be estimated ($D \times M$), but on the sparseness of the table H. Regions of H that are sparse (i.e. have low counts) will result in poorly recovered values. To give just some indication of the ability to recover underlying free-choice probabilities in a more complex example, Figure 5.6 shows the true and recovered/estimated choice probabilities for just one of the household groups in a larger synthetic experiment requiring the recovery of 1936 choice probabilities (484 dwelling types, by 4 household groups), with 5 sorting brackets. Although the true and recovered probabilities for only one household group are shown, choice probabilities for other household groups are recovered to a similar level of accuracy.

5.5 Applying the technique – real data

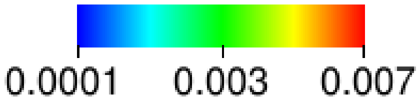
The technique I have developed is a general one, and could be applied to any city or region where aggregate cross-sectional census-style data is available. To demonstrate this applicability, and to make the potential of the technique more tangible, I now apply the method to estimate



(a) True probabilities



(b) Estimated probabilities



(c) Scale

Figure 5.6: True 'free-choice' dwelling choice probabilities for the first of four household groups, for each of 484 different dwelling groups. Values shown are actually proportional to actual per-dwelling probabilities, having been scaled up as in Figure 5.2.

dwelling-choice probabilities for the city of Sydney, Australia. As my primary aim is to describe and illustrate the general applicability of my method, I take as uncomplicated an approach as possible. A proper analysis of residential choice in Sydney, for example, would require a more detailed treatment than I provide here, but for my illustrative purposes, the simple approach I take is preferable.

5.5.1 Data

I use census data collected by the Australian Bureau of Statistics (ABS) for the 2006 census of population and housing, for households in a large sub-area of the Sydney Statistical Division[10]. This data, after some pre-processing[11], gives us $\approx$ 1.1 million household records[12], each of the form [*hhtype, incomebrak, dwelltype, location*], where *hhtype* is one of {young single, old single, young couple, old couple, single parent, couple with child under 15, couple with child 15+, other}, *incomebrak* is weekly household income in the ranges {under \$650, \$650 – \$999, \$1000 – \$1399, \$1400 – \$1999, \$2000 – \$2999, \$3000+}, *dwelltype* is one of {detached, townhouse/terrace/semi-

[10]See Australian Bureau of Statistics (2001) for reference to exact geographical boundary defined by the Sydney Statistical Division. The sub-area I use covers most of the Sydney metropolitan area, but excludes the Central Coast, Blue-Mountains, and some other peripheral areas.

[11]I have spatially aggregated the finer-scaled data the ABS provides, and have made other minor modifications such as reducing the number of income brackets and dwelling types. Some areas covering 'unusual' land uses, such as army barracks, were also excluded.

[12]This is slightly lower than one might expect for Sydney, but this is because my study area is smaller than the Sydney metropolitan region, and households with incomplete census records are excluded.

detached, apartment}, and location is a number in the range $[1 - 615]$, which is an identifier for which of 615 zones the household resides in. Because this is an illustrative application, I assume, for simplicity, that a household's housing budget is proportional to household income. Other variables, such as equivalized income, equivalized wealth, 'human capital' (see Börsch-Supan et al. (2001)), or other variables are perhaps preferable, but the best choice of budget constraint variable is a modelling issue, which, for clarity of exposition, I wish to avoid detailed consideration of. So, with household income as our sorting variable (i.e. households with higher household income get to choose before those on lower incomes), I define 1845 different dwelling types[13] (i.e. 3 possible dwelling structures by 615 possible locations), and assume dwelling preferences are homogenous within each of the 8 household types (i.e. household groups are defined solely by the *hhtype* variable[14], so there are 8 different household groups). Using the same terminology as that used in developing the likelihood function, $D = 1845$, $M = 8$, and $B = 6$.

Collating the census data gives the number of dwellings of each type in each zone, and also the number of households (of each group and income) in each zone. That is, simple collation of the available census data gives us the entries in the table H, required to estimate choice probabilities. Vacant housing is excluded, and so the number of households and the number of available dwellings match exactly.

Figure 5.7 provides some basic information on the geography of Sydney, and also shows the boundaries of the 615 zones used for analysis, as well as a few of the metropolitan centres of Sydney. The main geographic features are the harbour, running roughly horizontal across the centre of the figure, and the Pacific coastline running north-south along the eastern side of the figure.

5.5.2 Results

Rather than showing full results for all eight household types for each of the three possible dwelling-structures (requiring 24 figures), I report only selected results for some household group/dwelling structure combinations. In particular, I focus mainly on the spatial variation in choice probabilities for detached dwellings, as they are the most numerous and have the widest spatial distribution.

Figures 5.8a-5.8c show the location choice preferences for couples with children, where all children are under the age of 15. It is apparent from these three figures that this household group prefers detached dwellings in harbour-side and beach-side suburbs, as well as the leafy low-density suburbs adjoining Sydney's northern rail line. The patch of red and orange out in the north-west covers recently developed land in suburbs such as Kellyville (near Baulkham Hills) that have been popular with recent home-buyers. Note that white indicates here (as in all future figures) areas for which no choice probabilities could be estimated because dwelling counts were either zero (for that dwelling-structure), or else too low in those areas to obtain a reliable estimate of choice probability.

Figures 5.9a and 5.9b show the location preferences for lone person households. Figure 5.9a shows that singles under the age of 55 have a notable preference for inner-city apartment living,

[13] Although there are this many possible combinations, many of these combinations do not occur. For example, many of the 615 regions contain *no* apartments or townhouses, so there are less than 615×3 actual possibilities. The actual number of possibilities is around 1200.

[14] While I have defined household groups based solely on household type here, in a more sophisticated application, groups could be chosen using a clustering technique to group demographically similar households.

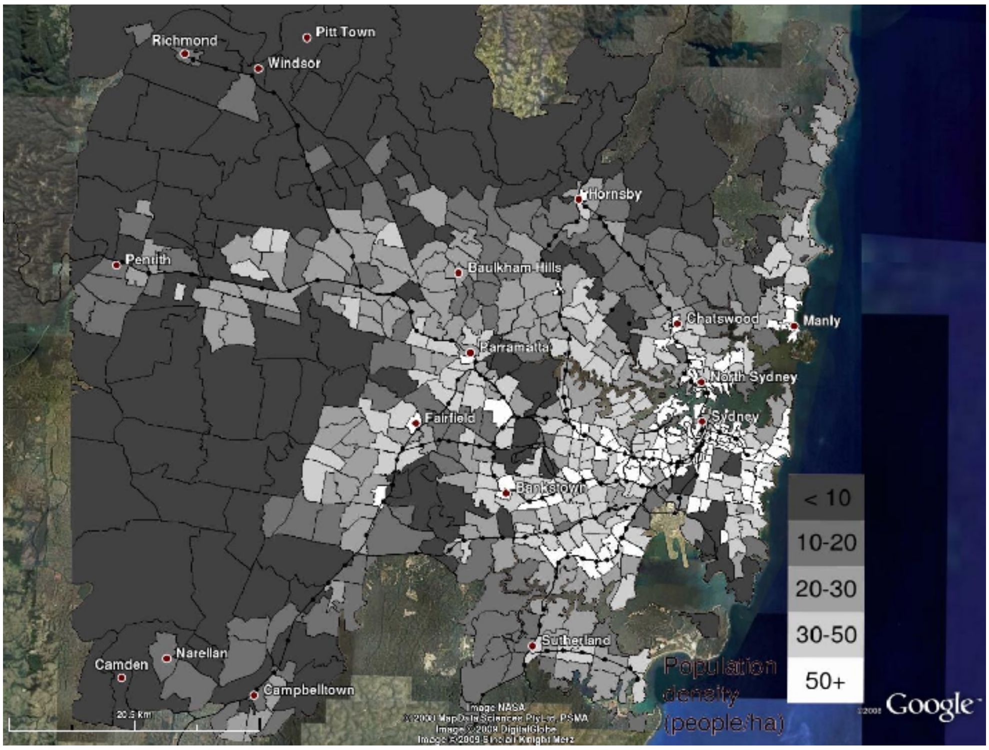
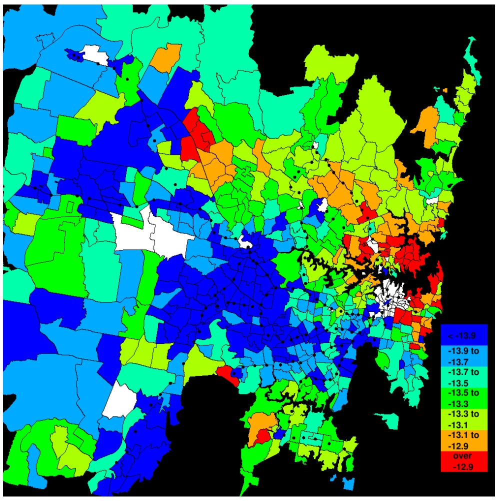
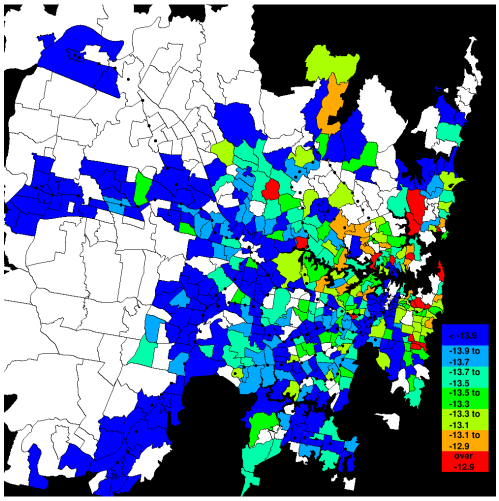


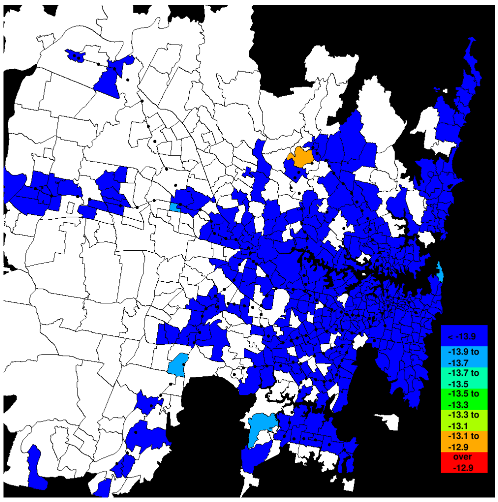
Figure 5.7: Basic geography of Sydney. Scale shows population density (people per hectare). The CBD spans the harbour, roughly centre-right of picture.



(a) Detached

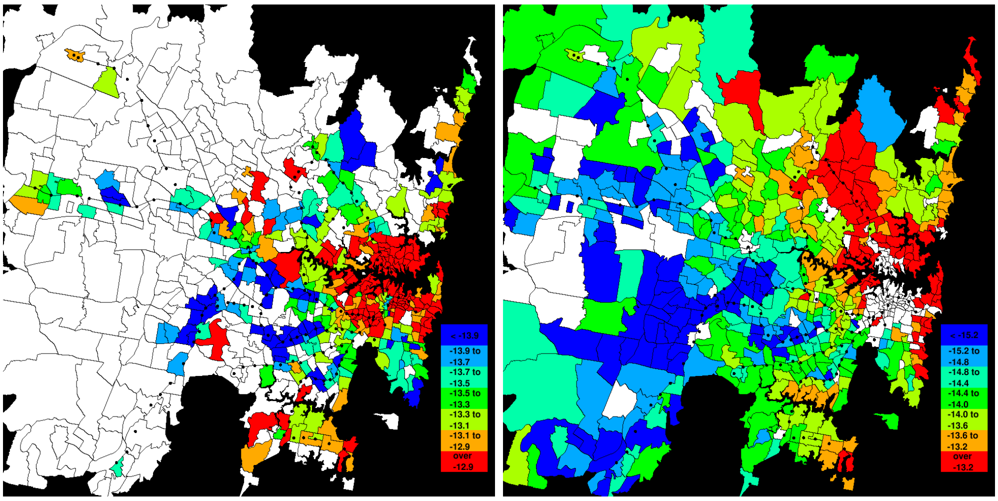


(b) Townhouse



(c) Apartment

Figure 5.8: Location choice log-probabilities for couples with young children, for different dwelling structures. The value plotted is $\ln(P(i))$ where $P(i)$ is the choice probability for a single detached dwelling in region i.



(a) Young singles (b) Older singles

Figure 5.9: Location choice log-probabilities for lone person households. The values plotted are for apartments in the case of young singles, and for detached dwellings for older singles. The value plotted is $\ln(P(i))$ where $P(i)$ is the choice probability for a single dwelling in region i.

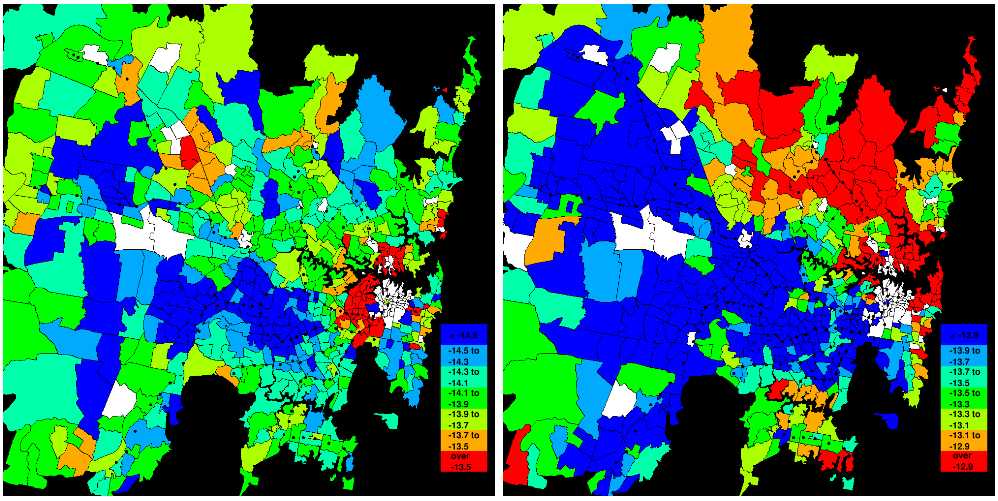
which is in-line with other published research into the housing preferences of young professionals in Australia (Reynolds and Porter, 1998; Vipond et al., 1998; Yates and Mackay, 2006). Older lone person households prefer coastal and harbour-side suburbs and those leafy low-density suburbs adjoining the northern rail line also favoured by households with children. There is a clear lack of willingness to inhabit the high-density urban areas ringing the central business district, compared with young lone-person households. This may be explained by the fact that the older households are less likely to be in the work-force, and so the access to employment provided by inner locations is of little value, with neighbourhood amenity factors instead dominating.

Figures 5.10a and 5.10b show the location preferences for couple households[15] without children. The location choice preferences of younger couples are again markedly different from those of older households. In particular, young couple households, like young lone person households, show a much stronger preference for suburbs adjoining the CBD, while older couples, like older lone person households, show a preference for those suburbs with high amenity – particularly harbour-side suburbs and those adjoining the northern rail line.

Figure 5.11a shows that single-parent households have preferences broadly similar to couples with children, while 'other' households, comprising mostly of group/share households prefer locations with good access to the CBD and the other major employment locations in Sydney, as shown in Figure 5.11b. This makes sense, given that such households are likely to have multiple full-time workers.

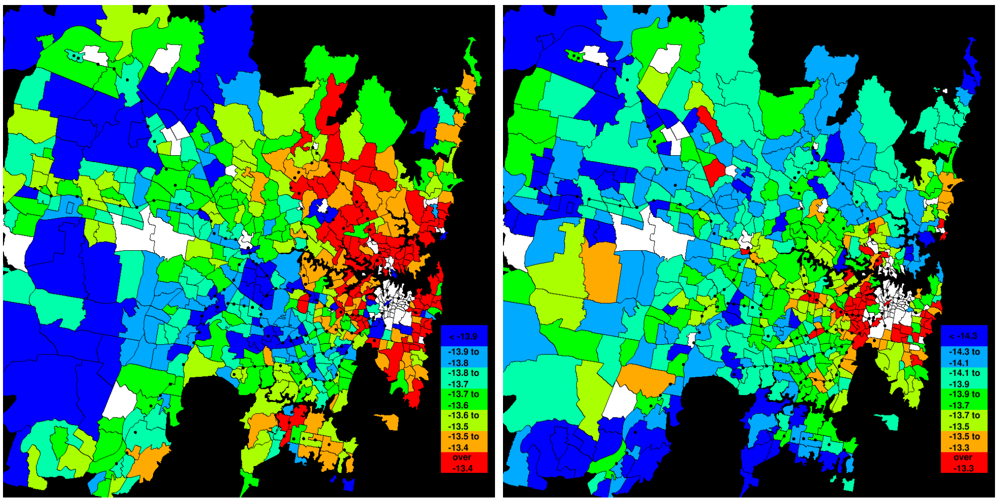
In general, the results for housing preference fit not just with the common understanding of preferences in the Sydney property market, but also, but also with academic studies into the preferences of households. Younger childless households, for example, show a strong preference for inner areas with good accessibility and recreation and consumption opportunities (as in Reynolds

[15]Whether married or in a relationship.



(a) Young couples (b) Older couples

Figure 5.10: Location choice log-probabilities for couple-without-children households. The value plotted is $\ln(P(i))$ where $P(i)$ is the choice probability for a single detached dwelling in region i.



(a) Single parents (b) Other

Figure 5.11: Location choice log-probabilities for single-parent and 'other' households (comprising principally of group/share households). The value plotted is $\ln(P(i))$ where $P(i)$ is the choice probability for a single detached dwelling in region i.

Figure 5.12: Mean 3 bedroom house prices in Sydney, from sales in calendar years 2000-2002. Source: Residex Pty Ltd.

and Porter (1998); Vipond et al. (1998); Yates and Mackay (2006)) with most other households having a notable preference for the leafy low-density suburbs along Sydney's northern rail line. Older households in particular, show stronger preferences than their younger counterparts for detached dwellings in traditional suburban locations, as suggested by Wulff et al. (2004). Households with children, unsurprisingly, have a preference for detached suburban dwellings, in line with international research (Tu and Goldfinch, 1996; Molin et al., 2000; Bhat and Guo, 2007). All household types value those harbour-side and beach-side suburbs with both good amenity and good accessibility, but the location preferences of young households without children suggest there is more of a willingness to trade off amenity for accessibility in these groups.

For interest, and comparison, mean zonal 3 bedroom house prices for the period between January 2000 and December 2002 are shown in Figure 5.12. This figure also adds some support to the choice models shown in Figures 5.8-5.11, as the universally desirable harbour and inner beach-side suburbs are also the most expensive, with prices also being high in the northern suburbs preferred by all household types except young singles and couples.

Although I have indulged in some speculation and commentary regarding the preferences of different households in Sydney, I should not get too carried away with making inferences about the reasons behind the location preferences of the different household groups. Because the main reason for conducting the analysis is to illustrate the application of a new technique for estimating residential preferences, I have taken a simple approach, and so should expect some irregularities in the results. It is, however, very encouraging that plausible results are obtainable even with the simple approach I take to sorting households and dividing them into groups.

The strong spatial auto-correlation structure evident in Figures 5.8-5.11 can be taken as evidence that the model is sufficiently constrained. No spatial correlation structure is forced during estimation, with each location-specific utility parameter being independently estimated, and yet the technique of maximizing the likelihood function developed in Section 5.3 produces an obvious spatial structure. I should also note that, just as in the synthetic experiments, it is possible to achieve repeated stable convergence to (approximately) the same choice probabilities, for multiple runs of the technique, given different initial conditions (i.e. different starting guesses for the free-choice probabilities). This is further good evidence for the stability and robustness of the technique, and against any claims that the model is over-parameterised. In fact, it suggests that the likelihood function used is, at least approximately, globally convex, although I am not able to prove anything to this effect.

5.6 Limitations

Some of the limitations in my analysis relate to the data used. It seems unlikely, for example, that the coarse division into household types will actually result in sub-groups that can be reasonably construed as having homogeneous preferences. At the very least, I expect that further dividing households based on age, education, ethnicity, or labour-force status would be required. More promising still would be the use of cluster analysis to divide households into subgroups. I acknowledge the limitations imposed by my particular use of data, but will not discuss these further, as they can be overcome by a more careful analysis with better chosen data. As my focus is on demonstrating the general applicability of the technique, I will, in the remainder of this section, concentrate on the inherent limitations of the technique, rather than any specific limitations brought about by the manner in which it was applied.

Several limitations are shared with traditional cross-sectional discrete choice approaches, and so are not specific to the technique. In particular, a cross-sectional discrete choice approach that treats current household location as an observed choice requires housing market equilibrium. Even in the absence of direct search and moving costs, it is unreasonable to expect such an equilibrium. Instead, households are likely to display a degree of inertia, and opt to remain in 'non-preferred' dwellings.

Another important unanswered question is whether the way in which the choice model is structured is a useful approximation of reality. Can one reasonably segregate households into groups, within which, underlying preferences are homogeneous? Tu and Goldfinch (1996) argue for just such an approach, but I am not aware of any comprehensive comparison of this approach with alternative approaches that estimate a single model and use descriptor variables to capture preference heterogeneity. For example, given that work location is household-specific, assuming homogenous preferences within household 'groups' does not allow commute time to be easily incorporated into the location decision. Another question that springs to mind is: how distorting is the assumption of a fixed housing budget required by my sorting model? Analysis by the Reserve Bank of Australia (2003) suggests that, for housing, the amount that a household *can* borrow is a strong determinant of how much they *do* borrow, which is embodied in my fixed budget 'capacity-to-pay' assumption. The significant variance in house prices that are not explained by changes in income, inflation, and interest rates allow for the possibility that a 'capacity-to-pay' model may be more robust when used to predict future household distributions than will any choice model based on prices. A general change to community expectations of capital growth, for example, may alter real house prices, but the ability of higher income/wealth households to outbid lower income/wealth households will remain. Clearly the strength of both the budget constraint assumption and the within-group homogeneity assumption needs further investigation.

In most discrete choice models, there are a small number of 'exemplar' choices that are considered distinct, and all actual choices belong to an exemplar category, with within-category variation in utility being modelled by additional variables describing each choice. In my alternate approach, because the cardinality of the choice set can be so large, the additional variables become unnecessary. This aids model estimation, but also means that the estimated choice model, by itself, gives one very little information about 'why' a particular household finds one housing option preferable to another. In other words, model calibration, in my alternate approach, has been reduced to the estimation of a very large number of choice-specific parameters, which, by themselves, tell us nothing about the reasons behind household choices. For some applications, this limitation may be relatively unimportant; however, even in the common case where the underlying decision process is of primary interest, the limitation is less serious than it first appears. If the utility value of choice i is U_i, and the probability $P(i)$ of choice i is proportional to e^{U_i}, and one has a vector $\mathbf{V}_i$ of dwelling and location specific variables for dwelling i (i.e. accessibility, amenity, local traffic conditions, and so on.), one can estimate regression equations of the form $\ln(U_i) = \alpha_i \cdot \mathbf{V}_i + \epsilon$, where α is a vector of coefficients to be estimated, and ϵ is the error term. The significant difference is that, rather than estimating coefficients jointly with utility values as part of the model calibration process (the normal case), one instead estimates parameter coefficients afterwards from known utility values.

5.7 Concluding discussion

I have presented a technique for estimating a discrete choice housing model that does not rely on house price data, but instead represents housing choice as a competition for housing where households with greater capacity to pay choose before households with lesser capacity to pay. This seems a reasonable way to represent actual household behaviour, but I am not in a position to mount a conclusive argument. Instead, I feel I have established that such a formulation is worthy of further investigation. It is also useful as a comparison to results achievable with more standard analyses.

There were two motivations driving us to develop an alternate method of household location. The first was a frustration born of the necessity of aggregating data over spatial regions so coarse as to make meaningless the real-estate mantra 'location, location, location'. The technique developed in this chapter obviates the need to aggregate in this way, by allowing for the independent estimation of a large number of parameters for each choice category. This is not the the only approach that could be taken, for while I estimate parameters for each zone/region without prescribing any spatial structure, there is perhaps much to be gained through explicitly representing spatial structure. Bhat and Guo (2004), for example, have made progress on this front, as have Cheshire and Sheppard (1995). The second motivation to develop this alternate technique was a general uneasiness about the stability of the income/price/utility relationship over time. As part of the larger modelling exercise being undertaken in Chapters 6-9, I require estimates of future distributions of households, and was reluctant to rely for this purpose on standard discrete choice models. It is difficult to accept, for example, that parameters relating house price and income to underlying utility will be of much use in any time period other than the one in which they were estimated. Easier to accept is the persistence of higher wealth households' ability to out-bid lower wealth ones.

On a practical front, the technique is able to estimate a large number of utility parameters, provided sufficient data is available to constrain the model. Given that the technique has less onerous data gathering requirements than a traditional discrete choice one, this will often be the case. In the particular application of the technique I describe (to housing choice in Sydney), I have used the resulting freedom to get spatially detailed results, but this is only one path. In principle, one could retain spatially coarse zones and instead have a fine-grained partition of households, or some compromise in-between. The very large choice set approach I take is in contrast to the usual method employed to capture local scale variation by employing a number of explanatory spatial variables, such as employment accessibility, local school performance, and the like. While less data is required to estimate such models, calculating and choosing which variables to include is itself a difficult process. In the case of the Sydney property market, for example, accurately capturing the variations in local amenity provided by ocean beaches (each of varying quality) is not possible with even complex proximity, accessibility, or amenity measures.

An interesting feature of the alternate choice model described in this chapter is that it is possible to directly calculate measures of how 'displaced' a household is from their optimal choice. Given that the choice model specifies the 'free choice' probability of each housing choice, and the housing allocation model determines the actual choice made by each household given budget and supply constraints, one could calculate measures of displacement (such as the difference between observed choices and those expected from 'free-choice' probabilities). Other measures are of course possible, but the essential point is that such measures are relatively easy to calculate and interpret. In a traditional discrete choice model, such analysis is less straightforward, because each household, by definition, obtains a utility-maximizing choice.

Of all the limitations mentioned in Section 5.6, I consider the reliance on housing equilibrium the most troubling. This is a problem with any model estimated on cross-sectional data. However, this assumption can be relaxed with some additional work. There is an extensive literature, by demographers and others, on household formation, household mobility, and demographic transition. Transition probability models, for example, have been developed (Zeng et al., 1997; McDonald et al., 2006), which estimate the probability of a given household type changing to another household type in a fixed time period. In addition to transition probabilities between household types, estimates of the propensity to move for each household type would also be required. Such a task does not seem to be difficult, and much work has already been done in this area (Deurloo et al., 1994; Goodman, 2003; Clark et al., 2006). Combining a demographic transition model with a mobility model and a discrete choice model would allow for the specification of a detailed household level model of residential choice. Given two consecutive census datasets, for example, one could begin with the observed distribution of households, demographically transition individual households, and determine whether they move in the inter-censal period. The competition for housing would then only take place amongst newly formed households (whether internal or through in-migration), and those who elected to move. One could also then include existing household equity to some degree, allowing one to model the ability of even moderate income households with significant home-equity to out-compete those without home equity. While I have only sketched some thoughts on how it might be done, I am hopeful that a useful integration of the work of demographers and housing-career researchers can be made, and will result in a more reliable model of describing, and particularly forecasting, residential choice.

A computer program, with source code, that implements the technique described in this chapter, is included in a CD attached to this thesis.

5.8 A note on the calculation of residential location satisfaction

In Chapter 9, where results for different planning scenarios for Sydney are presented, I find it useful to report, for each scenario, a measure of how satisfied the populace is with the available housing. The preceding discussion mentions that such a calculation is possible, but does not describe any such calculation in detail. This is now done here. The purpose for developing a measure of how satisfied the populace is with the available housing is that such information is crucial to understanding how politically achievable any housing policy is. Housing policy that calls for the provision of dwellings that people do not like (i.e. do not wish to live in) is likely to experience significant resistance from the population.

The measure I will use is easily calculated from the 'free choice' probabilities for each household group. If $P_{k,i}$ is the 'free choice' probability of a household in group k choosing a dwelling of type i, then the number of households in group k expected to make such a choice, *in the absence of any supply constraint* is $N_k \times P_{k,i}$, where N_k is the number of households in group k. Now, let us assume $H_{k,i}$ households of type k actually end up in dwellings of type i. If $H_{k,i} > N_k \times P_{k,i}$, then clearly $H_{k,i} - N_k \times P_{k,i}$ gives the number of households forced to make a dwelling choice that did not match with their desires. Summing over all possible dwelling choices and all household groups gives the number of households so displaced:

$$\sum_{k=1}^{M}\sum_{i=1}^{D}\max(0, H_{k,i} - N_k \times P_{k,i}) \tag{5.19}$$

The max function is required to prevent double-counting. Equation 5.19 can be expressed as a proportion of all households, if one wishes to obtain the proportion of total households displaced from their preferred choice:

$$\frac{\sum_{k=1}^{M}\sum_{i=1}^{D}\max(0, H_{k,i} - N_k \times P_{k,i})}{\sum_{k=1}^{M}\sum_{i=1}^{D} H_{k,i}} \tag{5.20}$$

The measure can even be calculated separately for a particular household group. If one wished to know the proportion of group k that were displaced from their preferred choice, for example, one need only calculate:

$$\frac{\sum_{i=1}^{D} \max(0, H_{k,i} - N_k \times P_{k,i})}{\sum_{i=1}^{D} H_{k,i}} \tag{5.21}$$

Rather than calculating the proportion of displaced households, I will report (in Chapter 9) its complement – the proportion of households who obtained their preferred choice. I will use the term 'satisfied' to refer to a household who obtained their preferred choice.

5.9 Addendum: Limitations of the housing choice model

The limitations of the housing choice model are already discussed in Section 5.6, but that material is fairly terse. As a result, two of the three examiners for this PhD requested that I engage in some more general discussion of the limitations, and I do this here.

The first thing to note is that the residential housing choice decision is an exceedingly complex one to characterize. People make location decisions based on far too many factors for any model to characterize well. For example, people locate to be near friends and relatives, or culturally similar groups of people, and adequately capturing this is very difficult – certainly beyond the power of the model described in this chapter. There are many other complex factors that influence the residential location decision that have not been considered in my model, nor indeed in any other econometric model of housing choice. However, we must choose between either *trying* to develop models that capture at least some of the mode general trends in housing choice, or else throw our hands in the air and say that the decision is simply too difficult to model. As the reader will no doubt have already guessed, I do not like the second approach. This does not mean that I am unaware of the severe limitations introduced as part of the modelling process. But, so long as those limitations are clearly stated, my inclination is to make a flawed attempt to model the process, and work on improving that model through further research.

If we put aside the more general criticism (that housing choice is too complex to model), there remain two important limitations of the model that should be understood before the reader proceeds to the main scenario-modelling work in this thesis. The first of these is that the housing choice model assumes that preferences do not change over time. If the data currently suggests, for example, that there is a strong preference for families-with-children to live in detached dwellings, then this preference is assumed to persist over time. This is a fairly common default assumption in any modelling exercise, but clearly may not hold. One can argue, for example, that attitudes towards higher density living have been becoming more favourable, and if this trend were to persist, one would see preferences for attached dwellings to strengthen. This is an area badly needing study. It is worrying that we know so little about the populace's general housing preferences, and how these changes over time. In the absence of more research in the area, however, or concrete evidence of changing preferences, the most conservative assumption is that preferences remain as they are.

The second important limitation of the residential choice model is that it is incapable of determining the very specific factors that influence housing preferences. The model can, for example, estimate that households with children prefer detached dwellings, but it cannot say *why* this is the case. It may be that the true preference for households with children is for quiet suburban areas with parks and low traffic volumes, and that dwelling form is itself unimportant, but serving as a proxy for these unmeasured variables. It is my strong intuition that there is at least some (and possibly a lot) of this going on. If I am right, then attached dwellings in quieter suburban areas would be greatly more attractive to households with children than estimated by the model. As I've said already – we are badly need of more empirical work in this area, to get at the true underlying preferences. This has proved, however, to be beyond the scope of this thesis, and so I have accepted parameter estimates as-is.

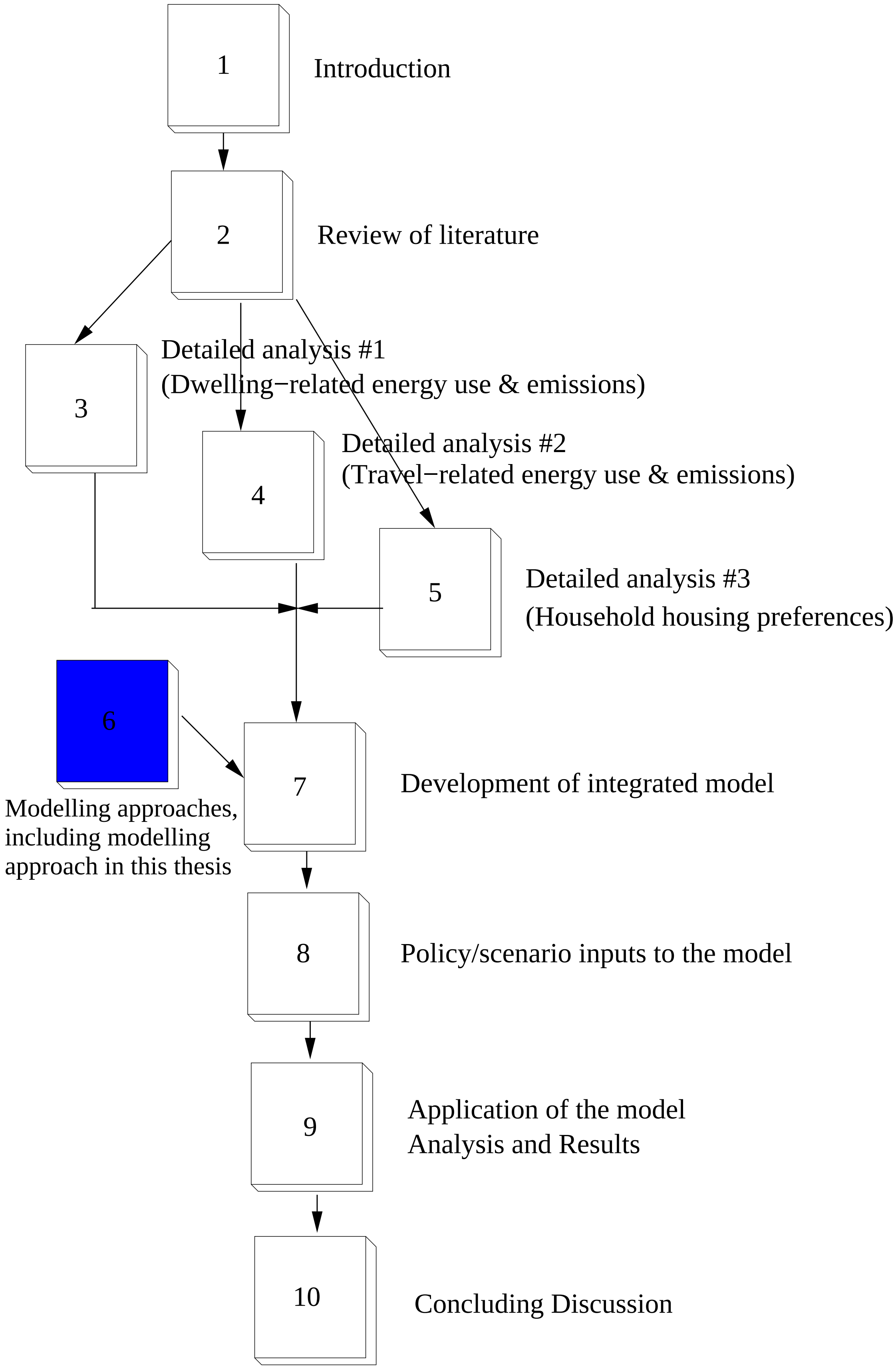
Given the general limitations outlined in this section, it is probably wise for the reader to take the 'housing satisfaction' measures in the following chapters with a grain of salt: they are a 'best guess' estimate, and certainly far from definitive. Understanding housing and location preferences is perhaps the single area most in need of further research, in my opinion.

5.10 Chapter summary

This chapter, as well as previous chapters, have discussed the importance of accounting for residential housing preferences. In this chapter, I have developed a model for estimating housing preferences using Census-style data, and demonstrated the applicability of the technique to Sydney. Having done this, I am now able to proceed to develop a metropolitan scale model of household behaviour, which is capable of assessing the impacts of metropolitan scale land use policies. This is done in Chapters 6-9.

Chapter 6

Approaches to Urban Analysis and Modelling



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(Travel−related energy use & emissions)
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7
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Application of the model
Analysis and Results
10
Concluding Discussion

> Make everything as simple as possible, but not simpler.
>
> Albert Einstein.

This chapter deals with the broad modelling approach taken in addressing the third question of this thesis, and includes a short literature review of the area of land-use/transport modelling. This chapter focuses on the general approach to modelling, and provides a consideration of some other existing approaches that could have been taken, but were not. This is followed, in Chapter 7, by a thorough description of the actual micro-simulation model developed in this thesis.

6.1 Modelling the impact of planning policy

Chapter 2 has already given a general overview of what we know about urban structure and energy use generally. This section discusses some of the approaches that are currently used to analyse urban systems and understand how cities function. There are several ways one might categorise the different approaches, but I find it helpful to divide them into two broad categories:

Analytical approaches: These approaches rely on typically closed-form mathematical descriptions or analyses of relationships between aggregate variables. Behaviour and variation at the individual level is usually not explicitly represented, nor are dynamic urban processes. Well known examples include the classic mono-centric city model of Alonso (1964); Mills (1967); Muth (1969), and Newman and Kenworthy's analysis relating urban density and transport energy (Newman and Kenworthy, 1989, 1999).

Computational approaches: A trend towards increasing complexity and disaggregation has been enabled by growth in computing power. Explicit representation of actors (firms, developers, consumers, etc.), and of their interaction, is possible. However, such approaches usually require a great deal of data, and greatly increased mathematical complexity, which sometimes renders the results difficult to interpret. Two widely known examples are Waddell's urban modelling platform – UrbanSim (Waddell, 2000, 2002), and RELU – Anas' regional land use model (Anas, 2007).

The above division is of course somewhat artificial. In some cases, the boundary between the two approaches is not clear, and some approaches do not fit neatly into either. Nevertheless, the categorisation is still a useful one for the purposes of the following exposition.

A complete history of the field is not warranted here, so the following summaries are necessarily selective.

6.2 Existing approaches: Analytical

The great bulk of both theory and quantitative urban research falls into this category. On a theoretical front, for example, the equilibrium land use model developed by Alonso (1964); Mills (1967); Muth (1969) has served as a useful framework for much empirical research (e.g. Mieszkowski and Mills (1993); Brueckner et al. (1999); Bertaud and Malpezzi (2003)). In its classic form, residents

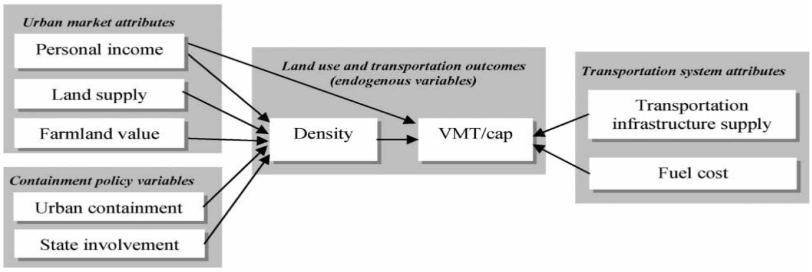


Figure 6.1: The basic regression modelling structure employed in the analysis of 25 U.S cities by Rodriguez et al. (2006).

select housing such that utility is maximized, subject to a housing/travel budget constraint. Numerous simplifying assumptions are made to produce a representative urban model. Some of the important assumptions are:

1. A circular city is assumed with all jobs at the centre;
2. Travel distance (to work) and housing consumption (m^2 of floor area) are the only variables affecting household utility; and
3. Households are identical (in terms of both budget and utility function).

A more complete treatment can be found in Brueckner (1987). Extensions to the model have been developed, to account for differences in spatial amenity (Cheshire and Sheppard, 1995), household preferences (Wheaton, 1977), and non-central employment locations (Henderson and Mitra, 1996). However, the requirement of analytical tractability places limitations on the complexity of any such model. This is true of analytical models in general. These limitations are part of the reason for the development of computational approaches (covered next, in Section 6.3).

Much empirical research in urban studies occurs in the absence of a constructive theoretical model. It is thus phenomenological, in the sense that it relates empirical observations of phenomena to each other, in a way which may be consistent with some fundamental theory, but is not directly derived from theory. This is not a deliberate choice, but takes place because the complexity of urban systems often does not allow for convenient and applicable theoretical models. As a result, descriptive statistical and econometric approaches are often used to obtain insights from available data. Statistical analyses on aggregate data are common. To illustrate by way of example, consider the multivariate regression performed in Rodriguez et al. (2006), which related per capita vehicle miles travelled to a number of aggregate demographic, economic, and policy variables, for 25 U.S cities. Figure 6.1 shows the regression structure adopted. This study is a good example of the pragmatic empirical approach taken in much urban research. Despite the need to rely on a collection of easily computable metropolitan-scale variables, and the difficulty in devising a representation capturing differences in city-specific urban containment policies, results from such studies can still be informative.

Another of the better known examples of such empirical work is that of Peter Newman and Jeffrey Kenworthy, who investigated (among other things) the relationship between urban density and transport energy consumption in Newman and Kenworthy (1989) (and in subsequent research, such as Kenworthy and Laube (1999); Newman and Kenworthy (1999)). This work was already covered in Chapter 2. It is important to note that their style of analysis is essentially phenomenological, as defined above. This is not a criticism. Indeed, it is scarcely conceivable that a consideration of travel and land use patterns in 32 cities could be anything but phenomenological. This illustrates the tension between complexity and applicability. The more detailed and sophisticated a model or mathematical description, the less general it becomes, and the more difficult and time consuming it is to apply. Short of throwing our hands in the air and declaring that urban areas are too complex to analyze, there is often no alternative to accepting the necessity of applying simple techniques to complex phenomena. In short, we need to accept that urban systems do not easily allow for the same sort of reductionist approach common in areas like physics (Næss, 2005), but that, nevertheless, there are valuable insights to be gained through simpler analytical and empirical analyses.

6.3 Existing approaches: Computational

In many ways, the move to a computational approach, enabled by advances in computer hardware and software, has grown out of a frustration with the limitations of the analytical approach. The history of development of transport/land-use models serves to illustrate the trend. Timmermans (2003) suggested three 'waves' of development, shown in Table 6.1. An older review can be found in Wegener (1994), with more recent reviews in US Environmental Protection Agency (2000) and Hunt et al. (2005).

	Type	Examples
Wave 1	Aggregate Spatial Interaction Models	ITLUP (DRAM/EMPAL), LILT
Wave 2	Utility Maximizing Logit Models	UrbanSim, RELU-TRAN, TRANUS, MUSSA
Wave 3	Activity-based Microsimulation Models	PUMA, ILUTE, RAMBLAS

Table 6.1: The three waves of transport/land-use models. Adapted from Timmermans (2003).

Without going into the model details, the history of development displays several clear trends. Firstly, there is a clear trend towards greater disaggregation of decision makers (households, firms, etc.), and of land uses. There is also a trend towards analysis at finer spatial scales. On the transport side, for example, we began, in the first wave, with the treatment of travel behaviour as the result of interacting aggregate spatial variables. Moving to the second wave, travel behaviour is considered at the household level. In third wave models, travel behaviour is decomposed further, down from household level behaviour to the individual trip/activity level. Such increasing complexity comes at some cost to both applicability and intelligibility. Behaviourally accurate models require a complex model, and consequently, a lot of data to calibrate. They are time consuming to develop and apply, and often difficult to interpret. The trend in transport modelling, towards behavioural accuracy and away from intelligibility, is not unique to this area, and nicely illustrates the general issues involved in moving from an analytical approach to a computational one. Once one commits to pursuing more accurate representations of underlying processes which *are* complex, there is no avoiding increased model complexity:

> The field has consistently been criticised for its complexity and black box character. It

> seems however that a simplification of the approach will be counterintuitive. Any valid model should represent the key complexity of the phenomenon under investigation. The plea for behaviourally better models implies further complexity and many people will therefore continue to argue that the models are black boxes. There does not seem an easy solution to this dilemma.

Timmermans (2003, page 26)

A valid argument against complex models is that it becomes difficult and/or expensive to calibrate and apply such models. This is where simpler, less behaviourally accurate models are required. The model used in this thesis is developed with the aim of requiring less specification and calibration than existing land-use/transport models. Jun (2005) is an example of a different approach to the same end (Jun develops a land use model that can be calibrated on generally available input/output matrix data).

6.3.1 Urban modelling: Economic and engineering traditions

There have been two separate traditions in land-use/transport modelling. One has been developed by economists, and the other by transport planners and others from a predominantly engineering background. At the risk of over-simplifying, economists have been more prone to focus on land use models, while those from the engineering tradition have tended to focus more on transport and travel. Land use models in the economists tradition have, unsurprisingly, typically adopted a structure whereby actors in the model (i.e. firms, residents) bid for resources (e.g. land, labour) in order to maximize profit or some utility function. Such behaviour drives resource prices to the equilibrium point where supply equals demand – so-called market clearing[1].

The economic tradition has its roots in the standard mono-centric city analytical model. Extentions using linear programming, such as in Mills (1972) retained a structure that allowed for a model equilibrium to be calculated. Modern models that have developed from this tradition retain an equilibrium structure. Unlike the earlier models in the tradition, however, where a single equilibrium existed and could be found, the complexity of modern models usually results in multiple equilibria. And, despite the prevailing view being that it is *long*-run equilibrium that is the more reasonable assumption, economic equilibria-based models typically equilibrate over short time periods (1-5 years).

In large part due to their adherence to prevailing economic principles, economists, prior to the development of stochastic choice models, had great difficulty in modelling observed travel behaviour. This opened the way for more pragmatic engineering models to be developed, and such models are still the predominant models used in city transport planning. In Australia, for example, there is the Melbourne Integrated Transport Model (MITM), the Brisbane Strategic Travel Model (BSTM) and Sydney's Strategic Travel Model (STM). Such models are not based on a strong underlying theory about the decision processes or aims of firms and households, but are instead pragmatic mathematical constructs designed to capture the observed variation in behaviour. Britton Harris eloquently describes the divide between economic and engineering approaches:

[1] While most economists since Keynes view *continuous* market clearing as unrealistic, such an assumption is generally still viewed as useful for longer-run analysis.

> [M]any of the pragmatic discoveries of modelling contained implications for economic behaviour which were long neglected, or even worse denied. ... planning and simulation have usually recognised that similar people in similar situations exhibit diverse behaviours. Gravity models capture that diversity, while standard economic models like linear programming do not. Only recently have the economists provided an alternative to their Procrustean bed in the form of discrete choice theory.

Harris (1985, page 547), ellipsis mine.

The tension between pragmatists (generally from the engineering tradition), and theorists (generally from the economic tradition) is well-illustrated by a few quotations from the different proponents. Consider, first, Paul Waddell, the author of the disequilibrium UrbanSim platform:

> The market allocation mechanism used to assign households and jobs to available space, then, is not done through a general equilibrium solution in which consumers and suppliers optimize across all alternatives based on perfect information, and zero transaction costs, with prices on all buildings at each location adjusting to the general equilibrium solution that perfectly matches consumers and suppliers to clear the market. Rather, the solution is based on an expectation of incomplete information (we sample alternatives) and nontrivial transaction and search costs (only a fraction of households move annually), so that movers attempt to obtain the most satisfactory location from the sampled vacant real estate stock.

Waddell et al. (2003, page 59)

Note, in contrast, the faint air of disapproval by economists to those models that do not rely on strong assumptions of market-clearing equilibria:

> The popular do-it-yourself modeling template of Waddell (1998), UrbanSim, is open source and it is easy to verify that prices are not market clearing and that it does not conform to economic theory.

Anas (2007, page 418)

> Though DRAM and EMPAL are the most widely used and applied land-use models for the USA, they have several limitations. One limitation is the lack of underlying economic theory.

Jun (2005, page 1313)

and, from Hunt et al. (2005, page 330):

> [A] fundamental assumption in constructing this review is that urban spatial processes play out within *markets* (for land, floor space, travel, goods and services, etc.), within which the production/consumption (supply/demand) processes interact to determine system outcomes. ... Thus, the ability of a model to capture market demand-supply interactions and to determine market prices endogenously is viewed as an issue of fundamental importance in assessing a given model's capabilities.

Believing in markets is one thing. Construing them in a classical light where they are assumed to clear in the short term is quite another. But most economic modellers seem unwilling to concede this point, assuming short-term market clearing in all markets, despite the fact that Keynes showed that employment markets, for example, can have high equilibrium levels of unemployment (i.e. labour does not clear). Even Edwin Mills, one of the founders of modern urban economics, recognised equilibrium is illusive in an urban setting:

> [N]o one believes that an entire metropolitan area is in equilibrium.
>
> Mills (2000, page 31)

It is worth noting that, while many researchers from an economics background have a natural tendency to prefer equilibrium models, it has not been conclusively demonstrated that such models perform any better in practice than either disequilibrium models, or spatial-interaction models without any in-built notion of market equilibrium. The argument thus far has been on theoretical grounds, with equilibrium modellers pointing to the benefits of the large body of work on equilibrium-economics, and disequilibrium modellers claiming that the equilibrium assumption is not a useful one in the context of urban modelling. Consider, for example, the case for disequilibrium modelling put by Batty (2008, page 769):

> Cities are the examples *par excellence* of complex systems: emergent, far from equilibrium....

Regardless of whether one considers urban systems to be dynamic, far from equilibrium systems; or whether one considers them to be in equilibrium (at least in the long run), the question of which modelling approach is most effective in practice has received little attention.

As I have mentioned, the history of modelling has been such that, prior to the 1990's, transport models were, in the main, developed in the engineering tradition, and land use models in the economic tradition. Since that time, the distinction has largely broken down, with modern models inheriting the normative theoretical underpinnings provided by economic theory, while at the same time acknowledging the practical necessity that models must exhibit sufficient flexibility if they are to accurately describe and predict behaviour which does not fit neatly with any simple normative model.

The following sections touch on a few of the better known transport and land use models, to give the reader a flavour for the different approaches. Agent-based and Cellular Automata Models are not discussed at length, as I concentrate on the more traditional and widespread land-use and transport models. For readers interested in cellular-automata style models, Torrens and O'Sullivan (2001) provide a useful taxonomy, and good examples of the application of such models can be found in Cheng and Masser (2004); Lau and Kam (2005).

6.3.2 Land-use models

Land-use models were originally developed by economists interested in the spatial distribution of firms and workers. This explains why their continued development has owed a lot to those hailing from an economic tradition. Examples of early work in the area include Christaller (1933); Isard (1956); Mills (1972).

The basic ideas underlying modern land use models are generally agreed-upon, with the principle points of difference being operational and/or technical in nature. The basic actors in most modern land-use models are:

Firms: Firms in different industries require different inputs to production. These costs vary according to location, and this determines the location preferences of each firm.

Consumers: Consumers maximize their utility, which in practice usually means limiting transport time/cost and maximizing consumption of both housing and goods.

Developers: Developers determine the supply of floor space at different locations.

Government is usually not explicitly represented, or else only through the imposition of fixed costs (such as property development levies or other taxes). Examples of modern land use models with this general classification of actors are MUSSA (Martínez, 1992a,b, 1996), RELU (Anas, 2007), UrbanSim (Waddell, 1998, 2002). Older models, such as ITLUP/DRAM/EMPAL (Putnam, 1983, 1991), based on spatial interactions rather than explicit modelling of market clearing, are still in widespread use, due in no small part to their more parsimonious data requirements. Models such as MEPLAN (Echenique et al., 1969, 1990) and TRANUS (la Barra, 1989) fit somewhere in-between, relying on spatially-aggregate economic interactions (derived from Input/Output tables) to determine general flows of goods and locational demand for labour, rather than having any explicit representation of firms, but using inter-zonal flow information to determine location-specific demand for floor-space. The direction of current research and development is away from spatial-interaction models towards ones based not on aggregate spatial interactions, but the explicit interaction of businesses and households.

A better understanding of the current state of the art in land-use modelling can be gained through a more detailed description of a particular model. Let us consider Anas' 'Regional Economy and Land Use' (RELU) model (see Anas (2007)). In RELU, firm production costs are comprised of labour, rent, and inter-industry inputs. The costs of each of these is itself determined through the actions of other actors. Rent, for example, is jointly determined by the supply of available buildings in each location (determined by the actions of developers), and the demand (from other firms) for those buildings. This demand is itself determined by the spatially varying cost of labour (determined by the supply of labour from each household, which is itself determined by the travel-time requirements of that households), and the spatially-varying cost of inter-industry inputs to production. Changing land-use is thus a continuing dance between developers looking to redevelop land to maximize profit, households looking to maximize utility[2], and firms looking to minimize production costs. As one can imagine, determining the simultaneous equilibrium in so many different markets is quite complicated, and typically requires computational approximations that, in any case, will converge to one of many equilibria.

6.3.3 Transport models

Models for land use and those for transport cannot always be easily separated. Those like ITLUP, based on DRAM/EMPAL, for example, determine inter-zonal transport requirements directly

[2]Which essentially means, in the case of RELU, trading off desire for housing floor space and access to consumptive goods in the presence of budget and time constraints.

from land-use and inter-zonal economic flows. This itself gives a kind of crude transport model, but is usually further refined using a more sophisticated transport model that takes account of different travel modes, transport network structure/capacity, and congestion.

Some of the land-use models already mentioned in Section 6.3.2 also contain integrated transport models. MEPLAN and TRANUS have integrated transport components capable of allocating the transport task (determined from land-use and inter-industry flows) to a transport network. More commonly, however, land-use models are 'coupled' with stand-alone transport models. Estimates of travel time and cost from the transport model are usually fed back into the land-use model, so that firms and households can respond appropriately to these costs. Such a loose coupling has the tremendous strength that land use and transport models can be developed largely independently, and different land use models can be coupled with different transport models. By far the most commonly used transport models are 4-stage gravity-model ones, using commercial platforms such as EMME/2. They are called 4-stage systems because modelling of the transport task is divided into four stages: trip generation; trip distribution; modal split; and traffic assignment. They are termed gravity models because the extent of travel between destinations is determined using mathematical formulæ akin to those used for gravitational pull between bodies. Non-gravity based models, where trip-generation is based on some model of traveller utility and transport costs, are more prevalent in the academic community, and are an area of active research (de Palma et al., 1997; Veldhuisen et al., 2000; Ettema et al., 2007). The trend in the field of transport models is similar to that for land use models, towards greater disaggregation, and more complexity.

6.3.4 Integrated land-Use/transport models

The discussion in the preceeding sections (6.3.2 and 6.3.3) makes it clear that integrated land-use/transport models are usually formed by coupling a land use model with a transport model, and allowing for some minimal transfer of information between them. In particular, by allowing travel time/costs to feed back from the transport model back to firms and households in the land-use model.

Although separate land use models and transport models can be coupled together, there are often complications arising from the artificial separation of the modelling into land-use and transport components. For example, a fully integrated model usually requires that residential location decisions of households be determined based on work location (and other factors). In particular, workers prefer a shorter commute, all other things equal. This means that travel time and cost must be known for the residential location model to run, but these cannot be determined until the transport model is run. The transport model, though, cannot determine residential location without housing cost information determined by the land-use model. Without some simultaneous determination of transport time/cost and location decisions, circular dependency issues like this are difficult to resolve without moving to a fully integrated model. As a result, most coupled models must accept some level of inconsistency arising from the artificial separation of land use and transport decisions. To give just one example, in MUSSA, place of employment plays no part in residential location decisions, because place of employment is determined in the transport model. Residential location, on the other hand, is determined in the land-use model, based on other factors (including regional accessibility), and the work-place decision is determined in the transport model conditional on this choice.

A recent example of the integration of land-use and transport models can be found in de Palma et al. (2005) (UrbanSim/METROPOLIS). A detailed fully-integrated model (RELU-TRAN) is described in Anas (2007). MEPLAN and TRANUS are good examples of older fully integrated models.

6.4 A detour on approaches to modelling

Before proceeding, in Section 6.5, to provide some details on the model structure adopted in this thesis, I would like to take a detour into a more general consideration on the nature of mathematical modelling. This is done in the hope that such a diversion now will allow for a better appreciation of some of the modelling decisions made in the remainder of this thesis.

6.4.1 Requirements of a model

Let us concentrate on four important requirements of a mathematical model[3]:

Consistent: We would like our models to be consistent with available data.

Realism/Plausibility: If we have some knowledge of the underlying process generating the observed data, we usually prefer our mathematical model structure to mimic that process, if possible.

Agreement with theory: For model results to be useful, it is often necessary for the model structure to be consistent with some framing theory. For example, when building models to describe consumer preferences certain model structures allow for model parameters to be simply interpreted as price elasticities of demand.

Intelligibility: Other things equal, we prefer our models to be understandable.

There are of course natural tensions and complementarities between items on this list. It is usually the case, for example, that realism and consistency are linked. This is, however, not always the case, and in such instances, a decision needs to be made about whether to prefer an implausible, but consistent model, or a plausible, but inconsistent one. Intelligibility and consistency are often in tension. There is little point in discussing at great length the relationships between the four items on the above list, but it is important to note that tensions cannot be resolved solely on mathematical grounds, but require a value judgement. The tensions also give rise to some confusion in the literature, as I will demonstrate, by way of example, in Section 6.4.2.

The central value position I take in this thesis is that intelligibility and consistency, though themselves in tension, are collectively more important than realism or any agreement with theory. Basically, I take the philosophical stance that model consistency outweighs the desire to be consistent with either any particular theory, or general understanding of the underlying process. There are two main reasons for this. Firstly, unlike some of the physical sciences, we are still a

[3]This list is not exhaustive. Other considerations, such as practicality of implementation, are of course important, but are not relevant to the discussion here.

long way from a firm understanding of the processes at work in our cities, and hence do not have strong theories on which to base empirical analyses. Secondly, adherence to strong theoretical tenets can be shown to have materially inhibited progress in the field to date, in that theory has been a barrier to the more accurate description of actual behaviour. In particular, this has been the case in modern transport/land-use modelling.

6.4.2 Tangled up in utility and rationality

> What seems terribly hard for many economists to accept is that all our models involve silly assumptions. Given what we know about cognitive psychology, utility maximization is a ludicrous concept; equilibrium pretty foolish outside of financial markets; perfect competition a howler for most industries.
>
> Paul Krugman, in "How I Work"

Economists' initial approach to the treatment of travel behaviour was to adopt a familiar general equilibrium model, solvable by linear programming (see Mills (1972); Hartwick and Hartwick (1974) for examples). While consistent with economic theory, such a model structure proved ineffective in accurately representing the heterogeneity observed in actual travel behaviour. Such problems have often afflicted normative models, when they have been adapted to describe actual behaviour. Predicted travel behaviour in such models was based on the assumption that travellers maximized a deterministic utility function – different travel choices had known utility, and the choice made was always the utility maximizing one. Concretely, if $U(\mathbf{A})$ is the utility of a choice with attribute vector $\mathbf{A}$, and there are N such choices (with attribute vectors $\mathbf{A}_1 \ldots \mathbf{A}_N$), travellers choose $U(\mathbf{A}_{opt})$ such that $U(\mathbf{A}_{opt}) > U(\mathbf{A}_i), \forall \mathbf{A}_i \neq \mathbf{A}_{opt}$. It is a matter of historical record that such models did not work well.

The adoption of a stochastic choice model arose from the pioneering work of Daniel McFadden (McFadden, 1974a,b). Here, travellers are still assumed to maximize a utility function, but a random error term is added, which has the effect of giving all choices a non-zero probability of being chosen, although choices with high utility are still more likely than choices with lower utility. Part of the appeal of McFadden's formulation is that it seemed to allow for better agreement with observation, while at the same time remaining faithful to the idea that travellers decision making processes are rational, and utility maximizing. For some, the mere fact that McFadden's models were practically estimable, and allowed for better agreement with observation was sufficient, but it is evident that to others, adherence to theory (in particular, utility maximization), was the appealing attribute. Consider, for example, the following, from Koppelman and Bhat (2006):

> The focus on utility maximization ... is based on its strong theoretical background, extensive use in the development of human decision making concepts, and amenability to statistical testing of the effects of attributes on choice.
>
> Koppelman and Bhat (2006, page 12)

While this is fine, it is merely the result of a particular value judgement. Furthermore, as I will argue in the next paragraph, notions of utility and rationality are illusory. In an academic context, for ease of discussion and interpretation, there are doubtless some advantages in remaining within a particular theoretical framework. However, this does not say anything about the comparative effectiveness of discrete choice models in predicting future choice behaviour. Nor does it explain the predominance of discrete choice models in practical applications. In some, and perhaps many, practical applications, it would be possible to achieve comparable or better fit to data using some statistical method, such as artificial neural networks (Rumelhart and McClelland, 1986; Haykin, 1994) not based on any economic theory at all (see Vythoulkas and Koutsopoulos (2003) for just one such case).

There is also some confusion in the field of transport choice modelling about what it really means to assume that people are rational utility-maximizers. Careful practitioners realise that the notion that people are utility maximizing, while useful, is essentially empty. It is easy to see that, *given any data on any observed set of problems involving the selection of one or more choices from a set of alternatives, the observed choices can be represented as the maximisation of an appropriately specified function*[4]. In other words, no matter what the observed choices, it is always possible to construct a mathematical function such that observed choices maximize that function. This is true regardless of the choices. Calling this function 'utility' may be handy, but has little meaning. The concept is useful because it is easier to work with real numbers (i.e. utilities) than directly with choice preferences (rankings), and 'utility' is shorter and punchier than 'objective function value'. The notion of rationality is also elusive. For example, variety seeking choice behaviour is often labelled 'irrational', but this can easily be recast as rational by adjusting the utility function to including a measure of novelty/variety. It thus rarely makes sense to label behaviour rational[5], or to pretend that one can demonstrate that people are utility-maximizing or not. There is still confusion on this front. Take this example, from Middelkoop et al. (2003, page 75):

> This article argues that tourists do not necessarily maximize their utility in selecting a travel mode; rather, their choice behaviour is context dependent.

The primary aim of the above discussion is to act as a philosophical justification for the adoption of a generally pragmatic and theory-free approach in much of the modelling that follows in the remaining chapters of this thesis. My aim is to produce models that are consistent with observed behaviour, and indicative of future behaviour. I generally do not subscribe to the view that there is a 'correct' way to model a particular phenomena, except where there is detailed knowledge about the process that produces the observed phenomena. And in urban environments, we rarely have such knowledge, so there is often little to recommend one approach over another.

6.5 Modelling approach taken in this thesis

> (One) needs to be a die hard to become involved in this area of research. Integrated land use-transport models attempt to predict (the dynamics) of land use patterns and travel patterns, and their interaction. Consequently, the topic area is inherently very complex and thus difficult to model, requires a tremendous amount of data, and

[4] Thanks to Professor John Quiggin for this wording.

[5] In a narrow logical sense, the term can make sense. For example, one may choose to define rationality as logical consistency: preferring A to B and B to C implies preference of A over C. The term is generally not defined so narrowly, and indeed is often used without definition.

> hence time before and test can be performed, and the integrated models are costly to implement because the responsible planning agencies need to invest in people, data and equipment to collect and update the data.
>
> Timmermans (2003, pages 2-3)

The two approaches I listed in Section 6.1 for assessing the impacts of planning policy were:

1. Analytical
2. Computational

For the largely self-contained supporting analyses of Chapters 3 and 4, I adopted an analytical approach[6], but for the main analysis work that occupies the remainder of this thesis, I have developed and adopted a computational model. Chapters 7 and 8 develop and describe the computational model I will use, but, given the discussion and review of different modelling approaches already provided in this chapter, this seems like the most appropriate place to say a few words about the general approach I take in developing my computational model.

6.5.1 Model complexity/applicability tradeoff

The more ambitious the scope of a model, and the more effort put in to modelling all the factors that influence household and firm decisions, the more complex the model becomes, and *the more data required to calibrate that model*. A great deal of data is required to calibrate the more sophisticated land-use transport models, and this has been a significant impediment to their widespread use. The fact that older Lowry-style spatial-interaction models are still in widespread use is due in no small part to the more limited data requirements of such models. Modern models based on behaviour at the household/firm level are regarded as superior because they more accurately describe the urban systems being studied, and the trend amongst the urban-modelling research community is towards greater levels of sophistication and detail. This additional sophistication comes at a cost of additional data requirements. For example, household level model of travel behaviour requires a certain degree of sophistication, to determine the number of trips made by the household, the distribution of trip destinations, and so on. This requires information about household type, household income, and aggregate travel behaviour at the household level. To further disaggregate, and go to the level of modelling *individual* travel behaviour, requires more detailed data on household composition, and a more detailed travel model capable of modelling not just aggregate travel behaviour at the household level, but the travel decisions of the individuals who make up each household.

The data requirements of the more sophisticated models are often so onerous that multiple data sets, from different years, must be used. It is not uncommon, for example, for data on travel time and cost to be many years out of date, and for this out of date data to be combined with other (differently) out of date data on land prices, employment distribution, fuel price elasticities, and so on. This is in the good cases where such data is even available.

When investigating the different possible modelling approaches, I came to the conclusion that existing disaggregate models were too complex for my purposes, as their scope was too broad (they

[6] Excepting the transport simulation study in Section 4.4.

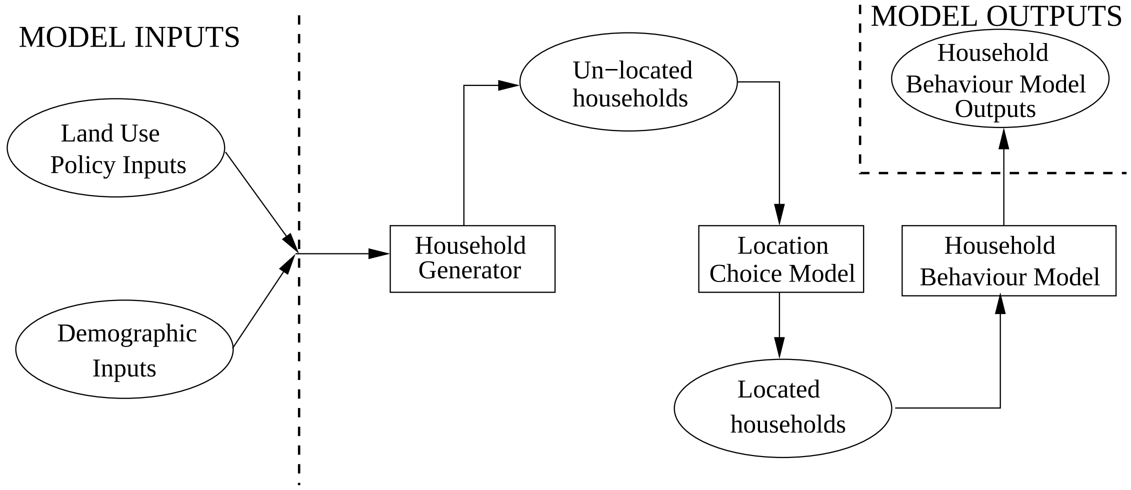


Figure 6.2: The core model structure. The core model is designed to be easy portable, and so requires only generally available data for calibration. Analysis-specific household behaviour models are attached as required, depending on available data and the outputs of interest.

attempted to model firm and household behaviour) and, in any case, the prospect of obtaining the data necessary to calibrate such a model was slim. However, I was also convinced, based on my review of the literature, and the supporting analyses in Chapters 4 and 3 (and especially Section 4.3), that a disaggregate model capable of describing behaviour at the household level was desirable. And so I decided to develop a computational model which did model behaviour at the household level, but which did not require an unreasonable amount of data to use. This lead me to adopt the overall structure shown in Figure 6.2.

Figure 6.2 shows that the 'heart' of the model structure is the residential location model, which has been described in Chapter 5. This model was specifically designed to require only widely available census-style data. Besides this census data, the only other data required by the model is policy and demographic data, and the data required by any household behaviour modules 'attached' to the core model (shown in the dashed box in Figure 6.2). In this thesis, two household behaviour modules are attached (a travel model and a dwelling-related energy module), but it is important to note that the number, and nature, of the modules attached can be varied depending on the circumstances. If, for example, data were not available to develop a disaggregate travel model, there is nothing to prevent an aggregate spatial-interaction style travel model being 'attached' instead. Thus, the amount of data required to calibrate the entire model is largely under the control of the modeller, with the data required for the 'core' residential location model being almost universally available. By selective simplification, I have developed a model which is complex enough to model household behaviour at a fine spatial scale, but which is easily applicable to just about any urban area.

6.5.2 Models as oracles, or models as exploratory tools

> There's no sense in being precise when you don't even know what you're talking about.
>
> John von Neumann

There is a trap that one can fall into when attempting to model something that is inherently complex. One can begin with a simple model that gives some approximation of reality, and then proceed to refine this model, whilst under the delusion that successive refinements are bringing you inexorably towards a 'true' model. One begins to view inaccuracies as the result of an incompletely specified model, which, with a little more model refinement, can be eliminated. And so an ever more complex model, capable of more precise modelling of the phenomena under study, is developed. But models can only ever be approximations to reality, and it is usually true that one quickly reaches a point of diminishing returns as a model grows more complex. So relatively simple models can often describe observed behaviour to some reasonable degree of accuracy, and successive improvements to the model's ability to describe observed behaviour come with greater and greater complexity. It is important to remember that the best that can be hoped for in a model is that it acts as a useful mental tool, and not a faithful representations of the truth. This is well put by Paul Krugman:

> The point is to realize that models are metaphors, not truth.
>
> Paul Krugman, in "How I Work"

Closely related to the failure to acknowledge the limitations inherent in any model is the tendency to concentrate on developing a model to obtain a 'right' answer. This is the result of failing to accept that, *especially when models are used for long range forecasting*, not only is there a limit to the *precision* achievable by any model, but also that there is an unavoidable degree of *uncertainty*. I do not use the term uncertainty in the sense of something being the outcome of a stochastic process, but instead, in the sense of the word perhaps best expressed by Keynes:

> By 'uncertain' knowledge, let me explain, I do not mean merely to distinguish what is known for certain from what is only probable. The game of roulette is not subject, in this sense, to uncertainty.... The sense in which I am using the term is that in which the prospect of a European war is uncertain, or the price of copper and the rate of interest twenty years hence.... About these matters there is no scientific basis on which to form any calculable probability whatever. We simply do not know.
>
> Keynes (1937, page 213)

A good example of a key transport-modelling variable subject to this kind of fundamental uncertainty is the price of petrol. Figure 6.3 shows the price of oil between 1861 and 2006. Since publication of this Figure (in BP (2007)), the price of crude oil rose to over $150 US/barrel in late 2008, before falling to below $50 US/barrel at the time of writing in early 2009.

Suppose then that one accepts then that land-use/transport models of urban areas, however sophisticated, suffer from the following limitations:

1. There are limits to the *precision* possible;

2. There is enough (stochastic) uncertainty within the system being modelled to admit a range of different possible outcomes, *given an identical starting point*; and

3. There is enough (fundamental) uncertainty to make their use in long-range forecasting questionable.

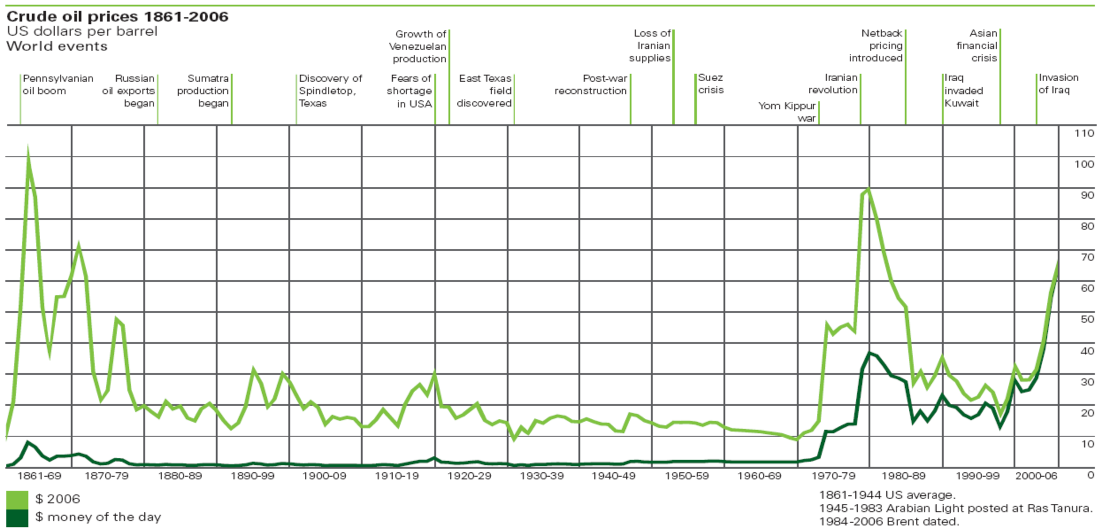


Figure 6.3: Changes in real oil prices, from 1861 to 2006, in 2006 U.S. dollars. From BP (2007, page 16). As of writing (April 2009), prices are ≈ 50 $US/barrel Brent crude.

Faced with these limitations, it is hard to avoid coming to the conclusion that land-use/transport models are much better employed to explore different *scenarios* rather than as long-range forecasting tools. In the influential keynote paper to the 10th International Conference on Travel Behaviour Research (entitled "The Saga of Integrated Land Use-Transport Modeling: How Many More Dreams Before We Wake Up?"), Harry Timmermans put it thus:

> [I]t does not seem realistic to expect that *any* integrated model of land use – transport with relative lack of data, can provide accurate land use forecasts . . . . We should adjust our expectations and claims. Perhaps . . . such models provide some rough possible qualitative indication for wider areas rather than a detailed quantitative assessment . . . . The potential of these models is perhaps in the area of policy scenario development in the sense that they provide a platform for discussion as opposed to being accurate forecasting tools.
>
> Timmermans (2003, pages 26-27)

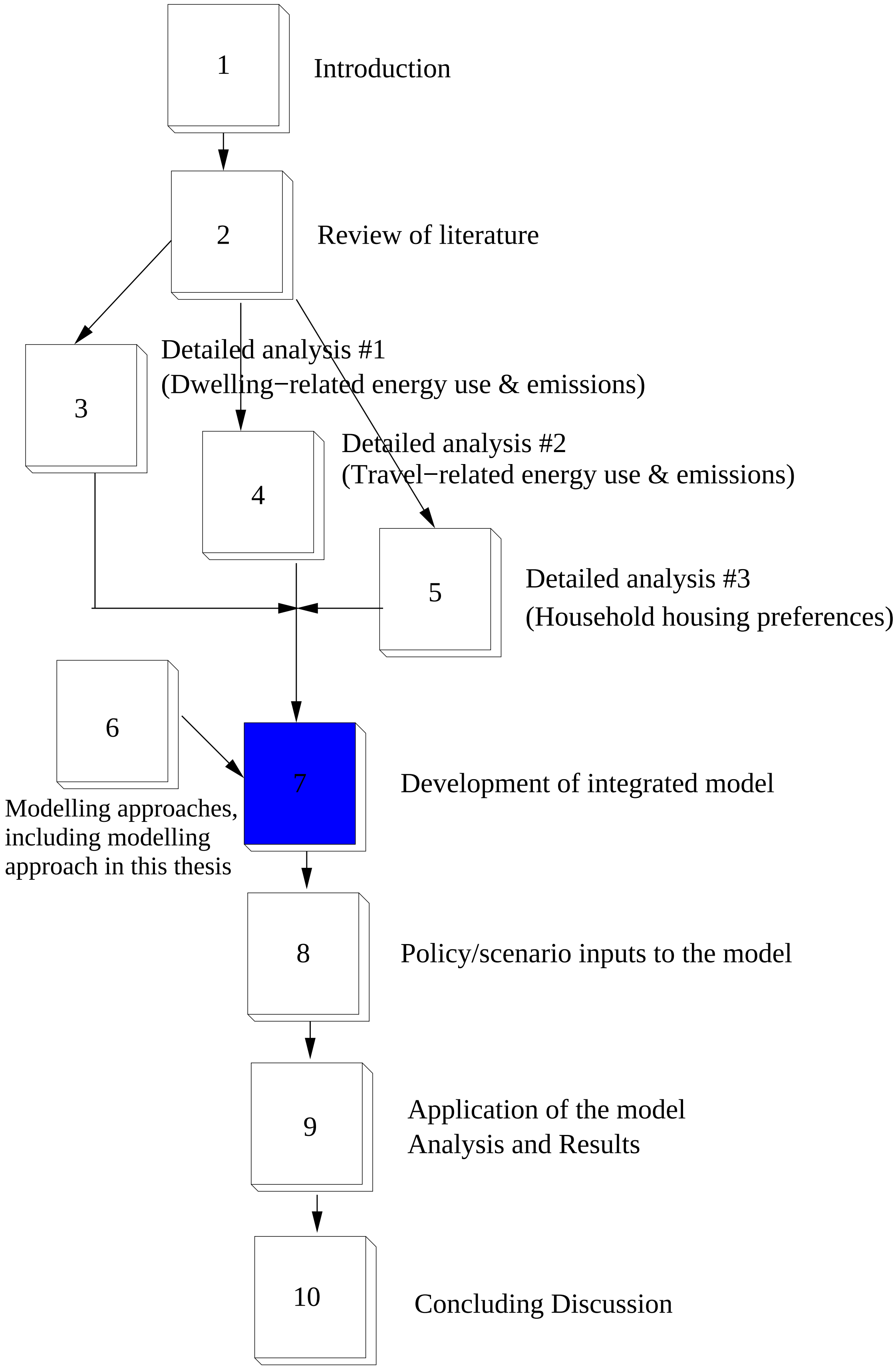
If done well, employing models for scenario evaluation and exploration rather than forecasting can facilitate the planning process by making different possibilities more tangible to decision makers *and* the wider citizenry. By presenting different possibilities, a model used in this way encourages dialogue. In contrast, when the focus is on the use of very complex models to obtain the 'right' answers, the tendency is for debate to be stifled, as model outputs are viewed as facts that cannot be debated, rather than as useful, but fallible, explorations of what is possible. If we are to encourage, as I think we should, more participatory urban planning processes, it is important to move away from the technocratic approach common in many city and state planning agencies, but this can only be done if there are effective means of informing and engaging a wider audience in the decision-making process:

> A problem in this context is that the long-term and global environmental and distributive issues often appear to ordinary people as far and abstract. Also the overall principles of the municipal master plan will often be considered diffuse and intangible. For planners, a great challenge lies in 'translating' and visualizing how our choices regarding housing types, location of development, transportation solutions and land use affect the possibilities to obtain a sustainable development.
>
> Næss (2001, page 519)

For all the reasons discussed above, I have decided to use a model to explore different scenarios for the city of Sydney. Accepting the limitations inherent in the modelling process, I have been content to develop a model that sits in a middle-ground between those very complex models at the forefront of land-use/transport modelling research, and simpler econometric/statistical models. One benefit of this approach is that the model has relatively modest data requirements, and hence, could be easily applied to other cities. Despite being somewhat simpler than other recently developed models, the model is sophisticated enough to generate a rich set of visual and other outputs to usefully serve in facilitating decision making processes.

Chapter 7

Development of the Integrated Model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> The sciences do not try to explain, they hardly even try to interpret, they mainly make models.
>
> John von Neumann

7.1 Introduction

Chapters 4 and 3 have provided important information about both the travel behaviour of households, and their dwelling-related energy use. While these analyses are useful in their own right, and contribute to the body of knowledge in those fields, I felt that a more holistic approach was required to better understand the effects planning policies can have on combined dwelling & transport related household energy use. The study in Section 3.3, for example, estimated that the independent effect of a household moving from a detached dwelling to an attached dwelling is a 10-15% reduction in in-dwelling energy use, and that each additional dwelling occupant increases in-dwelling energy use by $\approx 10\%$. However, this information alone is not sufficient for the formulation of a low-energy housing policy; for this, one needs to know the number and mix of households that need to be housed, and what options there are for providing the necessary housing given the prevailing economic, social, and planning constraints. If households are strongly averse to living in attached dwellings, and/or if higher density construction is not economically feasible (i.e. developers cannot make a profit by developing attached dwellings), then there is no point pursuing a planning/zoning policy that favours the development of attached dwellings. In addition, because of the economic link between dwelling type and dwelling location (i.e. attached dwellings occur in areas with high land values, such as centres), housing policy is likely to indirectly affect travel behaviour. It seems plausible, for example, that a policy encouraging the construction of detached dwellings on the city fringe would result in increased car use, and the VKT model developed in Section 7.3.3 supports such a claim. To start to obtain a more complete understanding of combined transport and in-dwelling energy use, the remainder of this thesis is devoted to the development of an integrated metropolitan scale model. This model builds on existing research, and on the supporting analysis conducted in Chapters 3-5. However, because of the metropolitan scope and complexity of the integrated model, some simplifying assumptions have been made. In particular, the integrated model is restricted to considering the effect of different metropolitan housing policies on overall household energy use. Major changes to travel behaviour, or to the public and/or private transport networks, or the distribution of employment, are not explicitly modelled. Unfortunately, the integrated model is not able to assess detailed transport *and* housing policies, as this has proved beyond the scope of what is achievable in this thesis. As a result, the model of travel behaviour (Section 7.3) is based on urban structure proxies, such as population density and distance from the CBD, rather than explicit measures of travel time, parking costs, fuel costs, and so on. Thus, the implicit assumption in many of the scenarios assessed in Chapter 9 is that the link between these proxy variables and travel behaviour remains constant over time. That is, if higher population density is currently associated with lower car ownership and use, this will continue to be the case.

The overall model structure adopted is shown in Figure 7.1, consisting of the 'core' model structure already shown in the previous chapter (Figure 6.2), with 'attached' household travel and dwelling-related energy use modules, which will be described in this chapter.

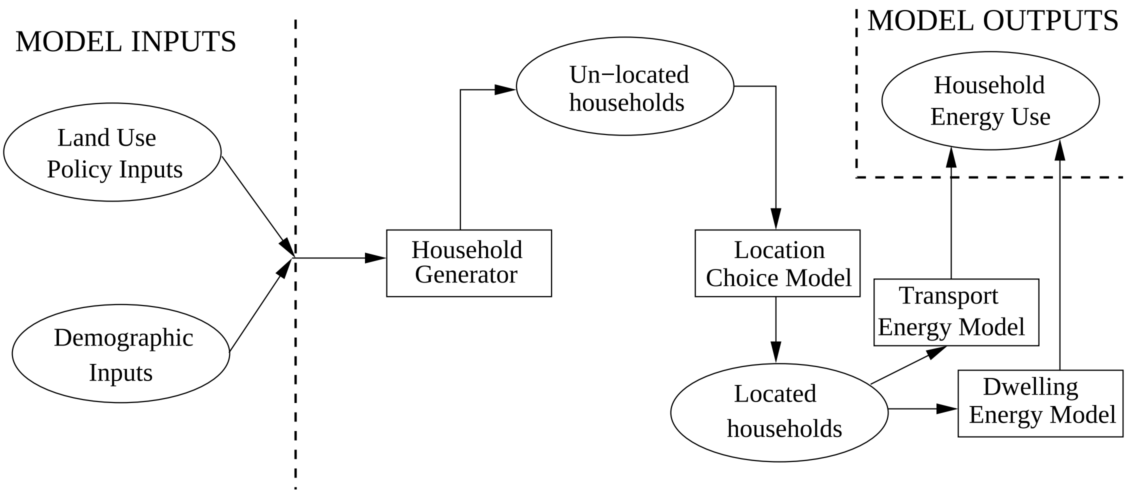


Figure 7.1: The model structure adopted for modelling in this thesis.

In the remainder of this chapter, a Section is devoted to the description of each sub-module in Figure 7.1 (represented by rectangular boxes), with policy and other input data (represented by oval boxes) described separately in Chapter 8. Section 7.2 provides some additional details on the residential location model (already largely described in Chapter 5). Section 7.3 describes the transport module, and Section 7.4 describes the dwelling-related energy use module. Section 7.5 illustrates the use of these models by showing some results for some 'representative' households.

7.2 Residential location model

The mechanics of the residential location component of the overall model have already been described in some detail in Chapter 5. I will not repeat any of that material here, but, as that chapter dealt more with the underlying mathematics, it is useful if a little effort is devoted in this section to provide the reader with a more concrete understanding of how the method is used in the modelling of different scenarios for Sydney.

The method described in Chapter 5 is used to estimate a multinomial discrete choice model for each of the eight household types shown in Table 7.1. Each multinomial choice model estimated specifies a choice probability (for that household type) for zone/dwelling-type combinations. The 615 zones used are aggregations of Australian Bureau of Statistics Census Collection Districts. Three dwelling-types are defined: detached; semi-detached/townhouse/terrace; and apartment. Figures 7.2-7.4, for example, show the spatial and dwelling-type variation in choice probabilities for couple households with all children under 15 for a choice model estimated using ABS 2006 census data. These figures indicate that this household type has a strong preference for detached dwellings, and for locations in the Eastern Suburbs, North Shore, and Baulkham Hills.

The preferences shown in Figures 7.2-7.4 are broadly plausible, but, by themselves are unsatisfactory, for three reasons.

Household Type	Definition
Young single	Single person household aged less than 55
Old single	Single person household aged 55 or over
Young couple	Couple household without children where *household reference person** is under 55
Old couple	Couple household without children where *household reference person** is 55 or over
Couple with young children	Couple household with all children aged under 15
Couple with older children	Couple household with at least one child 15 or over
Single parent	Single adult with children (all ages)
Other	All other households

Table 7.1: Household types used in modelling and analysis. * As defined in Australian Bureau of Statistics (2001).

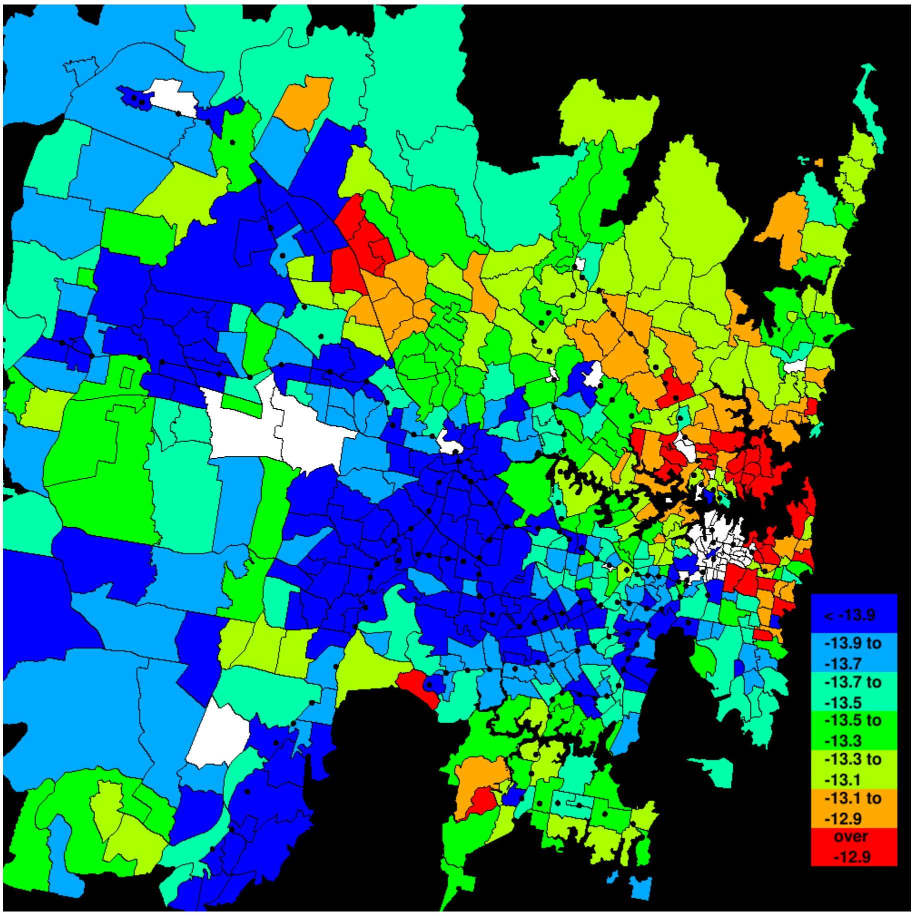


Figure 7.2: Location choice log-probabilities for couples with young children in detached dwellings. The value plotted is $\ln(P(i))$ where $P(i)$ is the choice probability for a single detached dwelling in region i.

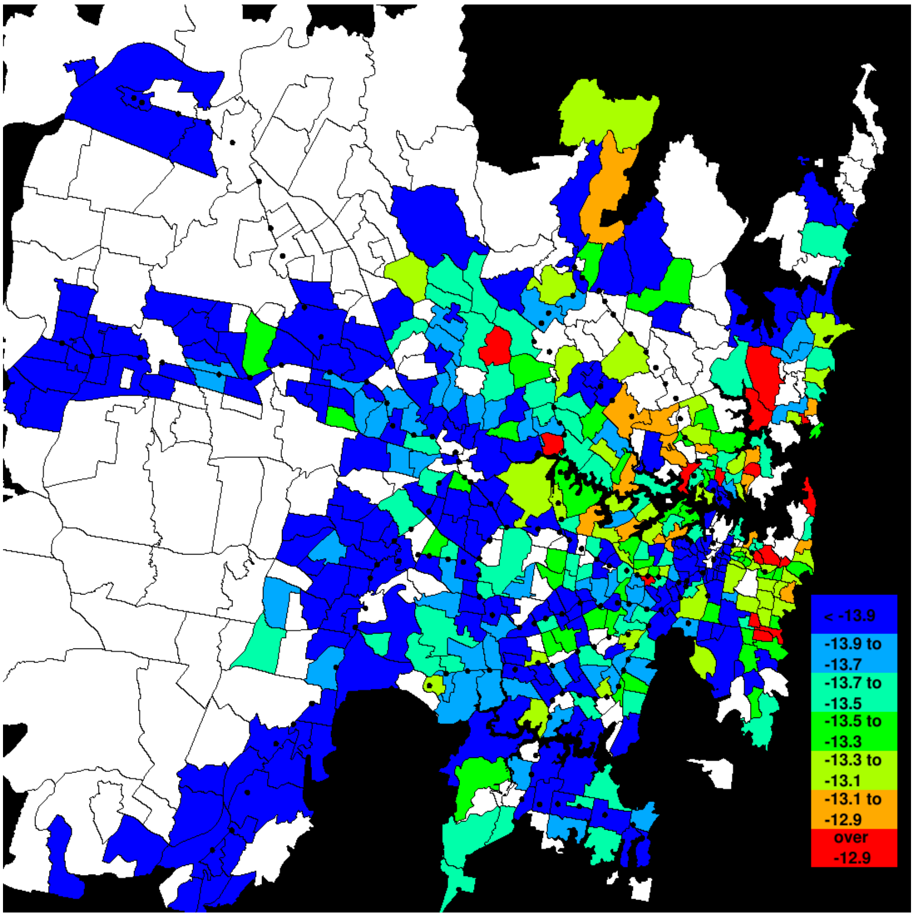


Figure 7.3: Location choice log-probabilities for couples with young children in semi-detached/townhouse style dwellings. The value plotted is $\ln(P(i))$ where $P(i)$ is the choice probability for a single semi-detached/townhouse dwelling in region i.

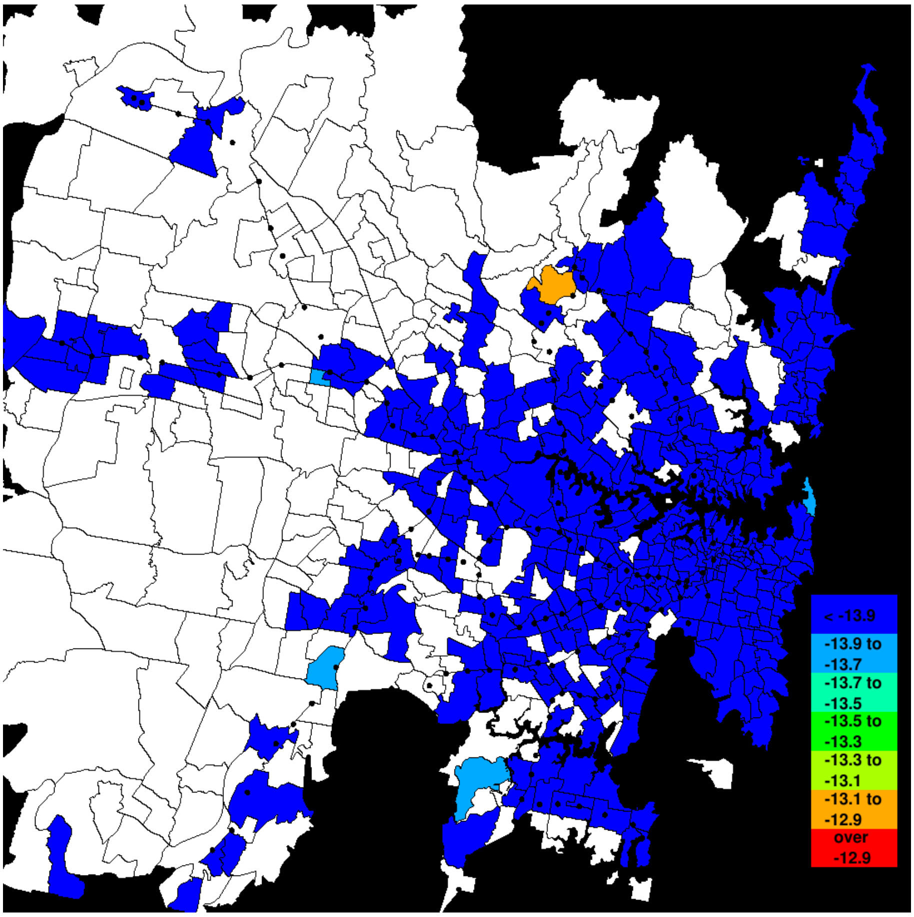


Figure 7.4: Location choice log-probabilities for couples with young children in apartments. The value plotted is $\ln(P(i))$ where $P(i)$ is the choice probability for a single apartment in region i.

1. The choice model provides only an estimate of the choice-probability of each zone/dwelling-type *at the time of the 2006 census*. What is required, however, is a prediction of choice probabilities in the year 2031 – the target year for scenario evaluation. The simplest way to obtain one from the other is to assume that both preferences and choices remain static, but this seems unrealistic, given that the redevelopment of some areas will doubtless affect the desirability of those areas for some household types. For example, substantial redevelopment of a zone (raising its dwelling and population density) may make it less desirable to some household types.

2. For zone/dwelling-type combinations with insufficient dwelling counts, it not possible to estimate a choice probability[1].

3. Some of the zone/dwelling-type combinations that can be estimated will be erroneous. For example, Figure 7.4 estimates that flats in the north western suburb of Westleigh are quite desirable to couple households with young children, and, in fact, are more desirable to that household type than detached dwellings in the same area. This *could* represent a genuine preference by those households for apartment living in that area. However, this does not seem likely, given the general pattern of observed preferences for that household type. More likely, there is some other unobserved explanation for the choice. For example, the dwelling-type classification made by the ABS may be wrong[2].

The preceding discussion suggests that, despite the general effectiveness of the technique in capturing the location and dwelling preferences of households, some post-processing is required to provide reasonable estimates for zone/dwelling-type combinations that have a missing or unreliable estimate. In addition, account needs to be made for the fact that we require estimates for 2031, even though our model is calibrated on 2006 data. The following section details how estimates of residential location preferences for 2031 are obtained from the noisy and incomplete baseline estimates obtained from 2006 data.

7.2.1 Predicting residential location preferences in 2031

I will use the term 'base estimate' to refer to the estimates obtained from the discrete choice model described in Chapter 5 when applied to 2006 census data.

From the base estimate for 2006, we need to obtain choice probabilities for all choices in 2031. Rather than dive directly into the mechanics of how choice probabilities for 2031 are estimated from the base 2006 estimate, I think it is preferable to show (by example) how it is done. After this, more details about each step are provided.

I will assume, throughout, that the total number of dwellings, their locations, and types, are all known for 2031 (the target year for all scenarios). Since this is a required input to the overall model (one of the 'policy inputs' shown in Figure 7.1), these projections must be made in any case for each scenario evaluated.

[1]This calibration issue has already been discussed is more detail in Section 5.4

[2]This cannot be ruled out. ABS Census Collectors are ordinary citizens hired on a casual basis for the purpose of conducting the census, and interpretations of the bureau's definition of different dwelling-types is bound to vary. My personal experience working with various ABS census data confirms this.

Step 1: obtain base estimate

The method already outlined in detail in Chapter 5 is used to obtain a partial estimate of choice probabilities for all zone/dwelling-type combinations. The reader has already been shown an example of what is produced. Figure 7.2 shows the log of the 'free choice' probability for detached houses in different areas of Sydney for households with young children.

Step 2: adjust for projected changes in density

It is too difficult a task to try and develop, as part of this thesis, a model of how preferences will change between 2006 and 2031. However, it *is* possible to make adjustments to base estimates for projected changes in population densities. Specifically, if we know that households with young children do *not* like to live in areas with high population densities, and we know that a particular area is projected to have many new additional dwellings (and hence people) between 2006 and 2031, it seems reasonable to assume that such an area will become less desirable. The exact method used to calculate the appropriate adjustment is described in Section 7.2.2, but for now let us concentrate on getting an idea of the effect of such adjustment. Figure 7.5 shows the choice log-probabilities after adjusting for projected changes in density resulting from the 'baseline' scenario defined in the next chapter (which is based on the state government's published long-term plan for Sydney (NSW Department of Planning, 2005)). Figure 7.5 shows that adjusting for projected changes in density does not result in substantially different probabilities from the base ones shown in Figure 7.2, though there are a few shifts. Also note that where a very large change in density occurs (i.e. a trebling or more), the base estimate for that region is discarded. This is because those areas undergoing very large changes in density are generally green-field or brown-field development areas, and basing the desirability of those areas on those few dwellings currently in the area seems unreasonable. In Figure 7.5, for example, notice the large white patches to the south-west and north-west; These are new land release areas. Similarly, a few other regions experience significant redevelopment, and will be substantially altered in the period 2006-2031. This seems likely to make present-day estimates of the region's attractiveness substantially less reliable.

Step 3: estimate missing values

As can be seen in Figure 7.5, there are a significant number of regions (shown in white) for which a reliable estimate of choice probability could not be made. This is usually due to a lack of dwellings in those regions. For example, the CBD area in the middle-right of the image contained very few detached dwellings at all, and so it is not possible to estimate the desirability of a detached dwelling in that area. However, the area does contain apartments, and it is possible, with some additional assumptions and regression modelling, to estimate the desirability of a detached dwelling from the known value for apartments. The technical details of how this is done are presented in Section 7.2.2. The general idea is that, if there is an estimate of free-choice probability for one dwelling type in a particular region, then this estimate can be used to obtain a plausible estimate for the free-choice probabilities of 'missing' dwelling type(s) by adjusting the known estimate based on observed dwelling type preferences of the household. In the case of couples with young children, for example, there is a strong preference for detached dwellings, and so preferences for detached dwellings in the CBD are obtained by 'boosting' the values estimated for apartments in the CBD.

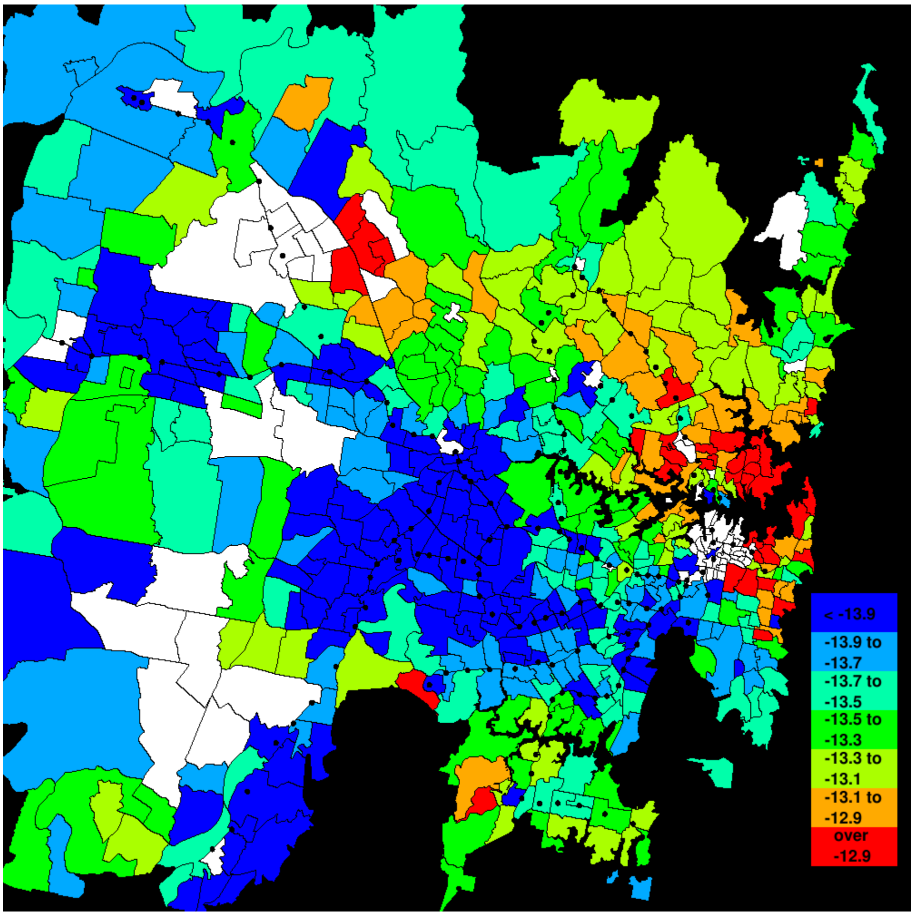


Figure 7.5: Location choice log-probabilities for couples with young children after adjusting for projected changes in density under the Sydney metro-strategy.

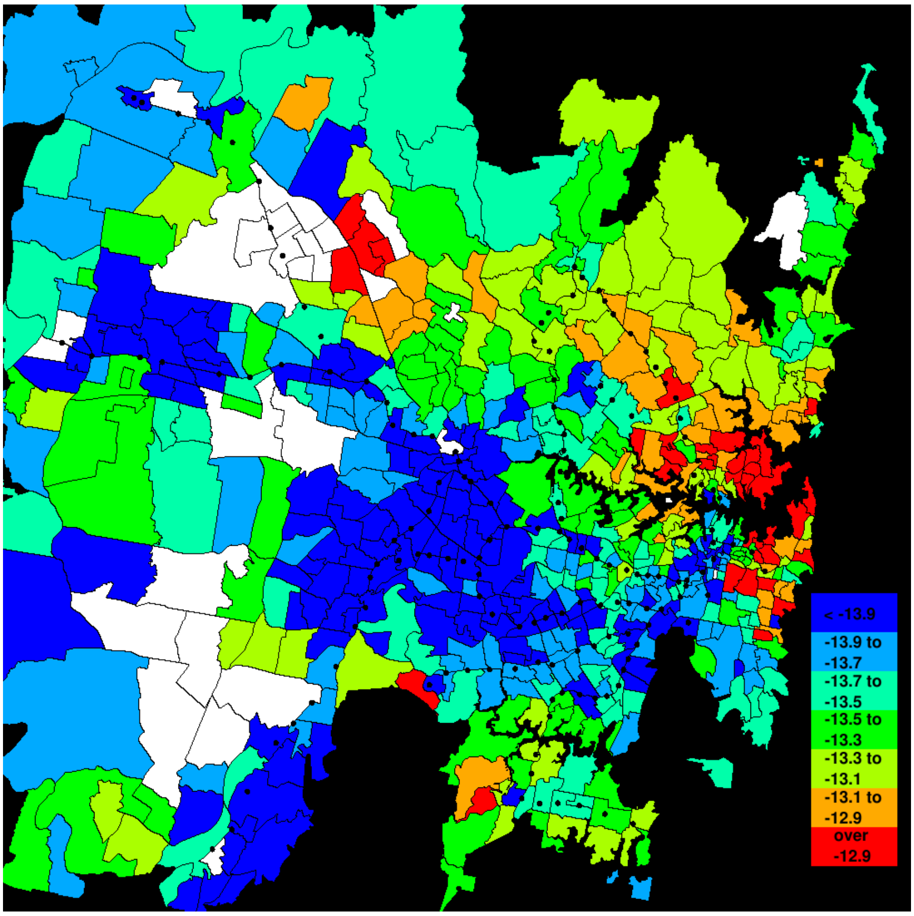


Figure 7.6: Location choice log-probabilities for couples with young children after missing values have been estimated from known values.

Figure 7.6 shows the results of filling-in missing values in the manner described. Notice in particular that there are now estimates for the desirability of CBD area detached dwellings, where previously (Figures 7.2 and 7.5) there were no such estimates.

Step 4: spatial smoothing and interpolation

Even after the first three steps, there remain two problems.

1. There are some regions where it is not possible to obtain *any* estimate. This happens in situations where either:
   (a) no estimate for *any* dwelling type was available for that region; or
   (b) estimates are available, but development activity in the region is anticipated to be so substantial that present-day estimates of preferences will not serve as a useful guide for future preferences.
2. The values for some regions are implausibly large, or small. This could be caused, for example, from either random or systematic errors in the data. Figure 7.4, the reader may recall, shows a particularly glaring example.

A spatial interpolation technique called inverse distance weighting (Shepard, 1968) is used to both obtain (by interpolation) estimates for missing values, and to 'smooth' out the variance of existing estimates. Full details are in Section 7.2.3, but the basic idea is that in data-sets where there is a significant degree of spatial correlation (i.e. where Tobler's first law of geography holds: "everything is related to everything else, but nearby objects are more related than distant objects"), it is possible to use 'nearby' values to both obtain estimates for missing values, and to dampen implausible 'out-of-place' values. Figure 7.7 demonstrates the results of applying the interpolation and smoothing to the data shown in Figure 7.6.

The final result now has the following advantages over the initial base estimate in Figure 7.2:

1. Estimates are available for all zones and all dwelling types (i.e. there are no missing values).
2. The effect of changes in density (from 2006-2031) have been taken into account.
3. Spatial correlation information has been taken into account to 'smooth' out irregular values.

Since I have only provided, thus far, an outline (and example), of the required steps, the full technical details are now provided (Sections 7.2.2-7.2.3).

7.2.2 Supporting method 1: Regression

Steps 1 and 2 in the process outlined in Section 7.2.1 require that we know:

1. The effect that changes in density have on household residential preference. (Required for Step 1); and
2. The effect of dwelling type on household residential preference. (Required for Step 2).

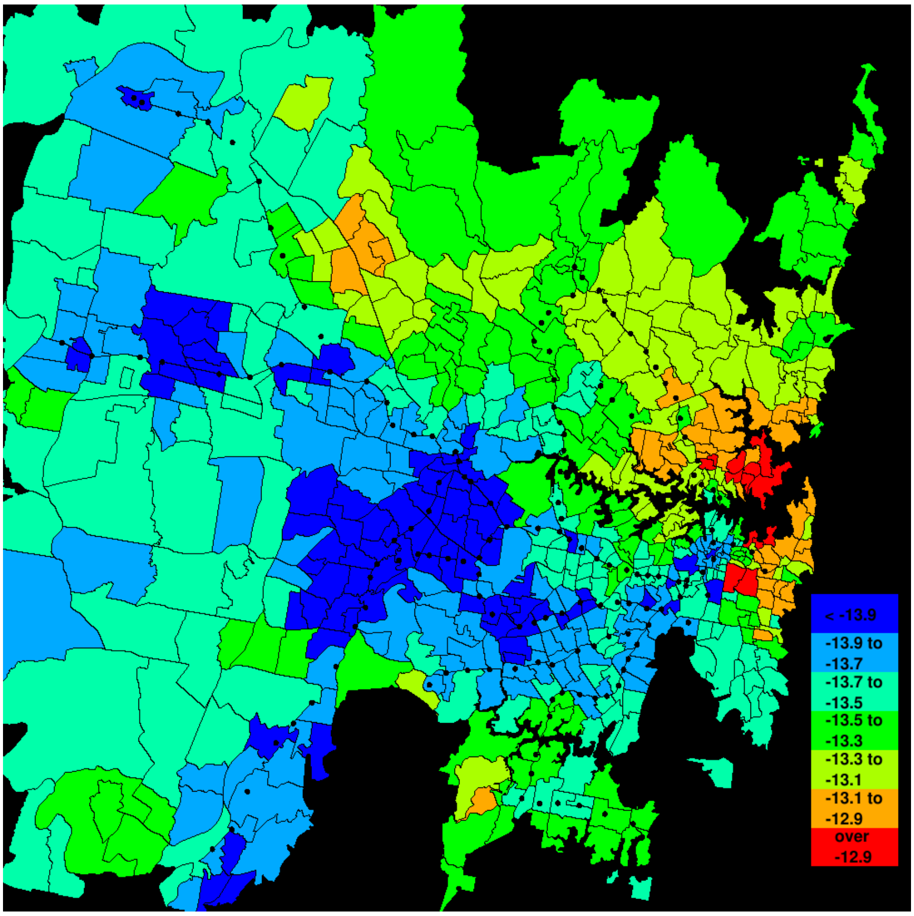


Figure 7.7: Location choice log-probabilities for couples with young children after inverse-distance-weighting interpolation and smoothing.

The multinomial choice model for each household type estimated by the technique outlined in Chapter 5 is a fixed-effects only model. That is, it estimates, directly, the choice-probability of each zone/dwelling-type combination. This is in contrast to most discrete choice models which estimate the utility of each actual choice. Concretely, normal discrete choice methods[3] estimate the parameter vector $\bar{\alpha}$ for the equation $U_i = \bar{\alpha} \cdot \bar{x_i}$, where U_i is the utility of choice i, and $\bar{x_i}$ is a vector of attributes describing that choice[4]. Since the specific fixed-effects model developed in this thesis estimates the U_i's directly[5], the need to estimate $\bar{\alpha}$ and collect $\bar{x}$ is avoided[6]. Although $\bar{\alpha}$ is traditionally estimated as part of estimating choice utilities, it is possible, in this case, to estimate $\bar{\alpha}$ afterwards. If U_i is the (known) utility for choice i, and $\bar{x_i}$ is the vector of variables describing choice i, we can estimate $\bar{\alpha}$ through simple linear regression, rather than the more usual (and complicated) estimation procedure required when both $\bar{\alpha}$ and the U_i's are unknown. Once $\bar{\alpha}$ is estimated, it is possible to use the simple regression equation to predict utility, rather that the direct estimate.

The variables that comprise $\bar{x_i}$ are chosen such that the values of those variables will be known in both 2006 and 2031. The variables that comprise $\bar{x_i}$ are:

distcbd: Distance from the CBD to the centroid of the zone, in kilometres. This is clearly constant from 2006 to 2031.

logpopdensity: The natural logarithm of the population density (measured as people per hectare). This is known in 2006, and can be reasonably approximated for 2031 given dwelling numbers for each zone (estimated as described in Section 8.3).

issemi: Is the dwelling a semi-detached, townhouse, or terrace style dwelling. (0/1 dummy variable).

isflat: Is the dwelling an apartment. (0/1 dummy variable).

Using these parameters and variables, one can form a standard linear regression equation in the following way:

$$U = \alpha_1 \times \text{distcbd} + \alpha_2 \times \text{logpopdensity} + \alpha_3 \times \text{issemi} + \alpha_4 \times \text{isflat} + \alpha_5$$

However, after a little experimentation, I found that a better form for actual estimation was:

$$e^U = e^{\alpha_1 \times \text{distcbd} + \alpha_2 \times \text{logpopdensity} + \alpha_3 \times \text{issemi} + \alpha_4 \times \text{isflat} + \alpha_5} - 1$$

Table 7.2 shows the coefficients values, with column headings for the corresponding variables. Also, since the coefficients are small, and it quickly becomes tedious to report everything in scientific notation, the coefficients presented here have been scaled up (multiplied) by a factor of 10^6, just to avoid reporting coefficients as $-2.46e{-}08$, and the like.

Are the results shown in Table 7.2 plausible? On first appearance, they certainly seem so. We see a strong preference for detached dwellings by larger households (i.e. couples with children).

[3]The following description is a little simplified, but captures the essentials. Standard reference texts, such as Koppelman and Bhat (2006) provide the details.

[4]Actually, $\bar{x}$ usually describes both choice and chooser (and possible interactions), but I have assumed that preferences are homogenous within household types, so it only makes sense in this case for $\bar{x}$ to contain variables

Household Type	constant	distcbd	logpopdensity	issemi	isflat	r^2
Young Lone	1.1903	-0.0263	0.0059^+	0.5723	1.2002	0.44
Old Lone	3.021	-0.0572	-0.2708	0.2107	0.0188^+	0.22
Young Couple	1.4766	-0.0267	-0.0215^+	0.5347	0.3494	0.32
Old Couple	3.2858	-0.0408	-0.3384	-0.5052	-1.0927	0.26
Young Family	2.3477	-0.0228	-0.1624	-0.2805	-1.062	0.40
Teen Family	2.3204	-0.0134	-0.1743	-0.8346	-1.3401	0.68
Single Parent	1.4947	-0.0082	-0.0205^+	0.0251^+	-0.6989	0.36
Other	1.3803	-0.0279	0.0764	0.099	-0.0596^+	0.31

Table 7.2: Scaled parameter coefficients for dwelling utilities for the eight household types defined. (Scaled up by a factor of 10^6.)
$^+$ Parameter not significantly different from 0.

Childless households, on the other hand, show a preference for attached dwelling stock. The convenience and low-maintenance of such dwellings could explain such a preference. I think it helps if we re-interpret distance from the CBD as a proxy for accessibility, and population density as a proxy for the compactness of a neighbourhood. Table 7.3 then shows the estimated preferences of different households. These all seem reasonable enough. Everyone prefers high accessibility areas. In agreement with conventional wisdom on the subject, older households and couples with children prefer quieter suburban living. Dwelling preferences vary neatly with family size – larger households prefer larger detached dwellings, with smaller households preferring semis and apartments. Older households, however, seem to prefer larger dwellings than their younger equivalents.

Household Type	accessibility	compactness	preferred dwelling
Young Lone	+		apartment
Old Lone	++	-	semi-detached
Young Couple	+		semi-detached
Old Couple	++	-	detached
Young Family	+	-	detached
Teen Family	+	-	detached
Single Parent	+		detached or semi-detached
Other	+	+	detached or semi-detached

Table 7.3: Interpretation of regression results in Table 7.2.

The plausibility of these results gives some additional confidence to the effectiveness of the novel technique employed to estimate utilities. Including a larger number of variables describing neighbourhood qualities (rather than the 2 variables used here) would allow for a more interesting investigation into the residential location preferences of households. Although this seems a fruitful area for future research, such an investigation is not required here, as the purpose for developing this regression model is limited to buttressing the base estimates of choice utility produced by the

describing the choice.

[5] In fact, the model *actually* estimates choice probabilities directly, but since choice probability is proportional to the exponent of choice utility, switching between the two is a simple matter of transformation and normalization.

[6] Recall that the need to avoid collecting a particular x_i (dwelling price/rent) was a primary motivation for the development of the new technique.

technique described in Chapter 5.

7.2.3 Supporting method 2: Spatial smoothing through Inverse Distance Weighting

The final two steps in the four stage process by which complete choice probabilities are obtained for each household are interpolation of missing values (Step 3), and 'smoothing' of anomalous values (Step 4). In the description of these steps, I did not include any detailed description of the method used to perform this interpolation and smoothing. I do this now, in this section.

Suppose we observe the outcomes from some very complex process. For example, suppose that we observe prices paid for dwellings in some city. The prices paid are influenced by a bewilderingly large number of factors. Suppose now that one wants to estimate the value of a dwelling for which there is no recently observed sale price. How should one go about this? There are two approaches. One approach is to develop a model that attempts to estimate the impact of all the possible factors. This approach is taken by hedonic price modellers (see Rosen (1974); Cheshire and Sheppard (1995)), but is an onerous task, requiring a lot of data, and a degree of mathematical sophistication. A second approach is to look at the prices paid for similar, nearby dwellings, and use this as a guide. This approach provides none of the insights of a structured hedonic model, but is a reliable method that can be easily applied. Why does this approach work? Because of spatial correlation. Whatever the complex underlying factors determining house prices, it turns out that 'nearby' dwellings have similar values, and so basing an estimate on those nearby observations is quite effective, if one is only interested in obtaining an estimate for the price of a dwelling.

Inverse distance weighting (IDW) (Shepard, 1968) is one of the mathematical techniques developed which can be used for spatial interpolation[7]. Suppose we have a set of observed data $d_1, \ldots, d_N$, distributed throughout a two-dimensional space, where each d_i is of the form (x_i, y_i, V_i), where x_i, y_i are the spatial coordinates of the observation, and V_i is the observed value. Calculating an interpolated value V' at point x', y' is done by taking a weighted average of all other points, where the weight applied for each other point is determined by the distance from that point to x', y'. Or, more formally:

$$V' = C \sum_{i=1}^{N} \frac{V_i}{d(x_i, y_i, x', y')^q} \tag{7.1}$$

where d is a function giving the distance between (x_i, y_i) and (x', y'), and C is a normalization constant chosen so that $\sum_{i=1}^{N} \frac{C}{d(x_i,y_i,x',y')^q}$ is equal to 1. The most common values chosen for q are 1 (weight declines inversely with distance) and 2 (weight declines with the inverse square of distance). In this thesis, a value of 2 is used for interpolating residential location choice parameters. The x_i, y_i are the centroids of the spatial 'zones' used in the modelling, and the V_i are the location choice parameters for those zones. Using inverse distance weighting allows the calculation of 'missing' parameters, that cannot be estimated due to insufficient data, but it can also be used to 'smooth' existing estimates. This is because the IDW estimate for any particular data point will (in general) be different from the original value. That is:

[7] There are many others, such as (to choose but one example) Kriging (Cressie, 1990), but I will not cover any of these. Interested readers are referred to Anselin (1988) for a good summary of some of the other possible approaches.

$$V_j \neq C \sum_{i=1, i \neq j}^{N} \frac{V_i}{d(x_i, y_i, x', y')^q} \tag{7.2}$$

Figure 7.8 shows a smooth[8] 'surface' fitted, using IDW, to the spatially varying parameters in one of the residential location models. In this case, the surface, while determined by the parameters from the location choice model, will not pass through the same values (i.e. the location choice model parameter values will not lie *on* the surface), and, as a result, the IDW surface can be used to smooth the parameters estimated in a residential location model by adjusting them so that they lie closer to the IDW surface. This is what is done in the smoothing of parameters described in Step 4 of the process already described. Specifically, the corrected/smoothed choice probability for each zone is taken to be the average of the actual value estimated by the residential location model described in Chapter 5, and the value of the IDW surface at the zone centroid[9]. The effect achieved by doing this has been shown already in Figures 7.6 (unsmoothed) and 7.7 (smoothed). The same figures also show the effect of using IDW for interpolating missing values.

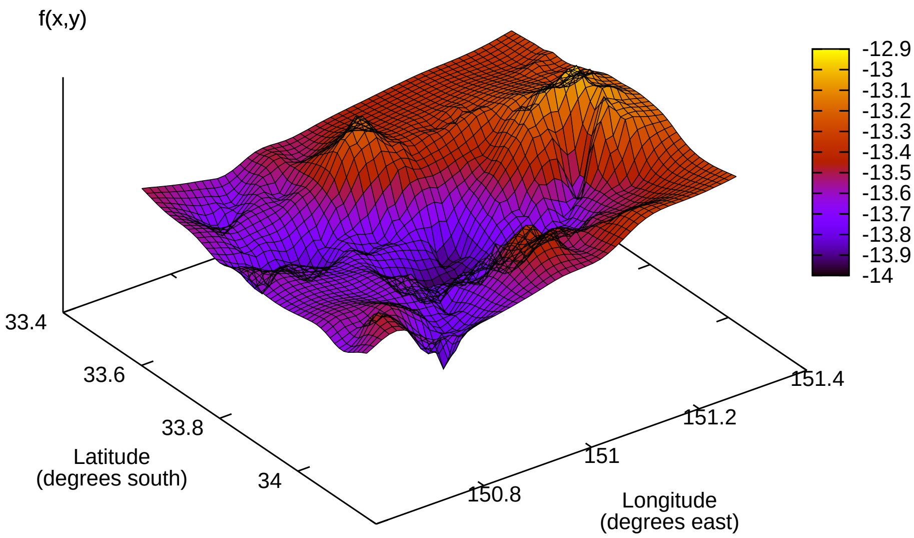


Figure 7.8: A smooth IDW 'surface' fitted to parameters from one the residential location models. Values shown (on the z-axis) are (smoothed) log-probabilities of selecting a detached dwelling by households with young children.

This now completes the description of how residential choice probabilities are obtained for different planning scenarios for Sydney in 2031. The next sub-component of the overall model – the transport model – is now described in the following section.

[8]The actual surface shown is not smooth, but is a piecewise linear approximation, but this is purely an artefact of the plotting software – the underlying function is smooth.

[9]After this smoothing, an additional normalization step is also required, to ensure that the sum of choice probabilities over all choices is one.

7.3 Transport model

The core residential location model produces choice probabilities for each dwelling available in any given scenario. These probabilities can then be used to allocate households to dwellings. The consequence is that we have available information on the household type, income, location, and dwelling structure for each household. These variables then serve as inputs to the travel model, the task of which is to estimate car ownership and travel behaviour for those households. Because I did not have time, in this thesis, to develop different detailed transport scenarios for Sydney in 2031 (i.e. with detailed future transport networks and travel times), I instead develop a simpler model that relies only on useful proxy variables, such as distance from the CBD, and population density, which can be easily calculated for future scenarios. There are of course limitations arising from this simpler approach, the most important of which is that it does not account for long term land-use/transport interaction effects. In particular, it does not allow me to fully capture the effect of improved public transport service arising from changes to land use that support efficient public transport services[10].

The first stage in the travel model is the estimation of a car-ownership model, as car-ownership is known to influence travel decisions (Kitamura, 1989; Dieleman et al., 2002; Hensher, 2003). Car-ownership information available from this model is used by the *daily* household travel model, the structure of which is show in Figure 7.9. The initial sub-model estimates whether any trip is made on a given day. If at least one trip is made, separate models are employed to estimate the distance and mode of those trips for car-owning and non-car-owning households[11]. Households without a car require only a public transport model to be estimated[12]. For households with at least one car, a private vehicle travel model is estimated, which gives an estimate of the number of kilometres travelled on a given day. The results of this private vehicle travel model influence the estimate of public transport travel in the final sub-model, as explained in Section 7.3.4.

The models described in the following sections are *daily* models, because the travel survey data on which the models were calibrated related to daily travel. Section 7.3.6 explains the process by which these models of daily behaviour are used to produce an estimate of yearly travel (which is slightly more involved than multiplying the daily results by 365).

A note on the estimation of the following models

The following models were all estimated using data from the New South Wales Transport Data Centre's Household Travel Survey (HTS). This travel survey consists of the daily travel undertaken by households in Sydney, with the daily travel behaviour of approximately 3,000 households being surveyed each year. Dwelling and demographic information about those households, and car-ownership information, is also collected. It is the largest, most detailed travel survey dataset in Australia, and I was fortunate enough to negotiate access to the dataset for the purposes of

[10]Improved public transport service can be *partly* taken into account – essentially to the extent that changes to local area density are correlated with changes to transit service/provision

[11]This split was deemed necessary after exploratory analysis of the travel behaviour of households. Households without cars exhibit markedly different travel behaviour because of the fact that travel by car is not an option.

[12]I ignore walking and cycling. Because walking and cycling represent a small proportion of trips in Sydney (and all other Australian cities), it is difficult to include them in a travel model. Walking/cycling trips are clearly at least partial substitutes for motorized trips, but ignoring them effectively treats them as if they were not made. For a model concerned solely with transport energy, this is defensible. To understand better the factors influencing walking/cycling trip behaviour, a more detailed model would be needed.

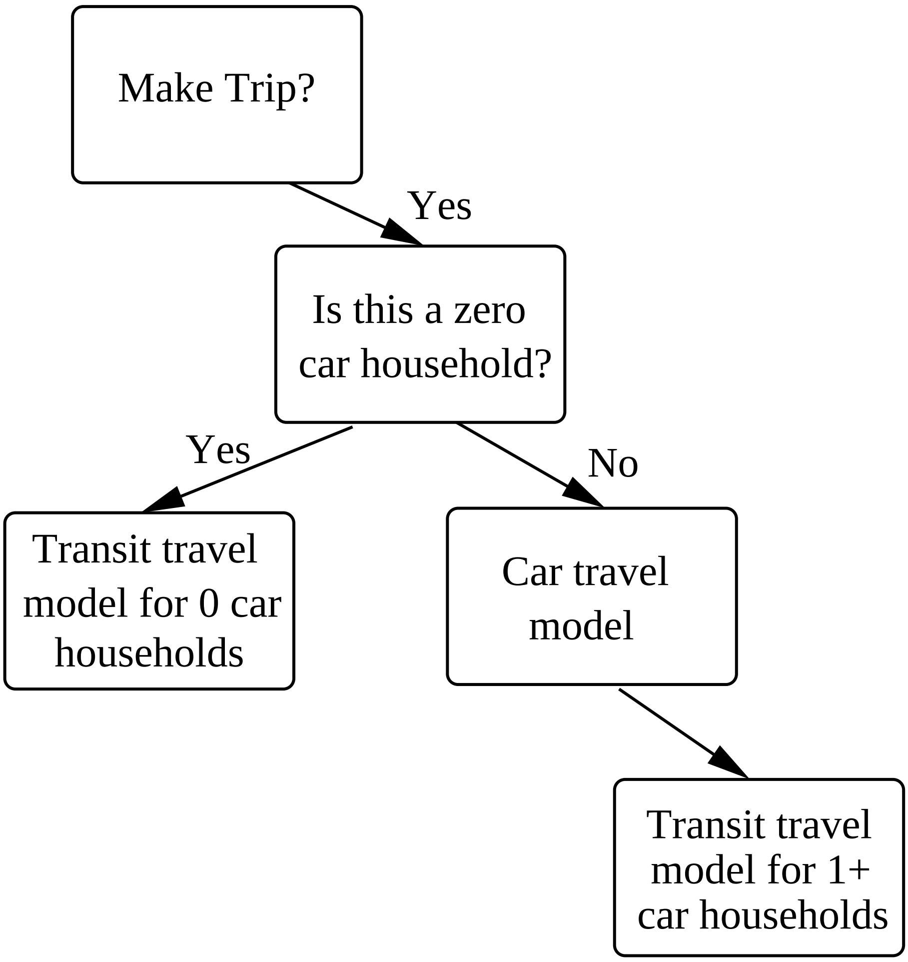


Figure 7.9: The structure of the household travel model for Sydney households.

estimating the following travel models. However, the Transport Data Centre is very conscious of protecting the privacy of those households surveyed, and, as a consequence, placed restrictions on my access to the data. Specifically, I was allowed access to the data for only two days, and only then by using a computer at the Transport Data Centre that was disconnected from the internet. The computer provided had the statistical package SPSS installed (but with no add-ons), and no other software was allowed to be installed. Having only two days to familiarise myself with the data, decide on model structure, and estimate and validate travel models, using only proscribed analysis software, meant that the only practical option was to estimate relatively simple, easy to validate models.

The data used for all the following models was five years worth of HTS data (2001-2005, inclusive), comprising $\approx$ 15,000 individual households, which, after applying weights[13], form 1,291,372 household records that are representative of Sydney households. It is the weighted records that are reported on in the models following, as this is what SPSS outputs, but the reader should be aware that there are only $\approx$ 15,000 actual survey data records used to generate this larger, partially synthetic data-set.

7.3.1 Car-ownership model

It is well known that car ownership levels have a major influence on travel behaviour. Thus, although a car-ownership model is not shown in Figure 7.9, it is still necessary to have such a model, because car ownership is a variable in each of the travel behaviour models.

The car-ownership models used in modern transport planning modelling can very complex (see De Jong et al. (2004) for a review) but I had to take a simpler approach, due to the limited time in which I had access to comprehensive data. I used an ordinal logistic regression to model car-ownership. The dependent variable was the number of cars in the household, ranging between 0 and 10. In this ordinal logistic regression, the probability of a household having k cars is $\frac{1}{1+e^{-\beta_k+\alpha_1 x_1+\ldots+\alpha_M x_M}}$, where the β and α_i's are the parameters to be estimated, and the x_i's are variables describing the household. Table 7.4 shows the parameter values estimated via ordinal regression for car ownership levels in Sydney households. For readers not familiar with ordinal regression, this table will be difficult to interpret, and so I present some examples (see accompanying framed box). The main thing to remember is that positive parameter values are related to *increased* car ownership levels, with the Wald test statistic giving an indication of the strength of the effect (see Agresti (2002, page 232) for more details on the Wald statistic). Thus, in Table 7.4, disregarding the constants (β's) we can see that lone households have the lowest car ownership, and couple households with children the highest. As was found in the earlier aggregate study (Section 4.2), higher density areas are associated with lower levels of car ownership, all other things equal. Households in units own fewer cars, all other things equal. These last two effects can be easily understood if one accepts that population density and dwelling type act as useful proxies for other variables directly influencing car ownership. It is easy to show, for example, that higher density areas where apartments are common are, in general, better serviced by public transport (see Cervero and Kockelman (1997); Rickwood and Glazebrook (2009)). Densely populated areas

[13]The weighting scheme used aims to correct for the fact that the sample is not exactly representative of the Sydney population, and also for the fact that the sample is spread over a number of years.

also tend to have more congestion, more expensive parking, and nearby shops and other activities. All these factors tend to reduce automobile ownership and use.

Variable	Parameter Estimate
β_0 (numcars=0)	-2.549
β_1 (numcars=1)	0.679
β_2 (numcars=2)	3.336
β_3 (numcars=3)	4.894
β_4 (numcars=4)	6.218
β_5 (numcars=5)	7.432
β_6 (numcars=6)	8.914
β_7 (numcars=7)	9.540
β_8 (numcars=8)	10.500
β_9 (numcars=9)	10.812
distcbd (km)	0.009
logpopden	-0.289
$\sqrt{\text{income}}$	.006
ishouse	-0.467
issemi	-1.229
isunit	-1.690
lone household	0.131
couple household	1.541
couple w. young children	1.856
couple w. older children	3.184
single parent	1.188
other household	1.975
Nagelkerke ρ^2	0.49
$-2\times$ Log-likelihood	
Constant only model	3331751.484
Full model	2578999.903

Table 7.4: Coefficients for the ordinal logistic regression car-ownership model

7.3.2 Daily trip/no-trip model

Exploratory analysis of the data suggested that households that did not make any trips needed to be treated carefully. Early attempts to include such households in the data used for model calibration resulted in skewed residual distributions. As an example, consider Figure 7.10, which shows the residuals histogram for a semi-log regression analysis for car travel. Two distinct 'humps' are visible in the residuals histogram – the main (right) hump being for those households that made one or more car trips and the smaller (left) hump being those that made no car trips. It is clear that the assumption of normally distributed residuals is violated in this case; hence the need to separate out no-trip households.

A binary logistic regression model was used to model the trip/no-trip decision. Logistic regression has already been covered in Section 4.3.2; readers should refer to that section to familiarise themselves if necessary, although some illustrative examples are also given in the framed box accompanying the in-text description. Table 7.5 shows results from the binary regression, with the dependent variable being 0 for trip and 1 for no-trip.For my purposes, non-motorised trips are

Ordinal Regression Examples

Example 1: Lone person household earning \$50,000 per annum, living in a semi-detached dwelling 10 km from the CBD in an area with population density of 2000 people per square kilometre (20 people/ha).

$$\begin{aligned}
P(\text{own 0 cars}) &= \frac{1}{1+e^{2.549+0.131+0.006\sqrt{50000}-1.229+10\times0.009-0.289\ln 2000}} \\
&\approx 0.335 \\
P(\text{own 0 or 1 cars}) &= \frac{1}{1+e^{-0.679+0.131+0.006\sqrt{50000}-1.229+10\times0.009-0.289\ln 2000}} \\
&\approx 0.927
\end{aligned}$$

Example 2: Couple family with children (at least one of which is 15 or over), earning \$100,000 per annum, living in a detached dwelling 20 km from the CBD in an area with population density of 1000 people per square kilometre (10 people/ha).

$$\begin{aligned}
P(\text{own 0 cars}) &= \frac{1}{1+e^{2.549+3.184+0.006\sqrt{100000}-0.467+20\times0.009-0.289\ln 1000}} \\
&\approx 0.005 \\
P(\text{own 0 or 1 cars}) &= \frac{1}{1+e^{-0.679+3.184+0.006\sqrt{100000}-0.467+20\times0.009-0.289\ln 1000}} \\
&\approx 0.107 \\
P(\text{own 2 or fewer cars}) &= \frac{1}{1+e^{-3.336+3.184+0.006\sqrt{100000}-0.467+20\times0.009-0.289\ln 1000}} \\
&\approx 0.631 \\
P(\text{own 3 or fewer cars}) &= \frac{1}{1+e^{-4.894+3.184+0.006\sqrt{100000}-0.467+20\times0.009-0.289\ln 1000}} \\
&\approx 0.891
\end{aligned}$$

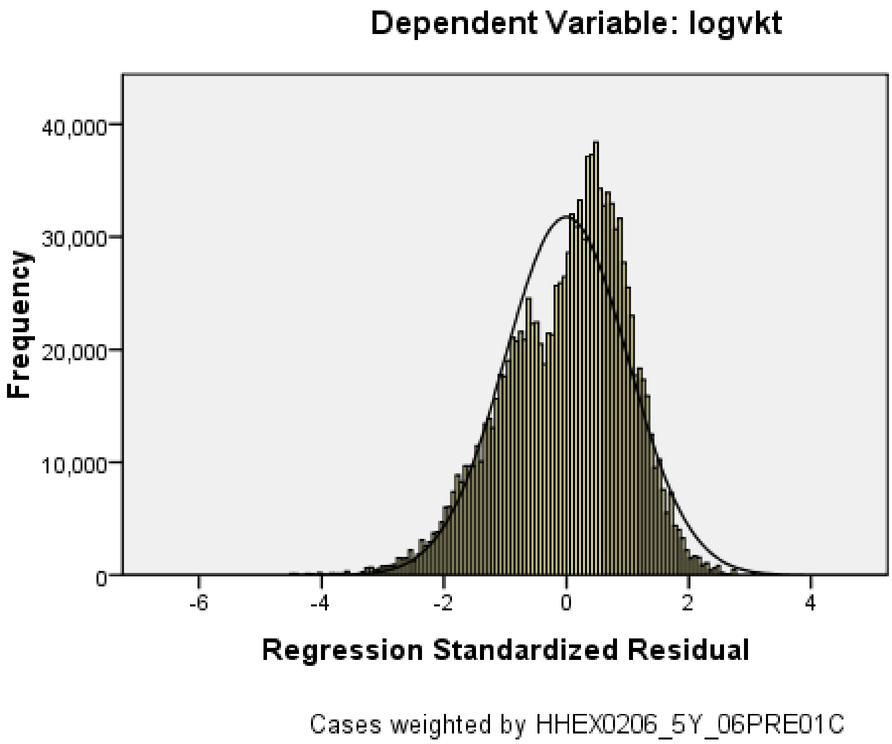


Figure 7.10: Residual frequency histogram for regression where both trip-making and non-trip-making households were included.

ignored. That is, a household that makes only walking or cycling trips is regarded as having made no trips. It should be noted that a relatively small proportion (2.5%) of households do not make a trip on any given day.

Variable	β	Wald test statistic	sig	e^{β}
$\sqrt{\text{income}}$	-0.004	3811.994	$< .001$	0.996
ishouse	0.509	1149.517	$< .001$	1.664
issemi	0.590	1125.951	$< .001$	1.805
numcars	-0.663	4849.355	$< .001$	0.515
lone household	0.498	381.090	$< .001$	1.645
couple household	-0.249	78.979	$< .001$	0.779
couple w. young children	-0.734	495.177	$< .001$	0.480
couple w. older children	-0.046	2.058	0.151	0.955
single parent	-0.249	70.340	$< .001$	0.780
Constant (C)	-2.399	6950.599	$< .001$	0.091
Nagelkerke ρ^2	0.123			

Table 7.5: Logistic regression coefficients for disaggregate trip/no-trip model.

The regression results show that lone person households are the most likely to make no trips, and households with young children the least likely to make no trips. The chance of making a trip is found to increase with household income. Higher levels of car ownership are also found to increase the chance of a trip. The most surprising, and interesting finding is that households in detached dwellings are more likely to stay home than are households in apartments. One possible explanation that springs to mind is that households in apartments may be more inclined to travel because they do not have access to private open space. Alternatively, maintaining the house and garden may keep households in detached dwellings at home. This intriguing finding begs for further investigation. There has been a suggestion by some that higher density apartment living is associated with increased ex-urban recreation travel (Holden and Norland, 2005). It is possible that access to private outdoor space results in reduced travel, as households are either disinclined to travel, or need to stay home to maintain their homes and yards.

Examples of Applying the Trip/No-trip Model

Example 1: A couple household without children, owning one car, earning $80,000 per annum, and living in a detached dwelling would have a probability of making no trip of:

$$\begin{aligned} P(\text{no trip}) &= \frac{1}{1+e^{2.399+0.004\sqrt{80000}-0.509+0.663+0.249}} \\ &\approx 0.02 \end{aligned}$$

Example 2: A lone person household, owning no cars, earning $35,000 per annum, and living in an apartment dwelling would have a probability of making no trip of:

$$\begin{aligned} P(\text{no trip}) &= \frac{1}{1+e^{2.399+0.004\sqrt{35000}-0.498}} \\ &\approx 0.066 \end{aligned}$$

7.3.3 Household VKT model

Most households (97.5%) *do* make a trip on any given day, and most households (87.4%) own a car. This model covers those households, and because it is relevant to the large majority of households, is the most important sub-component of the overall transport model. A linear regression model was used to estimate daily household travel by car, with a transformed target variable (the square root of the total *vehicle* kilometres). Parameter coefficients are presented in Table 7.6.

	Coefficient	Standardized*	sig.
Constant	2.574	NA	< 0.001
distcbd (km)	0.044	0.164	< 0.001
ln(popdensity)	-0.373	-0.103	< 0.001
$\sqrt{\text{income}}$	0.006	0.183	< 0.001
lone household	0.271	0.026	< 0.001
couple household	0.543	0.056	< 0.001
couple w. young children	1.101	0.110	< 0.001
couple w. older children	0.689	0.067	< 0.001
single parent household	0.318	0.024	< 0.001
numcars	1.702	0.419	< 0.001
r^2	0.431		
dependent variable	$\sqrt{\text{vehicle} - \text{km travelled}}$		

Table 7.6: Private automobile travel model for car-owning households.
* Standardized coefficients are the coefficients of the model if all variables are scaled to have mean 0 and variance 1.

The results shown in Table 7.6 are consistent with those in other research: population density is associated with reduced vehicular travel (Newman and Kenworthy, 1989; Golob and Brownstone, 2005; Giuliano and Dargay, 2006); increased distance from the CBD is associated with increased travel (Boarnet and Crane, 2001a; Næss, 2005; Corpuz et al., 2006); higher levels of car ownership are associated with increased car use (De Jong, 1990; Giuliano and Dargay, 2006); and higher-income households travel more than those on lower incomes (Schimek, 1996). By far the strongest influence is car ownership, with lesser influence from household income, location, and population density. However, note that income, location, and density were themselves important factors in the car-ownership model (see Table 7.4), and so their importance in influencing overall travel behaviour is understated in Table 7.6.

Figure 7.11 shows the standardized residuals for this model are well approximated by a normal distribution, as required for linear regression.

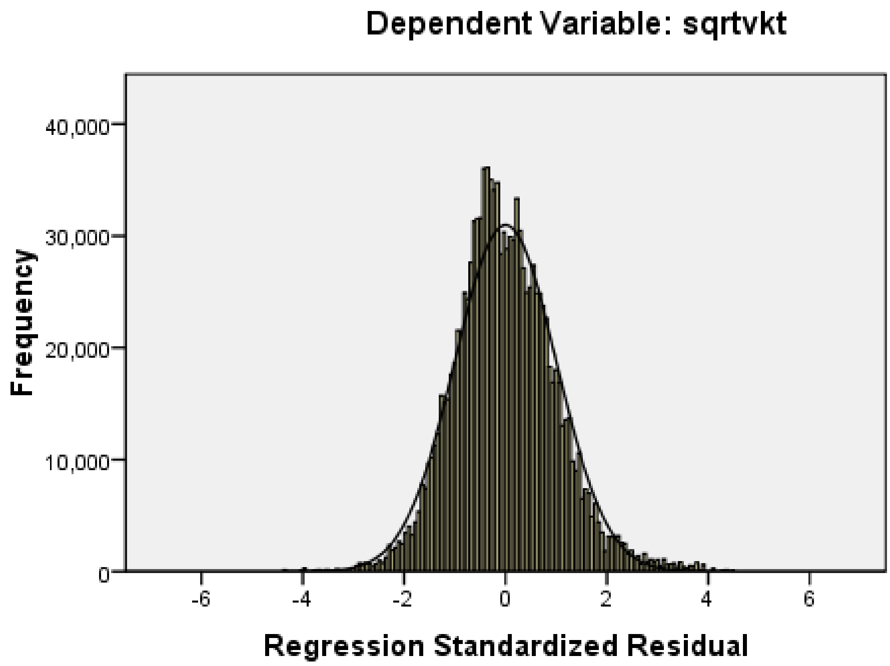


Figure 7.11: Standardized residual histogram from the household VKT model

Simplified Example: A couple with children (at least one of which is 15 or older), earning \$100,000 per annum, living in a detached house 20km from the CBD, in an area with a population density of 1000 people per square km (10 people per ha), who have opted not to stay home, and who own 2 cars, are predicted[a] to travel the following number of *vehicle* kilometres by private automobile on any given day:

$$\begin{aligned}
\sqrt{\text{vehicle km}} &= 2.574 + 0.689 + 0.006\sqrt{100000} - 0.373 \times \ln(1000) + 2 \times 1.702 + 0.044 \times 20 \\
&\approx 6.87 \\
\text{vehicle km} &\approx 47.2
\end{aligned}$$

Now, the above example is simplified by the fact that it is assumed that the number of cars owned by the household is known. But this is not the case. Instead, what we will have are only probabilities (from the car ownership model) of various levels of car ownership. For simplicity, let us assume that the car ownership model gives a 0.5% chance of the household owning 0 cars, a 10% chance of owning 1 car, a 52% of owning 2 cars, a 26% chance of owning 3 cars, and an 11.5% chance of owning 4 cars[b]. With these probabilities of car ownership, the calculation becomes:

$$\begin{aligned}
&\sqrt{\text{vehicle kilometres}} && \\
&\text{w. 0 cars (0.5\%)} &=\;& 0.0 \\
&\text{w. 1 cars (10\%)} &=\;& 2.574 + 0.689 + 0.006\sqrt{100000} - 0.373\ln(1000) + \\
& &=\;& 1 \times 1.702 + 0.044 \times 20 \approx 5.17 \\
&\text{w. 2 cars (52\%)} &=\;& 2.574 + 0.689 + 0.006\sqrt{100000} - 0.373\ln(1000) + \\
& &=\;& 2 \times 1.702 + 0.044 \times 20 \approx 6.87 \\
&\text{w. 3 cars (26\%)} &=\;& 2.574 + 0.689 + 0.006\sqrt{100000} - 0.373\ln(1000) + \\
& &=\;& 3 \times 1.702 + 0.044 \times 20 \approx 8.57 \\
&\text{w. 4 cars (11.5\%)} &=\;& 2.574 + 0.689 + 0.006\sqrt{100000} - 0.373\ln(1000) + \\
& &=\;& 4 \times 1.702 + 0.044 \times 20 \approx 10.27 \\
&\text{vehicle km per day} &\approx\;& 0.1 \times 5.17^2 + 0.52 \times 6.87^2 + 0.26 \times 8.57^2 + 0.115 \times 10.27^2 \\
& &\approx& 58.4
\end{aligned}$$

Even this example is still a simplification of the full calculation that should be performed. Using only maximum likelihood estimates from the vehicle travel model results in underestimation of household travel. Section 7.3.6 describes what must be done to obtain an unbiased estimate.

[a] Again, this is the maximum likelihood prediction only. Section 7.3.6 considers a proper treatment.

[b] These numbers are approximately right for this example household, but the chance of owning 5 or more cars is assumed to be 0% for simplicity.

7.3.4 Travel by public transport

The constraints imposed when working with the HTS data meant that a majority of available resources were devoted to developing the more important VKT model described. A less complete model for travel by public transport (representing only 13% of trips) is a consequence of this.

The essential feature of the model I will now develop is that public transport travel is assumed to be a substitute for car travel – a replacement for the travel that the household would have undertaken if they had had access to a car. Typically, the substition is not 1-for-1. The strength of the substitution is governed by the household's access to public transport, which is estimated using distance from the CBD and local area population density as proxy indicators. I assume that total travel *demand* is given by the distance that a household would travel (as estimated by the VKT model already described) *if they had full car ownership*. Full car ownership is assumed to be one car per adult over eighteen, and half a car for adults between sixteen and eighteen[14]. For car ownership levels below this, I assume public transport travel partially substitutes for the gap between total travel demand (i.e. estimated VKT with full car ownership) and actual travel demand (i.e. estimated VKT with actual car ownership). Public transport is thus proportional to the product of the estimated public transport mode split for that household, and the difference between the total travel demand and that taken with the lower level of car ownership. For example, if a couple household would have travelled U km with two cars (i.e. 'full' car ownership), and are estimated to travel C km with one car, and are projected to have an 80/20 car/transit mode split, that household is assumed to travel $\alpha \times 0.2 \times (U - C)$ kilometres on public transport, where α is a constant of proportionality calculated across all households so as to make sure that summing individual household passenger kilometres matches published aggregate figures for Sydney. A value for α is determined in the next section, but first a simple mode-split model is required. This is estimated using one of the data sets analyzed in Rickwood and Glazebrook (2009) – aggregate mode share for the journey-to-work at the travel zone level for travel zones in the Sydney basin. Note that although using journey-to-work data will result in higher mode shares for public transport, this is corrected later by scaling the results back (with parameter α) so that overall public transport travel matches Sydney aggregates (see next section for details). The aggregate mode share model used is:

$$e^{\text{mode share}} = 2.2236 - 0.0678 \ln(\text{popdensity}) + 0.0106 \times \text{distcbd}$$

This model has an r^2 of 0.59 when calibrated using travel survey data aggregated at the Travel Zone level from Rickwood and Glazebrook (2009). Residuals for the model are normally distributed (see Figure 7.12), and it brings in the two main proxy variables (distance from CBD and population density).

It must be admitted that the model for public transport use developed in this section involves some speculation. It may help the reader appreciate the nature of the public transport model to show an example of its output. To this end, Figure 7.13 shows the per-capita public-transport energy consumption (which is proportional to passenger-kilometres) estimated by the public transport model for the 'baseline' scenario developed in the next chapter.

[14]The exact composition of individual households is not known, but average composition is known, and these averages are used instead.

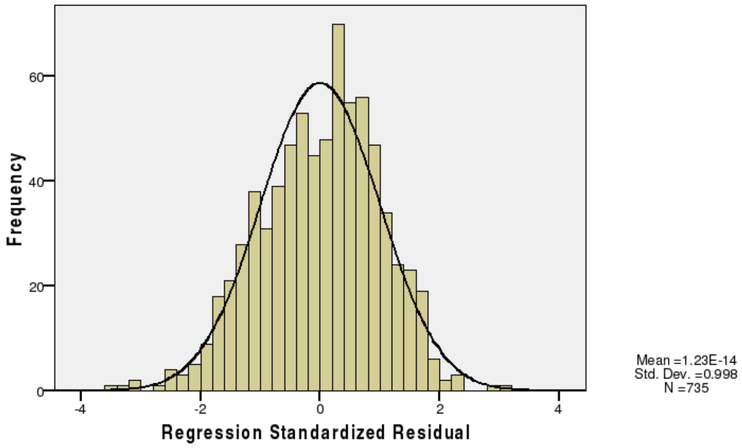


Figure 7.12: Residuals for the simple mode-split model employed, when applied to data from ABS 2006 journey-to-work data.

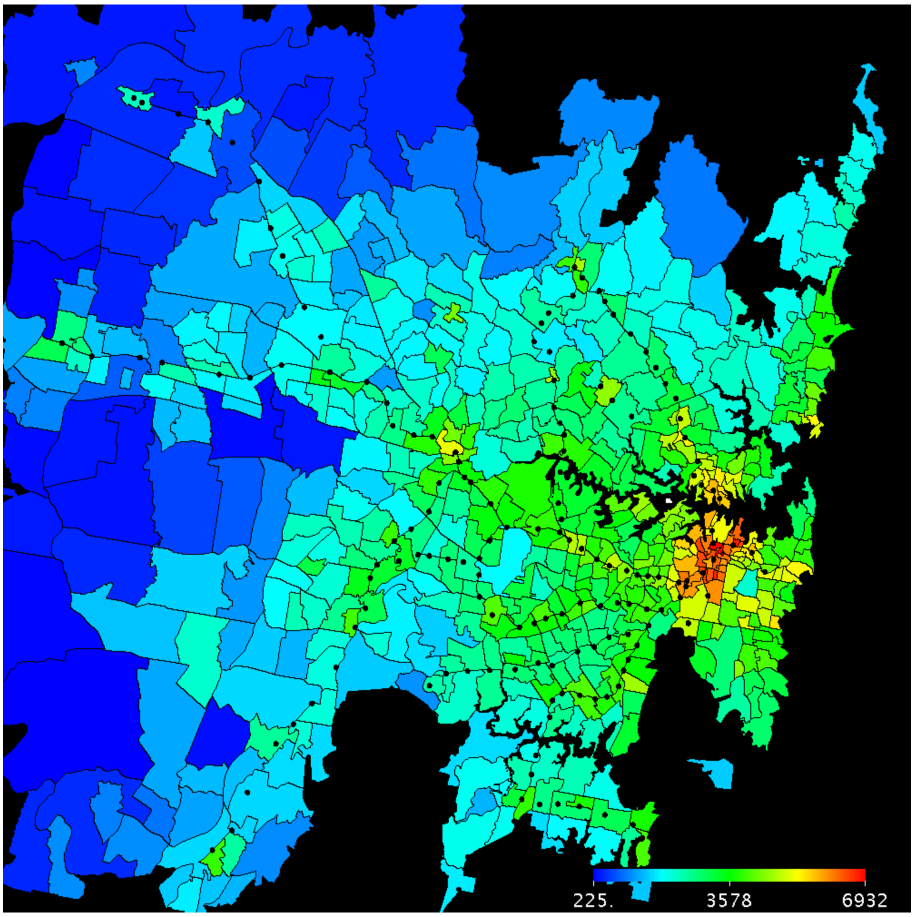


Figure 7.13: Public-transport related energy use (MJ/annum) per person in 2031, by zone, for baseline scenario.

7.3.5 Final adjustments to match 2006 aggregates

The models described in Sections 7.3.1-7.3.4, when applied to population data for Sydney from the 2006 Census, allow the calculation of city-wide estimates for average car ownership, and average daily travel by car. These values are then checked against the most recent city-wide estimates for Sydney (Transport Data Centre, 2008), and adjustment factors are applied to the models so that the model aggregate values match those reported in Transport Data Centre (2008).

In addition to calculating correction factors to ensure consistency with the recently published data in Transport Data Centre (2008), there is still the matter of calculating a value for the parameter (α) in the public transport model. The value of α required to make the public transport model agree with published data is 2.4. This gives public transport a 13% share of total passenger kilometres in Sydney, in line with that reported in Transport Data Centre (2008) for the 2006 year[15]. Remember that the 'substitution model' used for public transport is of the form passkm $= \alpha m u$, where m is the mode share of public transport for the journey to work and u is the unsatisfied travel demand (i.e. the additional distance the household would have travelled with full car ownership). Taking the city-wide average for m of 0.25, and assuming average vehicle occupancy of 1.5, this means that each passenger-kilometre of unmet vehicle travel is substituted by $\frac{0.25\times2.4}{1.5} = 0.4$ passenger kilometres of travel on public transport. This suggests that, in total, lack of access to a vehicle still results in significant reductions in total passenger-km of travel, as only a fraction of the travel 'suppressed' due to lack of access to a vehicle is replaced by travel on public transport. This is consistent with other published research (Gliebe and Koppelman, 2002).

After the final adjustments described above, I am now at the point where I have available a travel model that has been calibrated on the best travel data-set available for any Australian city, describes trends at the households level that are both believable and consistent with other published research, and also matches city-wide aggregate statistics published in Transport Data Centre (2008). Section 7.3.6 illustrates how the travel model is used to estimate travel for individual households. Later in the chapter, Section 7.5 shows model outputs for some example households.

7.3.6 Obtaining an estimate of annual household transport energy use

It may not be clear to the reader how the car ownership and travel models presented in the preceding sections can be combined to produce an estimate of household transport energy use. This section shows, by example, how this is done. This mostly consists of straightforward calculations, such as multiplying vehicle kilometres travelled by estimates of per-kilometre vehicle energy use. Not all calculations, however, are of this straightforward kind. In particular, the calculations shown in the examples in previous sections are simplified. The examples all show the calculation of maximum likelihood estimates of travel, but using maximum likelihood estimates alone will result in the systematic *underestimation* of household travel. The clearest way of showing this, and of showing how the preceding models can be combined to produce an estimate of household

[15]In fact, that source only reports easily calculable share of passenger-km for the average week-day, where public transport has around 16% of all passenger-km, but working backwards from other reported figures allows one to calculate that on an average day (including weekends), public transport carries between 12 and 13 percent of all passenger kilometres. The higher end of this range is taken due to an increase in public transport patronage since 2006.

transport energy use, is to develop a running example. I will use an example household to show how the models are used to produce an estimate of transport energy use for that household. It should be clear from this example how the calculations would be made for any household. The running example is developed in a series of framed boxes in this section, with interleaved commentary and discussion taking place outside of those framed boxes.

Example: We wish to calculate the annual transport energy used by a couple with children (at least one of which is 15 or older), earning $100,000 per annum, living in a detached house 20km from the CBD, in an area with a population density of 1000 people per square km (10 people per ha).

The first step is to obtain an estimate of car-ownership for this family. While the car-ownership model calculates probabilities of different levels of car ownership from 0 to 9 or more, I will truncate this estimate at 4 or more, just to keep the example manageable. The full range is used in the actual calculations for the scenarios evaluated in Chapter 9.

Car-ownership: The car-ownership probabilities for the example family have already been calculated in the previous section; They are:

$$
\begin{aligned}
P(0 \text{ cars}) &= 0.5\% \\
P(1 \text{ cars}) &= 10\% \\
P(2 \text{ cars}) &= 52\% \\
P(3 \text{ cars}) &= 26\% \\
P(4 \text{ cars}) &= 11.5\% \\
P(5 \text{ or more cars}) &= 0\% \qquad \text{(Set to 0 to simplify example))}
\end{aligned}
$$

Once car ownership probabilities are estimated, the annual household transport energy for each of the possibilities must be estimated. In the above case, for example, we need to estimate household energy for the four cases with non-zero probabilities. Those four estimates are then combined (weighted by probability) to produce an overall estimate. So, if, for example, E_i is the transport energy used by the example household in the case where it owns i cars, the general estimate for the household would be $0.005E_0 + 0.1E_1 + 0.52E_2 + 0.26E_3 + 0.115E_4$. To prevent the example becoming too complex, I will proceed to develop the example only for the case where the household has two cars (with probability 52%). The calculations for the other cases should be obvious given this example. The only case that would require different treatment is the case where the household owned no cars, where the no-car public transport model would need to be used, as shown in the overall model structure (Figure 7.9). With this noted, I will proceed with the example, confined to the case where the household possesses two cars.

After car ownership is determined, the next step is to calculate the probability that the household stays home (i.e. makes no trips).

Trip/No-trip: The household is a couple with older children, earning \$100,000 per annum, living in a detached house and owning two cars[a]. Applying the trip model (Table 7.5), we get:

$$\begin{aligned} P(\text{no trip}) &= \frac{1}{1+e^{2.399+0.046+0.004\sqrt{100000}-0.509+2\times 0.663}} \\ &= 0.01 \\ \therefore P(\text{trip}) &= 0.99 \end{aligned}$$

[a]Other factors, such as distance from the CBD, and local area population density, are not relevant for the trip model

In the case where the household makes no trip, the transport energy for that day is clearly zero. The case where the household does make a trip requires more work. This requires the use of the 'Household VKT model' (Table 7.6). However, the simplified example accompanying that model cannot be used to obtain an unbiased estimate of household vehicle travel. This is because the target variable is actually the square root of the actual variable of interest (vehicle kilometres travelled), and, because of this transformation, the maximum likelihood estimate for vehicle kilometres travelled will be different from the expected mean value, which is what is actually required. To get some idea of how much difference this can make, consider a household that has a maximum likelihood estimate for vehicle km travelled of 36 km (i.e. the estimate for $\sqrt{\text{vehicle km travelled}}$ produced by the model is 6). The standard error of the underlying estimate (for $\sqrt{\text{vehicle km travelled}}$) is 3.08, which makes the mean value for vehicle kilometres travelled[16] approximately 45, significantly higher than the maximum likelihood value of 36. To distinguish the maximum likelihood estimate from the mean estimate, I will use $\bar{V}$ in the remainder of this section to represent the expected mean value for vehicle kilometres travelled.

[16]Calculated by evaluating $\lim_{K\to\infty}\sum_{i=1}^{K}\frac{\max(X,0)^2}{K}$, where X is a random variable drawn from $N(6, 3.08)$ (a normal distribution with mean 6 and variance 3.08). Note that in this calculation, X can be negative, which clearly does not make sense for the variable of interest ($\sqrt{\text{vehicle km travelled}}$), so values are restricted to being non-negative. In any case, the unrestricted limit ($\lim_{K\to\infty}\sum_{i=1}^{K}\frac{X^2}{K}$) is usually very close to the restricted limit, as indicated by the histogram of residuals shown in Figure 7.11.

The maximum likelihood estimate for $\sqrt{\text{vehicle km travelled}}$ can be calculated for the example household (with 2 cars) using the parameters reported in Table 7.6. This, in fact, has already been done for the example household in question (see framed box in Section 7.3.3), and so we know that the maximum likelihood estimate is 6.87. Calculating the expected mean value, $\bar{V}$, by evaluating $\lim_{K\to\infty}\sum_{i=1}^{K}\frac{\max(X,0)^2}{K}$ $\quad (X \sim N(6.87, 3.08))$ (see main-text discussion), we get:

$$\bar{V} \approx 56.4$$

Note this estimate is around 10 km per day higher than the squared maximum likelihood estimate, which highlights the importance of doing the full calculation. After applying adjustment factors (see discussion in Section 7.3.5) this becomes an adjusted figure of 71.6 km.

Now, multiplying by 365 gives us an annual estimate of vehicle kilometres travelled of 26134. Multiplying this by the estimate of 4.6 MJ/vehicle-km (determined in Section 8.4.1) gives us an estimate of $26134 \times 4.6 = 120216$. The example household is thus estimated to use 120216 MJ of primary energy per annum for private vehicular travel.

Since we have an estimate of energy used in travel by automobile, all that remains is to estimate the energy used by the household for public transport. This is done using the method described in Section 7.3.4.

The example household is a couple household with older children. Full car ownership for this household type is assumed to be three cars[a], and, with this level of car ownership the household would drive the following number of vehicle kilometres:

$$\begin{aligned}
\sqrt{\text{vehicle km}} &= 2.574 + 0.689 + 0.006\sqrt{100000} - 0.373 \times \ln(1000) + 3 \times 1.702 + 0.044 \times 20 \\
&= 8.57 \\
\text{vehicle km} &\approx 73.4 \\
\text{and } \bar{V} &= 105.4 \text{ after adjustment}
\end{aligned}$$

So, with full car ownership, the household would travel 105.4 km per day, but at present (i.e. with 2 cars), it travels only 71.6 km per day. This means there is a suppressed demand for 33.8 km of travel, and this is partly taken up through use of public transport. The extent to which it is taken up depends on how readily substitutable public transport is for car travel. This is assumed to be proportional to the percentage of work journeys from the households location that are made by public transport, as estimated by the equation laid out in the preceding section on public transport – see equation 7.3 in Section 7.3.4. In this case, the equation yields:

$$\begin{aligned}
e^{\text{jtw car mode share}} &= 2.2236 - 0.0678\ln(\text{popdensity}) + 0.0106 \times \text{distcbd} \\
e^{\text{jtw car mode share}} &= 2.2236 - 0.0678\ln(1000) + 0.0106 \times 20 \\
e^{\text{jtw car mode share}} &= 1.97 \\
\text{jtw car mode share} &= 0.68 \\
\therefore \text{jtw public transport mode share} &= 0.32
\end{aligned}$$

So, the 33.8 km of 'suppressed' vehicle travel is assumed to be replaced by $0.32\alpha \times 33.8$ passenger-km of travel on transit, where α is a fixed constant chosen so that public transport travel matches household average figures published in Transport Data Centre (2008). The value for α required for this has been calculated at 2.4 (refer back to the Section 7.3.5 on final adjustments). Thus, each kilometre of suppressed vehicle travel is substituted with $0.32 \times 2.4 = 0.77$ kilometres of travel on public transport, for a total of 26 passenger-km. Multiplying this by 365 to get annual travel distance, and then by 1.4 (the estimate used in this thesis for MJ/passenger-km, see Section 8.4.1 in the next chapter) gives a total of $26 \times 365 \times 1.4 = 13286$ MJ of energy used on public transport.

[a] This is an average figure for this household type, but will be too high or too low for individual households. The number of cars required for 'full' ownership for the other household types are as follows: Single person 1; Couple 2; Couple with young children 2; Couple with older children 3; Single parent $1\frac{1}{3}$; Other 2.7.

Having estimated the annual energy used by the example household on both private and public transport, we now need to add them, and then adjust for days where the family makes no trips.

Energy used in private vehicle travel:	120216 MJ/year
Energy used in public transport travel:	13286 MJ/year
Sub-total:	133502 MJ/year
Adjusting for no-trip days:	$133502 \times 0.99 = 132167$ MJ/year

This is the total transport energy estimate for this household, but *only* for the case where the household owns two cars. To obtain the full estimate, the entire process must be repeated for other levels of car ownership, and the average of all those estimates, weighted by car-ownership probabilities, gives a final estimate for the household.
The only thing that must now be done is to estimate the embodied energy in private automobiles owned by the household. This, however, is left for Section 7.3.7.

7.3.7 Embodied energy of vehicles

I take account of the energy embodied in private automobiles simply by assuming a single value for each vehicle. I do this because I do not have the necessary data for any embodied energy model which accounts for different vehicle types. I assume a value of 210 GJ of embodied energy per vehicle, taken from Treloar et al. (2000). This includes energy embodied in the car chassis and fittings of 130 GJ, and ongoing maintenance of 4 GJ per year over the assumed life-span of 20 years[17], (calculated from attrition/scrappage figures for NSW reported in Australian Bureau of Statistics (2007b)). Indirect energy related to car registration, purchasing costs and financing are ignored. The 210 GJ figure translates to 10500 MJ per annum per vehicle. For the two car household used in the example in the previous section, this represents approximately 15% of the energy consumed through petrol.

7.4 Dwelling-related energy-use model

Dwelling related energy is comprised of in-dwelling energy use, and energy embodied in the dwelling structure.

7.4.1 In-dwelling energy

The in-dwelling energy used by a household is estimated using a simplified version of the full model presented in Section 3.3.5. The simplification is necessary because the full range of variables in that model is not available, and so a stripped-down model must be used. The basic methodology, and data used for calibration, however, are identical to that described in Section 3.3.5. The simplified model coefficients are shown in Table 7.7.

Although fewer variables are available than in the model of household energy use developed in Section 3.3.5, the simpler model shown in Table 7.7 still captures the same general trends. In particular, larger households use more energy than smaller households, but less than if energy use was proportional to household size. Or to put it another way, per capita energy use decreases with increased household size, even though overall household energy increases with increased household size. Richer households use more energy, all other things equal, and households

[17]Vehicle life, and not average ownership period, is considered the more appropriate measure.

with air-conditioners use more energy than those without. Inhabitants of apartments and semi-detached dwellings use less energy, as these dwellings are both smaller than detached houses, and additionally require less heating/cooling energy per square metre (see Chapter 3 for a fuller discussion and review of relevant literature).

	Coefficient	Standardized*	sig.
Constant	10.311	NA	< 0.001
income $(1-9)^{+}$	0.049	0.202	< 0.001
lone household	-0.375	-0.271	0.001
couple household	-0.23	-0.188	0.003
couple w. children	0.06	0.055	0.431
single parent household	-0.147	-0.088	0.078
has-air-conditioning	0.052	0.048	0.063
semi-detached	-0.104	-0.061	0.017
apartment	-0.37	-0.179	< 0.001
r^2	0.273		
dependent variable	ln(MJ energy used)		
Data Source	NSW Independent Pricing and Regulatory Tribunal (2006)		
N	1225		

Table 7.7: Regression model for energy used in private dwellings in Sydney.
* Standardized coefficients are the coefficients of the model if all variables are scaled to have mean 0 and variance 1.
+ Income is an ordinal variable ranging from 1-9. Each number represents an income range, with higher numbers indicating a higher income range.

Because the target variable in the regression is a log-transformation of the actual variable of interest, the same sort of correction needs to be applied as was the case for the household travel model (Section 7.3), only in this case, we need to correct for the fact that the target variable is log-transformed. The easiest was to explain how this is done, and to illustrate the application of the model, is with an example:

Example: A couple household, earning \$160,000 per year (placing them in the top income bracket) living in a semi-detached dwelling with air-conditioning, has a maximum likelihood estimate for in-dwelling energy consumption per annum of:

$$\begin{aligned}\ln(\text{MJ in} - \text{dwell. energy}) &= 10.311 - 0.23 + 0.049 \times 10 - 0.104 + 0.052 \\ &= 10.519 \\ \therefore \text{MJ in} - \text{dwell. energy} &= 37012\end{aligned}$$

Now, correcting for the fact that the maximum likelihood estimate will underestimate mean in-dwelling energy consumption:

$$\begin{aligned}\text{MJ in} - \text{dwell. energy (corrected)} &= \lim_{K\to\infty} \sum_{i=1}^{K} \frac{e^X}{K} \quad (X \sim N(10.519, 0.46)) \\ &= 41109\end{aligned}$$

This gives the total MJ of delivered in-dwelling energy. To convert this back to primary energy requires a conversion factor. Assuming a delivered-to-primary conversion factor for household energy use of 2.7 (the derivation of this factor is determined in Section 8.4.1), this becomes 110994 MJ of primary energy.

Air-conditioning penetration

Both the restricted regression analysis for in-dwelling energy use presented in Table 7.7, and the more comprehensive analysis in Section 3.3, found, unsurprisingly, that the presence of an air-conditioner resulted in an increase in household energy use. All households are assumed to own an air-conditioner with probability p, where p is a tunable parameter of the model that can be adjusted for different scenarios. For the baseline scenarios, 75% of households are assumed to live in a dwelling with air-conditioning installed (i.e. $p = 0.75$). This is somewhat higher than the currently observed penetration of 60% (Australian Bureau of Statistics, 2006, page 194), and allows for the projected increase in ownership of air-conditioners (see discussion in Section 3.2.1).

In-dwelling energy use in high-rise apartments

It is surprising how little is known about in-dwelling energy use in high-rise apartments. There are some suggestions (e.g. Randolph and Troy (2007, page 19)) that energy use in high-rise apartments is higher than low-rise apartments due to energy use in common areas (i.e. lighting of common foyers and corridors, lifts, etc.), and, while such a claim is certainly plausible, there is, as yet, no clear evidence. The study most often referred to as 'evidence' for increased energy use in high-rise dwellings is the study by Myors et al. (2005), but this was a descriptive study only, and did not involve any controlled analysis, which limits the inferences that can be drawn. The study on in-dwelling energy use in Section 3.3 did include a controlled analysis of three separate data sets, and suggested that energy use in apartments was significantly lower once one controlled for other factors such as inhabitant income and dwelling occupancy. However, the limited number of high-rise apartments in that study leaves open the possibility that energy use *is* significantly higher in high-rise dwellings.

In the absence of firm evidence one way or the other, I make the assumption that household energy use in high-rise dwellings is 33% greater than the energy used by the same household in a low-rise apartment. This is the calculated difference between per-dwelling energy use in low-rise apartments and per-dwelling energy use in high-rise apartments, in the re-analysis of data from Myors et al. (2005) performed in Section 3.3.5 (see Figure 3.13). While 33% is the default value used, different values are used for some of the scenarios in Chapter 9.

7.4.2 Embodied energy in buildings

In light of the review (in Section 3.2.2) of the literature on embodied energy in residential dwellings, it seems quite clear that for low to mid-rise buildings, embodied energy costs per square metre are more or less independent of dwelling type. I will assume 11.7 GJ per square metre, the average of values reported in a survey of dwellings in Sydney by Pullen et al. (2006). I also assume ongoing maintenance of 0.117 GJ per square metre (i.e. 1% of the initial embodied energy), derived from Treloar et al. (2000). High-rise apartments are considered separately, as there is good evidence that the embodied energy required per square metre is significantly higher for such dwellings (see Section 3.2.2). To account for this, high-rise dwellings are assumed to require 40% more embodied energy per square metre than other dwelling types. This estimate was obtained by reference to Treloar et al. (2001a).

Property Council of Australia (2007) reports that the average constructed detached dwelling in 1900 was 150 m^2, rising to 200 m^2 by 1950, 250 m^2 by 1990, and 325 m^2 by 2005. Instructive as this trend is, without a proper inventory of the housing stock to determine dwelling ages and demolition rates, no firm number for the mean dwelling size can be calculated. In the absence of any such reliable inventory of housing[18], I use a value of 230 m^2 for all detached dwellings[19], 160 m^2 for townhouse/terrace/semi-detached dwellings, and 130 m^2 for apartments [20], and assume a life-span of 80 years for all dwellings. It seems likely that higher-density forms should last longer than lower density forms, for several reasons, not least of which being the more complex ownership and strata-titling arrangements that tend to go with apartments. However, despite this speculation, in the absence of concrete evidence to the contrary, I assume that dwelling life is independent of dwelling type.

7.5 Profiles of representative households

In any large modelling exercise, it is easy for one to get bogged down in details. This is natural enough, especially in disaggregate modelling, where attention is required in structuring and calibrating numerous household level models. Because attention has been focused on data gathering, estimation, and validation of each such sub-model, it is useful, at this point, to step back and get a better feel for what all the sub-models tell us, in total, about several example households. In

[18] A curious blind-spot of the Australian Bureau of Statistics, which reports neither dwelling size nor age.

[19] Including garage.

[20] This is high because it assumes faster growth in attached dwelling floor space than in detached, and also includes common area construction, as gross floor area is the relevant measure for embodied energy calculations.

this section, I present results for the total household energy used by five households. This serves two purposes: firstly, it illustrates to the reader some concrete results, at the household level, of the application of household energy use models; secondly, it allows for some basic validation of the model – making sure that the sub-models, when combined, produce results for households that are generally as we expect, or at least plausibly in-line with other comparable findings. These illustrative examples do not take the place of more rigorous testing, but are a complement to it.

7.5.1 The five representative households

The five example households used are:

1. *Urban single:* A single person household earning \$50,000, living in a low-rise apartment in Randwick (7 km from CBD, near Clovelly, population density 80 people/ha).
2. *Retired middle-suburban couple:* A retired couple on the aged pension (\$25,000), living in a semi-detached dwelling in Denistone (17 km from CBD, population density 28 people/ha).
3. *Professional middle-suburban couple:* A couple earning a combined income of \$120,000, living in a semi-detached dwelling in Balgowlah (10 km from the CBD, population density 20 people/ha).
4. *Fringe young family:* A family with young children on \$70,000, living in a detached house near the south-western Sydney fringe (30 km from the CBD, population density 7 people/ha).
5. *Wealthy suburban family:* A family with older children earning \$150,000, living in a detached house in Roseville (12 km from the CBD, population density 17 people/ha).

Table 7.8 shows the collected details for the five example households[21].

	km from CBD	Population density (people/ha)	Income (\$,000)
Urban single	7	80	50
Retired middle-suburban couple	17	28	25
Professional middle-suburban couple	10	20	120
Fringe young family	30	7	70
Wealthy suburban family	12	17	150
Sydney average	19.4	27	73

Table 7.8: Details of the example households analyzed.

[21] Note that the 'Sydney average' value of 27 reported in the table below is just the city-average density for Sydney as reported in (Rickwood and Glazebrook, 2009).

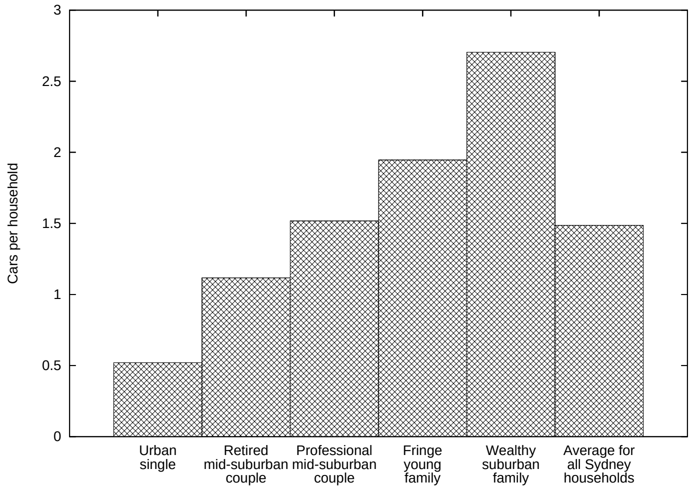


Figure 7.14: Cars per household for the example households.

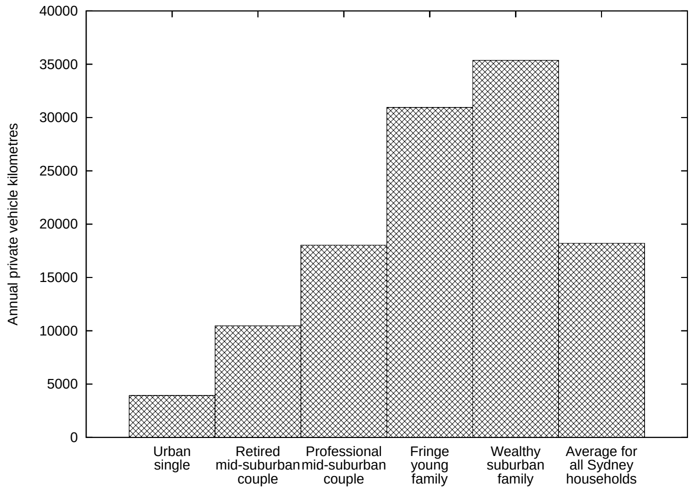


Figure 7.15: Vehicle-kilometres travelled per household for the example households.

7.5.2 Results for the representative households

Selected results are shown for the example households in Figures 7.14-7.19. Figure 7.14 shows the number of cars for each household; Figure 7.15 shows the number of (private) vehicle kilometres travelled by each household; Figure 7.16 shows total transport energy for each household (including public transport energy use); Figure 7.17 shows the in-dwelling energy use for each household; Figure 7.18 shows total energy consumption (both transport and dwelling-related, including embodied energy). Perhaps the most illuminating figure is Figure 7.19, which shows that for larger households, transport-related energy use increases relative to dwelling-related energy use. This is consistent with the observation that there are significant savings resulting from sharing for in-dwelling energy use (i.e. space heating/cooling, lighting), whereas transport energy-use is related more strongly to individual behaviour.

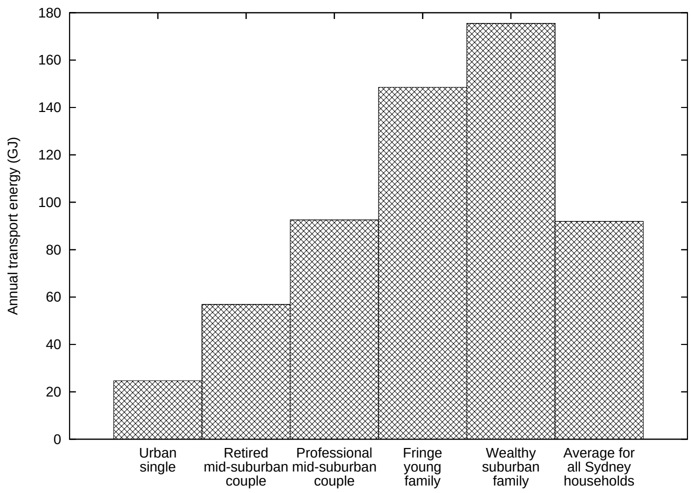


Figure 7.16: Total transport energy per household for the example households (excludes embodied).

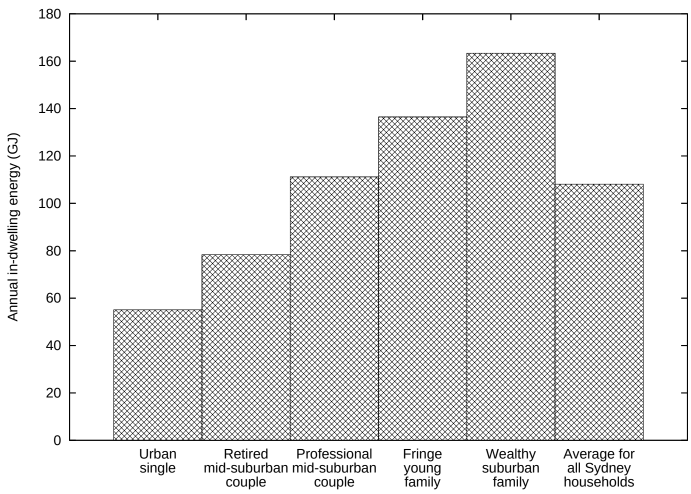


Figure 7.17: In-dwelling energy use per household for the example households.

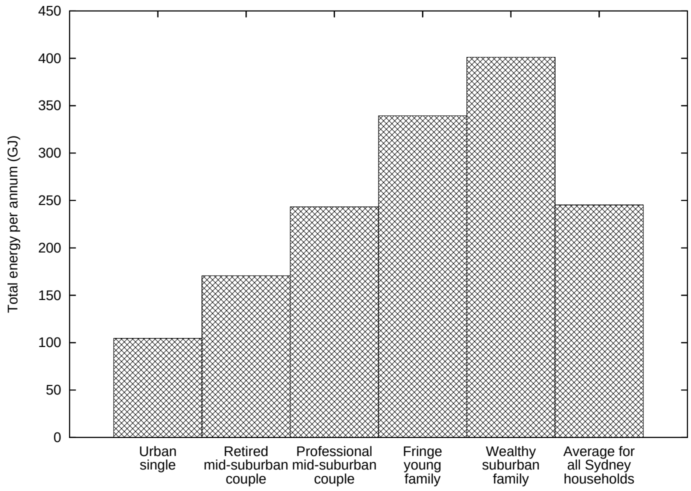


Figure 7.18: Total energy (transport and dwelling related, operational and embodied) for the example households.

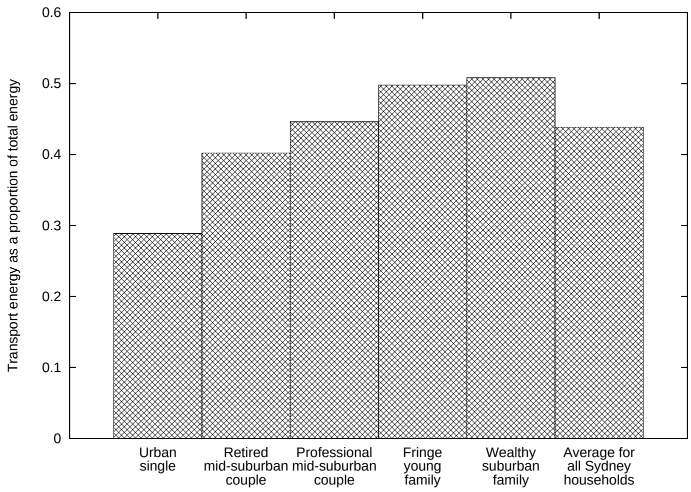


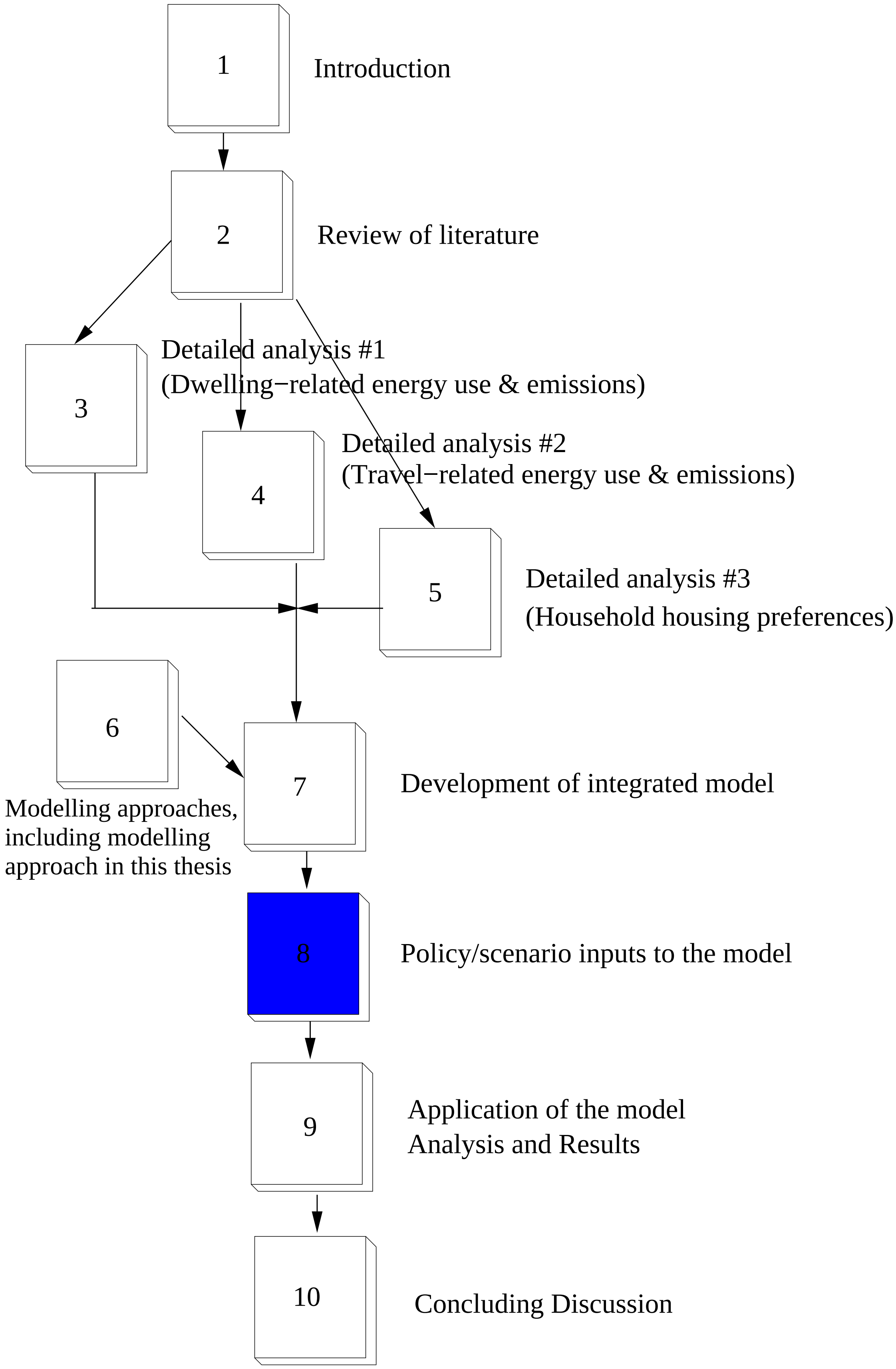
Figure 7.19: Total transport-related energy (operational and embodied) as a proportion of total energy use (transport and dwelling-related, operational and embodied) for the example households.

7.6 Chapter summary

This chapter has described in detail the model that will be used to evaluate different land use scenarios in the following chapter. In particular, this chapter has described a detailed household level travel model and a household level in-dwelling energy model, and has provided further information about how the technique developed in Chapter 5 is employed in the model. This chapter has dealt with the core model components (shown in Figure 7.1), and with the calculation of model outputs from those components, but model inputs are still not specified. This is done in the following chapter, after which the detailed modelling work is performed.

Chapter 8

Scenario Development and Model Inputs


1
Introduction
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Review of literature
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Detailed analysis #1
(Dwelling−related energy use & emissions)
4
Detailed analysis #2
(Travel−related energy use & emissions)
5
Detailed analysis #3
(Household housing preferences)
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Modelling approaches,
including modelling
approach in this thesis
7
Development of integrated model
8
Policy/scenario inputs to the model
9
Application of the model
Analysis and Results
10
Concluding Discussion

8.1 Introduction

This chapter describes the demographic and policy inputs to the microsimulation model for a 'baseline' scenario, against which all other planning scenarios will be compared. A significant amount of work has gone into making this baseline scenario consistent with the Sydney metro-strategy – the state governments long term planning strategy for Sydney (NSW Department of Planning, 2005). The main principle of the metro-strategy, from a land-use point of view, is that housing and employment should be concentrated in designated 'centres'. While most planning researchers agree that concentrating development in centres or along corridors that can be well serviced by public transport is desirable (Frey, 1999; Newman and Kenworthy, 2000; Hensher, 2003), the metro-strategy's definition of a centre is sufficiently loose that committing to concentrating development in 'centres' is less constraining than it first appears. (The exact definition of a centre will be covered in more detail in Section 8.3.) Rather worryingly, the metropolitan strategy contains almost no information on changes to transport infrastructure, limiting itself mainly to the expression of general principals and aspirations rather than committing to major changes to transport infrastructure. A more detailed description and analysis of the metro-strategy can be found in Searle (2006).

The overall model structure, which the reader has already seen in previous chapters, is reproduced here for convenience as Figure 8.1. The previous chapter dealt with the model components and model outputs; this chapter deals with the demographic and land use policy inputs for the baseline scenario, and describes how these inputs can be modified to 'generate' alternate scenarios. A few other input parameters are also specified in this chapter, such as those used to convert travel into energy use and related emissions.

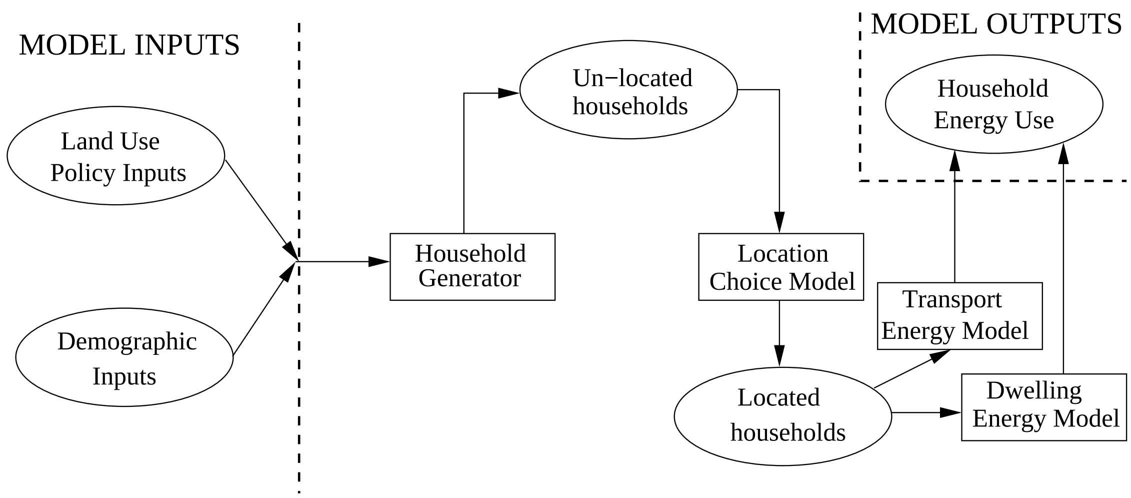


Figure 8.1: The model structure adopted for modelling in this thesis.

8.2 Demographic inputs

Households are divided into eight different household types, as defined in Table 8.1. The table contains precise definitions of each household type, but for simplicity, households will be referred to by the 'short' name given in column 1 of the table. Terminology used in the precise definition is exactly as defined in Australian Bureau of Statistics (2001).

Household Type	Definition
Young single	Single person household aged less than 55
Old single	Single person household aged 55 or over
Young couple	Couple household without children where *household reference person** is under 55
Old couple	Couple household without children where *household reference person** is 55 or over
Couple with young children	Couple household with all children aged under 15
Couple with older children	Couple household with at least one child 15 or over
Single parent	Single adult with children (all ages)
Other	All other households

Table 8.1: Household types used in modelling and analysis.
* As defined in Australian Bureau of Statistics (2001).

In order to evaluate policies in the year 2031 (the target year for all scenarios), the mix of households, and their income distributions, must be specified. Let us first consider the projected household mix for the baseline scenario, before considering income. Figure 8.2 shows the current household mix in the study area (my calculation, from 2006 census), and the household mix assumed for the base scenario in 2031. I estimate the mix of households in 2031 based on estimates from both the Sydney metropolitan strategy (NSW Department of Planning, 2005), and Series

II projections for NSW by the Australian Bureau of Statistics (Australian Bureau of Statistics, 2004a). The most remarkable trend evident is the significant increase in the proportion of lone and couple households.

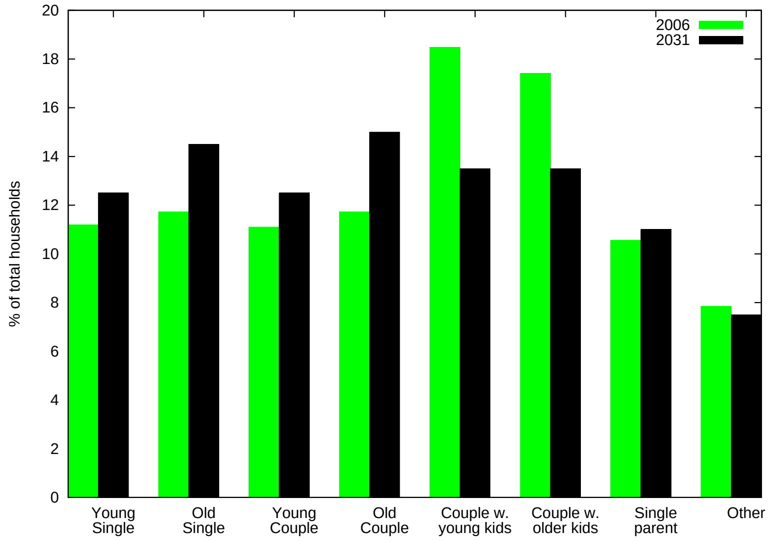


Figure 8.2: Current and projected mix of household types in the study area (2006 and 2031). 2006 figures are my estimates based on 2006 census data. 2031 figures are my estimate based on NSW Department of Planning (2005) and Australian Bureau of Statistics (2004a).

8.2.1 Household income

Household income is a key variable known to affect car ownership (see Section 7.3.1), travel behaviour (see Section 7.3.3), in-dwelling energy use (see Section 3.3.5), and residential location. Thus, for a model that aims to project household energy use in 2031, it seems that household incomes for 2031 must be projected. This is not because I am interested in household income *per se*, but because of the influence of household income on household energy use. In fact, what is *really* required is a projection of household income *and* energy prices *and* the long-run relationship between income and prices (i.e. elasticities). Given the uncertainty involved in all of these, I think it is it clear that any such projections can be little more than guesses. This is one of the reasons why my approach is to evaluate multiple scenarios, rather than trying to specify and evaluating a single 'most likely' scenario. Justifications for this scenario-based modelling approach have already been discussed in Chapter 6. Furthermore, because my interest is on concentrating on the effect of urban structure on energy use, I would prefer to keep income and price effects *out* of the modelling. The following simplifying assumption allows me to do this:

> Changes to incomes, energy prices are such that changes to income are offset by changes to prices and income/price elasticities.

This is a very convenient simplification for modelling purposes, and, although unrealistic (like all simplifying assumptions), is plausible enough for a future where energy prices are likely to rise in real terms (due to scarcity and/or carbon taxes). The most important consequences of the simplifying assumption stated above are that the coefficients estimated for the household travel (Section 7.3) and in-dwelling energy consumption (Section 7.4) modules do not need to be adjusted. This is equivalent to assuming that energy prices, real household incomes, and elasticities do not change. Because of this, fixed household income brackets can be used. They need not be adjusted for anticipated increases in real income *because* it is assumed that the effect on energy use is offset by changes to energy prices. The income brackets used for all scenarios are given in Table 8.2.

Income bracket	Weekly income (in 2006 energy dollars)
1	Less than \$650
2	\$650–\$999
3	\$1000–\$1399
4	\$1400–\$1999
5	\$2000–\$2999
6	\$3000+

Table 8.2: Household income brackets used in all scenarios

It is possible to obtain a baseline estimate for the mix of households, as I have just done (shown in Figure 8.2), by referring to other generally available estimates, but this is not the case if one wishes to project the distribution of income within each household type. I am not aware of any publicly available forecast of income distributions by household type for 2031 (or any nearby year). Most projections of income are usually limited to projecting aggregate wage growth, and other more easily estimatable measures. In the absence of widely available measures, I have produced my own estimates, shown in Figure 8.3.

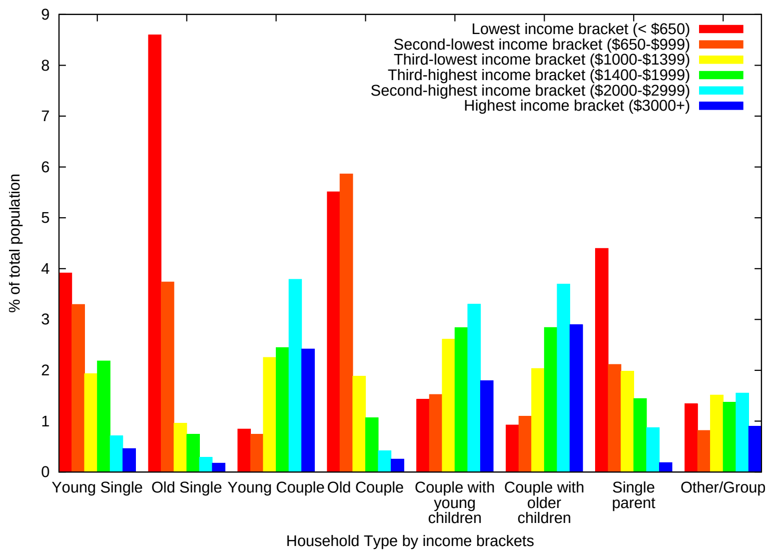


Figure 8.3: Projected household income distributions for 2031. Source: author's calculations based on ABS 2006 census tables.

A description of the precise procedure for producing the estimates shown in Figure 8.3 would be unnecessarily tedious, and serve little purpose (remember, we are only after plausible numbers), so I will eschew such a description and provide details of the general methodology only.

The precise method used is specified by the program `makeincomedistprojection.py` in the `energymodel_finalforthesis`→`utilityscripts` directory on the software CD accompanying this thesis (see Appendix A). Here is an outline of the general method:

1. Proportions by household type are already given (see Figure 8.2).
2. The distribution of income within each household type is known for 2006, and assuming this remains constant, provides an initial estimate for the distribution for each household type in 2031.
3. Adjustments are made to the initial estimate in step 2 *for older households only* (i.e. Old Single and Old Couple households), to reflect the fact that Australia's compulsory superannuation contribution scheme (an enforced savings scheme) will result in increased incomes for a significant number of older households.

The adjustment at step 3 is required because the current generation of older households rely to a great extent on the government pension for their income. In the future, Australia's compulsory retirement saving scheme should see a large number of older households providing for their own retirement incomes. While this 'self-funded pension' will, for many households, be comparable with the aged pension[1], there will be a significant number of households with retirement incomes greater than the aged pension. Given these factors, it seems reasonable to expect that there will be fewer older households on the lowest income brackets in 2031 than there were in 2006. A moderate adjustment to account for this is made: 20% of households in the lower three income brackets are moved to the next highest bracket. This adjustment does not result in income distributions greatly different from those currently observed, but it seems difficult to justify a large adjustment, for a few reasons. Firstly, while those in the 'Baby Boomer' cohort[2] currently enjoy high levels of personal wealth (and incomes, for those still in the workforce), a significant number of the wealthy 'Baby Boomer' cohort will have died by 2031, so the bulk of the older household types will be made up of non-Boomer households, who are not as wealthy. Without a large inter-generational transfer of wealth (deemed unlikely by Kelly and Harding (2004)) from the Boomers to younger generations, it seems likely that post-Boomer retirees will enjoy retirement incomes somewhat higher than the current generation of retirees, but somewhat lower than the Baby Boomers. The moderate adjustments capture this situation. Further information about the projected changes to population age structure and retirement incomes in Australia can be found in Australian Treasury (2004), with academic analysis and further references in Kelly and Harding (2004).

The main point to note about the household income distributions shown in Figure 8.3 is that the projected increase in the proportion of older households results in a significant increase in the overall proportion of households in the lowest two income brackets. This shift does not represent a decline in average wages, or anything else contentious, but instead is a natural consequence of an aging society.

[1]The Australian government makes up any shortfall between a self-funded pension and the government aged pension.

[2]Referring to those born shortly after World War 2. No definitive definition exists, but the period covering the Boomers generally begins shortly after the war and extends into the 1960s.

8.3 Housing policy inputs

Most modern microsimulation land-use models determine the demand for housing and commercial floor space endogenously, by determining the utility/profit maximizing location for each household/firm. While modelling of demand for housing and floor space is well developed, modelling of the supply response is less so. As Hunt et al. (2005) note in their review of land-use/transport models:

> Across all integrated models, housing/floor space supply models are probably the least well developed of any component of the entire modelling system.
>
> Hunt et al. (2005, page 358)

This was one reason I made no effort to include any modelling of land or housing supply, and instead specify them as user-inputs to the model. In the absence of a plausible housing supply model, I felt this was the safer option. The other reason I declined to model housing supply response, even though I do estimate housing demand (through the residential location model), is that it represents a move away from the scenario-evaluation approach. If housing supply is endogenously determined, through economic interactions, this essentially amounts to eliminating any explicit role for land-use planning. There is a tension between planners and economists on this front, with economists criticising planners for neglecting to take into account the influence of land economics, and planners criticising economists for failing to take into account the effect of planning policy. Both criticisms have some validity. Planners who assume that they can determine land-use by *fiat*, simply through the specification of various planning policies, are overly naïve – it doesn't matter if their plan calls for greater development at site X if there is insufficient demand for housing or commercial floor space at site X to cover development costs. On the other hand, economists who relegate government (in general) and planners (in particular) to a role of near complete passivity, and assume that all outcomes are determined in markets, are similarly naïve – planning restrictions *do* have an effect, and are the result of more complex political and social interactions than can be captured in an economic model. It thus seems both simpler, and safer, to allow housing supply to be an exogenous input to the model.

For the baseline scenario, I have determined housing supply by reference to the Sydney metropolitan planning strategy (NSW Department of Planning, 2005). I choose to use the metro-strategy at a base because a lot of work has already gone into the projections in the metro-strategy, and it seems silly to duplicate this work. Because the metro-strategy is referred to in order to obtain housing supply estimates for the baseline scenario, it is probably worthwhile if the reader is at least passingly familiar with the Sydney metropolitan strategy. To this end Figure 8.4 is a reproduction of one of the main figures in the metropolitan strategy document, showing the main 'centres' defined, and the important corridors, as well as other information about the transport network[3]. Figure 8.5 shows the ABS-defined statistical subdivisions of Sydney, together with the metro-strategy dwelling 'targets' for each of those regions. The major new land release areas are identified with a black border, in the North-West and South-West subdivisions. Table 8.3 shows the same information in a different format. Note that the dwelling numbers in both Figure 8.5 and Table 8.3 do not include new dwellings in the major land release areas.

[3] Already, this planned transport network is obsolete; The heavy-rail extensions to the new land release areas have been scrapped.

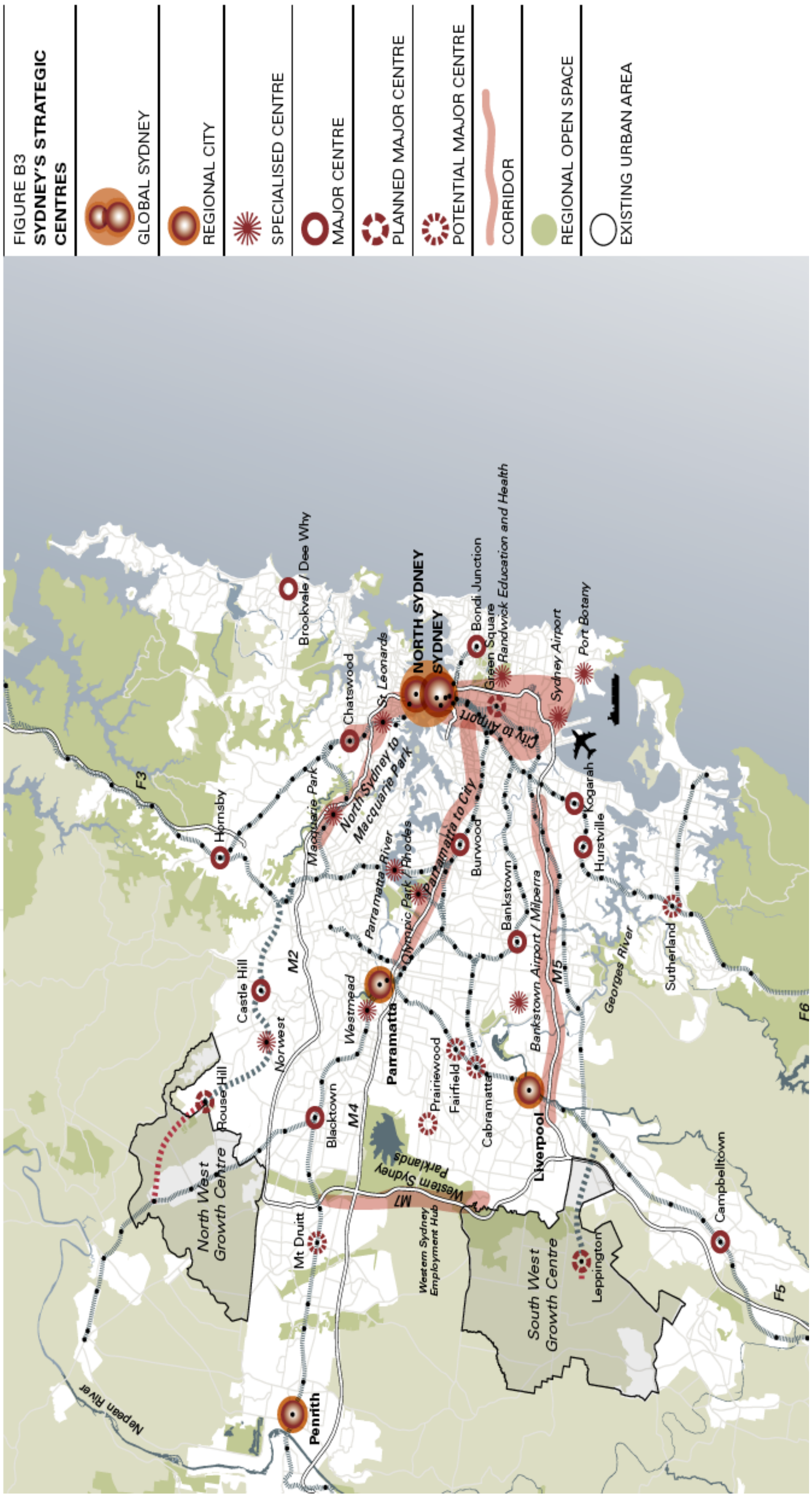


Figure 8.4: Shows the Major Centres in the Sydney Greater Metropolitan Region, which is the region under study in this thesis. From: NSW Department of Planning (2005)

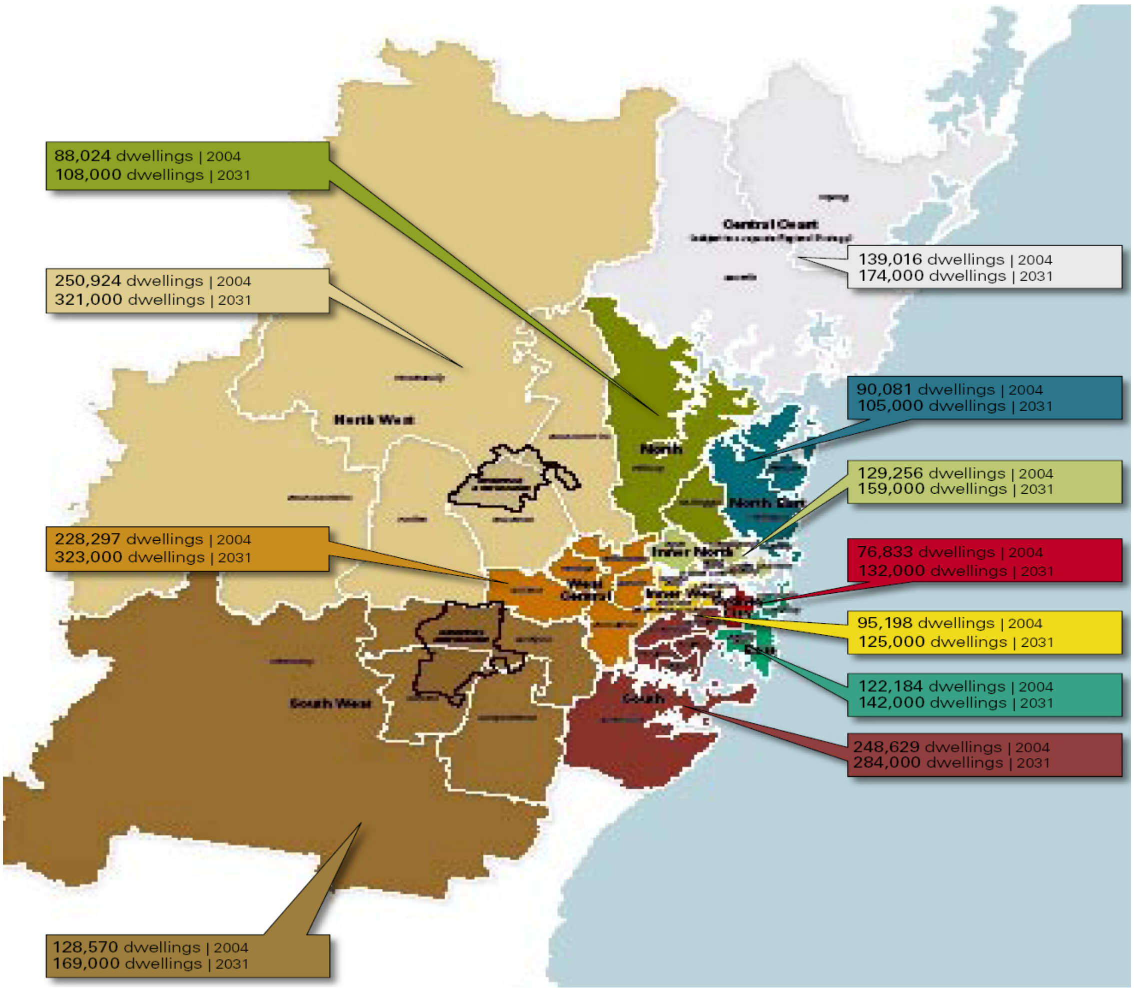


Figure 8.5: Statistical Subdivisions of Sydney, with Sydney Metrostrategy Dwelling Targets for 2031. Land release areas shown with a black border, in the North-West and South-West subdivisions.

TABLE C5 **POTENTIAL NUMBER OF DWELLINGS IN THE EXISTING URBAN AREAS OF SYDNEY'S SUBREGION**

SUBREGION	EXISTING DWELLINGS 2004	% IN 2004	ADDITIONAL DWELLINGS IN EXISTING AREAS BY 2031	TOTAL DWELLINGS IN EXISTING AREAS BY 2031	% CHANGE 2004–31
SYDNEY CITY*	76,833	5%	55,000	132,000	72%
EAST	122,184	8%	20,000	142,000	16%
SOUTH	248,629	16%	35,000	284,000	14%
INNER WEST	95,198	6%	30,000	125,000	32%
INNER NORTH	129,256	8%	30,000	159,000	23%
NORTH	88,024	6%	20,000	108,000	23%
NORTH EAST	90,081	6%	15,000	105,000	17%
WEST CENTRAL	228,297	14%	95,000	323,000	42%
NORTH WEST	250,924	16%	70,000	321,000	28%
SOUTH WEST	128,570	8%	40,000	169,000	31%
CENTRAL COAST	139,016	9%	35,000	174,000	25%
TOTAL	**1,597,012**	**100%**	**445,000**	**2,042,000**	**28%**

* THE DATA FOR CITY OF SYDNEY (INCLUDING THE FORMER SOUTH SYDNEY) IS BASED UPON AN ASSESSMENT OF THE DEVELOPMENT POTENTIAL OF SPECIFIC SITES THAT HAS BEEN UNDERTAKEN IN CONSULTATION WITH THE CITY OF SYDNEY. THE CITY OF SYDNEY LOCAL GOVERNMENT AREA IS CONSIDERED ITS OWN SUBREGION

Table 8.3: Planned additional dwellings in existing areas by 2031. From: NSW Department of Planning (2005)

It is a stated aim of the metropolitan strategy that 70% of the new dwellings provided by 2031 will be in existing urban areas, with the remaining 30% in new land release areas. Of the 70% in existing areas, 80% is intended to be provided in 'centres'. This decision to concentrate development in centres is the basis on which the metro-strategy is subtitled 'A City of Cities'. However, on closer inspection, the definition of a 'centre' is less restrictive than one might first assume, with anything from a small neighbourhood group of shops up to the CBD being classified as a 'centre'. Tables 8.4 and 8.5 show the centre types defined in a companion document to the main metro-strategy document (NSW Department of Planning, 2007).

Despite the detailed information in the metrostrategy, there is insufficient information for one to derive, directly, the dwelling targets for each of the 615 zones used in my analysis. Instead, I had to estimate dwelling numbers for each of these zones, based on:

1. the regional targets shown in Figure 8.5;
2. sub-regional targets available for *some* of the regions in Figure 8.5;
3. some assumptions about demolition rates;
4. some approximate calculations of the likely density of development in different areas, given land-economic conditions.

Apart from providing the general constraints under which the projections were made, it is not practical to specify in detail how the projections are done, as this would take up a good deal of space, and be exceedingly tedious reading. Instead, I include the source code for the program that is used to make the projections (see Appendix A). This program constitutes a

Global Sydney	The main focus for national and international business, professional services, specialised health and education precincts, specialised shops and tourism, it is also a recreation and entertainment destination for the Sydney region and has national and international significance.	Sydney City* North Sydney
Regional Cities**	With a full range of business, government, retail, cultural, entertainment and recreational activities. They are a focal point for regional transport and jobs.	Parramatta Liverpool Penrith
Specialised Centres	Areas containing major airports, ports, hospitals, universities, research and business activities that perform vital economic and employment roles across the metropolitan area. The way they interact with the rest of the city is complex and growth and change in and around them must be	Macquarie Park, St Leonards, Olympic Park/Rhodes, Port Botany, Sydney Airport, Randwick Education and Health, Westmead, Bankstown Airport/Milperra, Norwest
Major Centres**	The major shopping and business centre for the surrounding area with a full scale shopping mall, council offices, taller office and residential buildings, central community facilities and a minimum of 8,000 jobs.	Bankstown, Blacktown, Bondi Junction, Brookvale/Dee Why, Burwood, Campbelltown, Castle Hill, Chatswood, Hornsby, Hurstville, Kogarah

* Sydney City includes the CBD, Sydney Education and Health Precinct, Pyrmont/Ultimo, Kings Cross, the NSW State cultural institutions, the Walsh Bay cultural precinct and the St Vincent's/Darlinghurst Health Precinct.

** Outside the Sydney Metropolitan Area, Wollongong is the regional city for the Illawarra and Newcastle is the regional city for the Lower Hunter. Gosford is the regional city for the Central Coast and Tuggerah is a Major Centre on the Central Coast. Separate but related strategies will guide growth and change in these three regions within the Greater Metropolitan Region; however, Gosford and Tuggerah's employment capacity targets and housing capacity targets are incorporated into the Metropolitan Strategy.

Table 8.4: Main (large) centre types in the Sydney metro-strategy

Type	Definition
Town Centre	**A town centre** is a larger group of shops and services with one or two supermarkets, sometimes a small shopping mall, some community facilities such as a local library, a medical centre and a variety of specialist shops. Examples include Bondi, Auburn, Top Ryde and Cabramatta. Town centres have to balance activities including customer parking, service vehicles and through–traffic with making a pleasant residential and pedestrian environment. They also have to integrate malls/large stores into the main outdoor centre. The extent of a town centre is approximately an 800 metre radius which is widely accepted as a comfortable 10 minute walk.
Village	**A village** is a strip of shops for daily shopping and typically includes a small supermarket, butcher, hairdresser, restaurants and take away food shops. Examples include Bronte, Granville and Oatley. Villages need to develop an enjoyable public environment with a mix of uses and good physical links with the surrounding neighbourhood. The extent of a village centre is approximately a 400–600 metre radius.
Neighbourhood Centre	**A neighbourhood centre** is a small group of shops that you can walk to and buy milk and the newspaper. Examples are any street with a corner shop. Neighbourhood centres as well as other larger centres, should have a public transport focal point to link it with other centres. Many of these exist but new centres may be possible if transport services improve. Neighbourhood centres should have child care centres, schools and other compatible activities located close together and have some medium density housing, mainly townhouses and villas in the immediate area to add vitality, safety and create a sense of place. The extent of a neighbourhood centre is approximately a 200 metre radius.
Enterprise Corridor	**Enterprise corridors** are the areas immediately along and generally up to a block back from our busiest roads. These corridors recognise the important economic role that the mix of commercial, retail and light industrial activities perform along these busy roads, including servicing the local community. They also often provide lower rent locations for niche retail and office or retail space for start up enterprises. Residential development is often pursued in these corridors to take advantage of lower land costs. This should only occur however where the noise and air quality impact of the road can be minimised and good quality, high amenity residential dwellings created.

Table 8.5: Minor (small) centre types in the Sydney metro-strategy

complete specification of the calculation method employed, and can be found in the file called `generate2031vectors.py` on the CD-ROM attached to the thesis.

The result of the dwelling projection procedure is that the number, and type, of new dwellings is determined for each of the 615 zones used in my analysis, for the year 2031. They are determined such that:

1. no neighbourhood changes too much (except special cases);
2. all sub-regional and local government area targets are met, to within 10%, or 1000 dwellings (whichever is greater);
3. the city-wide dwelling mix for 2031 is plausible (determined by showing the estimates to one of the main architects of the Sydney metro-strategy, Pat Fensham);
4. the proportion of new dwellings in different centre types is comparable to the targets specified in the metropolitan strategy (see Figure 8.6); and
5. the dwelling-type mix projected for 2031 is in-line with metro-strategy estimates (determined by consultants Pat Fensham and Rod Simpson, both of whom had major roles in the Sydney metro-strategy). Figure 8.7 shows the projected dwelling-type mix.

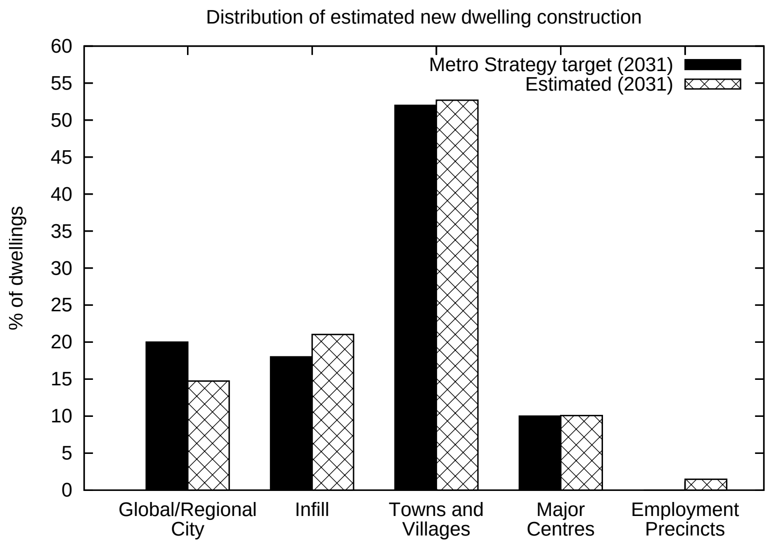


Figure 8.6: New infill dwelling construction by neighbourhood classification (2006 to 2031). Compares the proportions projected in the Sydney metro-strategy (NSW Department of Planning, 2005), versus those estimated by the author.

The number of new dwellings (irrespective of dwelling type), projected to be built in existing areas for the baseline scenario, based on the Sydney metro-strategy, is shown in Figure 8.8, expressed as new dwellings per hectare.

In addition to (re)development of the existing urban area (i.e. infill development), the metropolitan strategy designated two new land release areas, and specifies dwelling targets for each of those areas. The land release areas are shown in Figure 8.9. These do not match exactly with the land

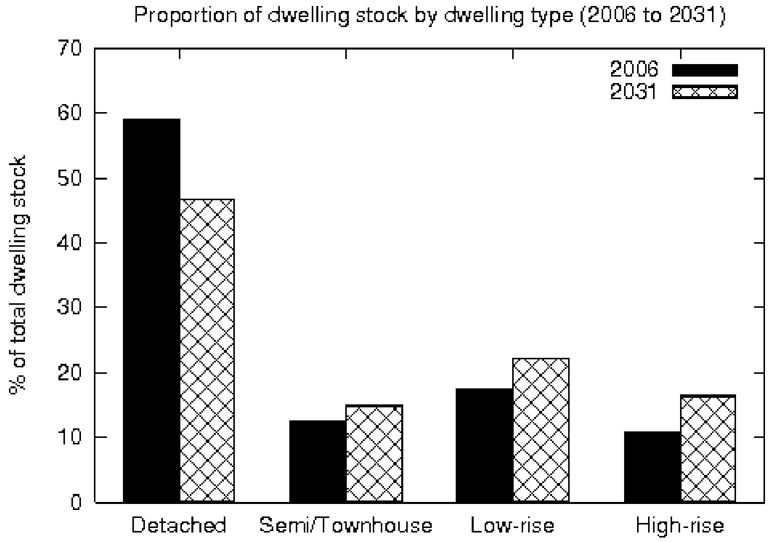


Figure 8.7: Proportion of dwellings of each type in both 2006 (from ABS Census data) and projected for 2031 (author's calculations). Note: This is projected total dwelling stock, including existing dwellings, new land release dwellings, and infill (re)development.

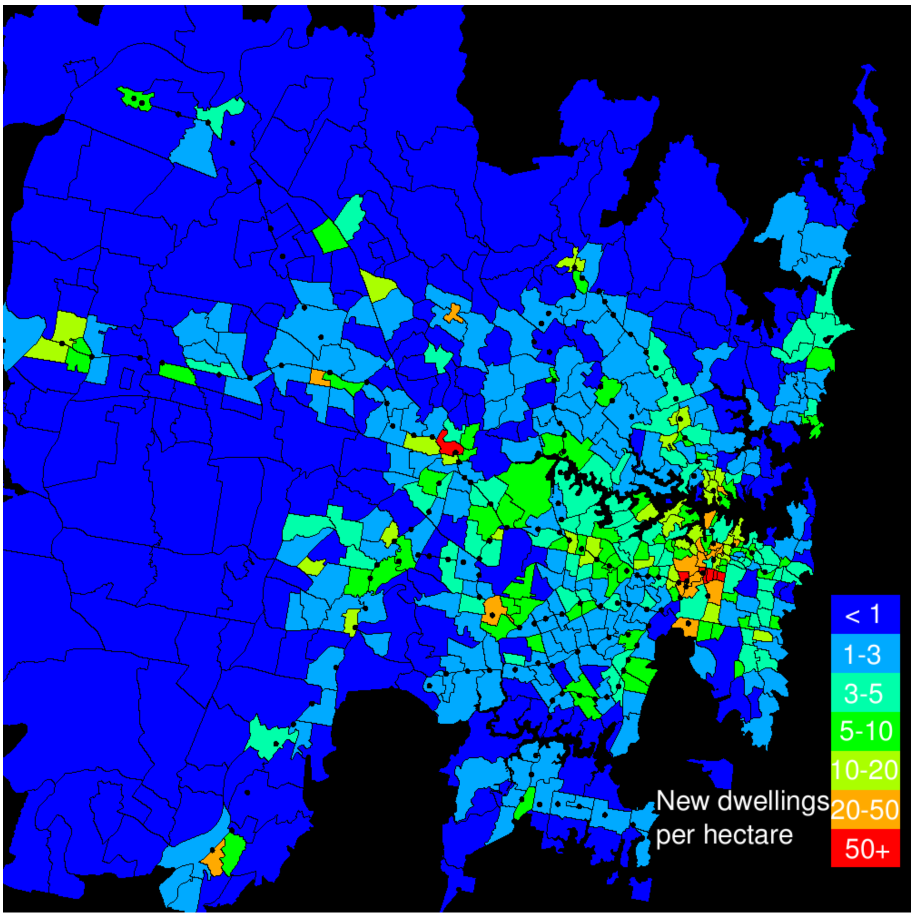


Figure 8.8: Projected new infill development in Sydney, from 2006 to 2031.

release areas specified in the metro-strategy, because the zones used for analysis in the modelling do not allow this.

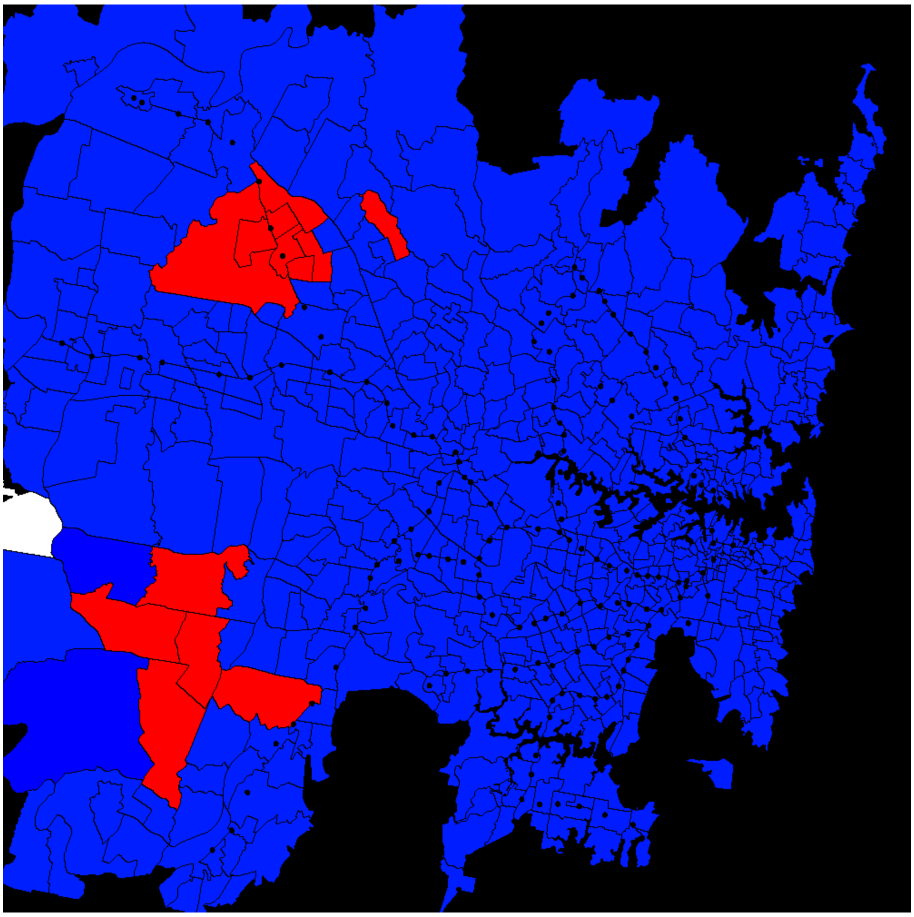


Figure 8.9: Designated zones for new fringe development.

8.4 Other inputs & conversion parameters

8.4.1 Primary energy conversion factors

The travel model outlined in Section 7.3 calculates the number of kilometres driven by each household, and the number of passenger-kilometres travelled on public transport, but to convert these into transport-related energy or greenhouse-emissions requires the specification of conversion factors. Similarly, while the in-dwelling energy model described in Section 7.4 gives an estimate of the 'delivered' energy used by each household, this needs to be converted back to in-ground primary energy and greenhouse-emissions related to this primary energy.

Tables 8.6 and 8.7 show the conversion factors used in this thesis. Sections 8.4.2-8.4.4 (following) describe briefly how each of these numbers was derived.

	conversion factor
MJ primary in-ground energy per MJ in-home energy	2.7
MJ primary in-ground energy per vehicle-km	4.6
MJ primary in-ground energy per passenger-km on public-transport	1.4

Table 8.6: Primary energy conversion factors

	conversion factor
greenhouse gases per MJ in-home energy	175 grams
greenhouse gases per vehicle-km by private vehicle	260 grams
greenhouse gases per passenger-km on public transport	95 grams

Table 8.7: Greenhouse gas conversion factors

8.4.2 How were the in-dwelling energy conversion factors derived?

In-dwelling delivered energy use is assumed to be comprised of 60% electricity and 40% gas. This is the ratio estimated nationally by Australian Bureau of Statistics (2006). A survey of the Sydney region reported values implying a 53.6%/46.4% electricity/gas split (NSW Independent Pricing and Regulatory Tribunal, 2006), but sampling error and the effects of a non-random sample could explain the difference. Historically, gas availability has been greater in Victoria and Queensland, due to large reservoirs in those states, so one would not expect proportionally higher gas use in the Sydney region, and this is another reason to prefer the national figure.

Extraction cost conversion factors are used for each energy fuel source to take account of the energy used to extract that fuel source from the ground and transport it to the site of consumption (see Section 1.4 for a full explanation). The extraction cost conversion factor for coal is 1.2 (Treloar et al., 2001b), and 1.3 for gas (Harrington and Foster, 1999).

Taking power station generation efficiency of 35% and station power use and transmission losses of 7.4%, as reported in Australian Greenhouse Office (2007, pages 18-19)[4] results in a coal-to-electricity conversion factor of $1.2 \times \frac{1}{0.35} \times \frac{1}{1-0.074} = 3.7$ (delivered to the dwelling).

[4] I assume principally black-coal fired power (most common in NSW). Values for gas-fired stations are similar.

Given that each MJ of in-dwelling delivered electricity requires 3.7 MJ of primary energy, and each MJ of in-dwelling delivered gas requires 1.3 MJ of primary energy, and assuming a 60/40% electricity/gas split, we can calculate that each MJ of in-dwelling delivered energy equates to $0.6 \times 3.7 + 0.4 \times 1.3 = 2.7$ MJ of primary energy.

The greenhouse-gas conversion factors are obtained in a similar fashion by using values of 85 grams of greenhouse emissions per MJ of primary coal energy (Australian Greenhouse Office, 2007, page 15), and 51.3 grams of emissions per MJ of primary gas energy (Australian Greenhouse Office, 2007, page 15). Note, however, that due to difficulties in obtaining reliable estimates for extraction-process-related emissions, the greenhouse emissions figures do *not* include extraction-related emissions. In other words, the greenhouse emissions figures reported in these results cover emissions resulting from primary fuel energy use, excluding extraction energy-related emissions.

8.4.3 How were the private vehicle travel conversion factors obtained?

Estimates for the efficiency of vehicles vary. Very detailed transport models, such as those in Hensher and Ton (2002), have detailed vehicle fleet models. With such a detailed model, one can allow for the difference in fuel efficiency of different vehicle types. In principle, the model structure developed in this thesis could include a detailed vehicle-fleet sub-model, but time and data constraints did not allow for this, and so a uniform vehicle fleet is assumed. Table 8.8 shows some estimates used in other work. I use a value of 3.8 MJ per vehicle kilometre, which is the value from the most recent study (Australian Greenhouse Office, 2007), as well as being in-line with the value reported in Kenworthy and Laube (2001), if one corrects for observed increases in private vehicle efficiency since 1995 (reported in Australian Greenhouse Office (2007, page 28)).

MJ/vehicle-km	Source	Data Region & Year
3.8	Australian Greenhouse Office (2007, page 28)	Australia (2005)
4.0	(Kenworthy and Laube, 2001)	Sydney (1995)
4.9	Glazebrook (2002b)	Sydney[5](1975/6)
4.0	Troy et al. (2003)	South Australia[6](1997/8)

Table 8.8: Various estimates of the energy cost of travel in private automobiles, from various Australian and international sources.

The value used of 3.8 MJ per vehicle-km does not include any extraction costs related to obtaining petroleum spirit from crude oil in the ground. Using a conversion factor of 1.2 (as estimated in Glazebrook (2002b)) gives a final estimate of 4.6, as reported in Table 8.6.

For greenhouse emissions, I use a value of 68.4 grams of emissions per MJ of in-vehicle petrol consumed (Australian Greenhouse Office, 2007, page 27), which equates to 260 grams per vehicle kilometre (excluding extraction-energy-related emissions).

[5]The reported value of 4.0 MJ/passenger-km has been adjusted back to MJ/vehicle-km using the quoted average occupancy figure of 1.45 in the same report (the same number as quoted in Stopher et al. (2007)). The value has also been corrected for petrol extraction and distribution energy costs, which were included in Glazebrook (2002b), but not in the other studies. This allows for a direct comparison with the other estimates which do not include those costs.

[6]Secondary Source. Primary Source is an unpublished consultant's report.

8.4.4 How were the public transport conversion factors obtained?

I assume that 66.6% of passenger kilometres in Sydney are by train (Kenworthy and Laube, 2001), with the remainder by bus (ferry and light rail are ignored). Kenworthy and Laube (2001) report values of 1.09 MJ per passenger-km for bus in Sydney, and 0.42 MJ per passenger-km by train, but this is secondary energy only. Sydney has an electrified rail system, and I use a value of 3.5 to convert secondary energy back to primary energy[7], which gives a value of 1.47 MJ of primary energy per passenger-km for rail. With extraction costs for petrol of 1.2, and 1.09 MJ per passenger-km for bus, as reported in Kenworthy and Laube (2001), we obtain a value of 1.3 MJ per passenger kilometre of bus travel (the same as reported in Glazebrook (2002b)). Combining the two (assuming a 66.6%/33.4% rail/bus passenger-km split) gives a value of 1.43 MJ of primary energy per passenger-km on public transport[8].

To convert passenger-km to greenhouse emissions, I use a value of 68.1 grams of emissions per MJ of bus secondary energy (Australian Greenhouse Office, 2007, page 27), which gives a value of 74.2 grams of primary-energy related emissions per passenger-km by bus. For rail, I use a value of 85.0 grams per MJ of rail secondary energy[9], which equates to a value of 105 grams of primary-energy related emissions per passenger-km by rail. The weighted average of rail/bus is 95 grams per passenger-km, as reported in Table 8.7.

8.4.5 Embodied energy conversion factors

Embodied energy values for cars and dwellings are already provided in Sections 7.3.7 and 7.4.2. To convert embodied energy to greenhouse emissions, I use a value of 70.0 grams of greenhouse emissions per MJ of embodied energy (from Troy et al. (2003, page 39)).

8.5 Variations to inputs for alternative scenarios

In the preceeding discussion of model inputs, I have described the inputs for the baseline scenario only. A number of other scenarios are evaluated in the following chapter. However, because many of the inputs are shared across different scenarios (for example, the demographic inputs do not change), deviations from the baseline scenario inputs are discussed along with the results for each scenario, rather than listing all such deviations for all scenarios here.

Worth mentioning here is that some of the scenarios involve additional fringe growth, and, to allow for this, I designate 'spillover' fringe growth zones, shown in Figure 8.10.

[7]This is slightly lower than the value of 3.7 derived for households in Section 8.4.2 because losses in the rail system are less, due to higher voltage, and because distribution and transmission losses occur largely within the city-rail electricity network, and so are already accounted for in the estimate in Kenworthy and Laube (2001).

[8]Ferry and light rail are ignored, but constitute such a small percentage of passenger-km in Sydney that the effect of ignoring them is negligible.

[9]Assuming electricity is the power source for rail, this is based on my calculations from data reported in Australian Greenhouse Office (2007).

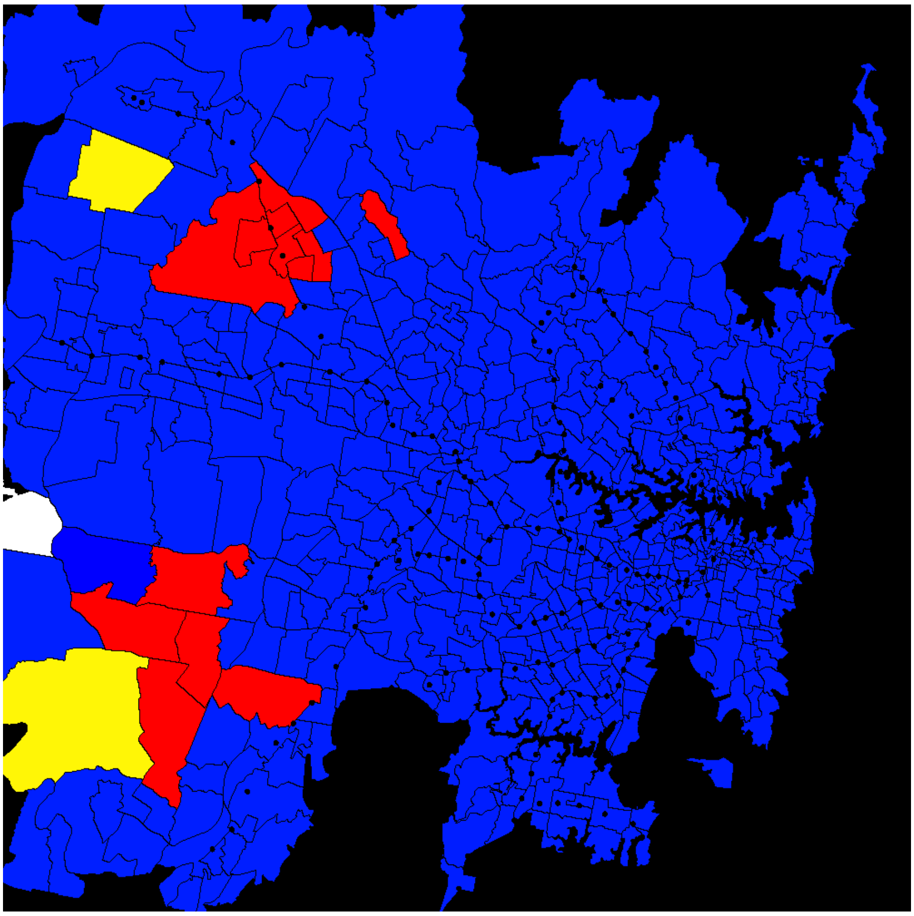
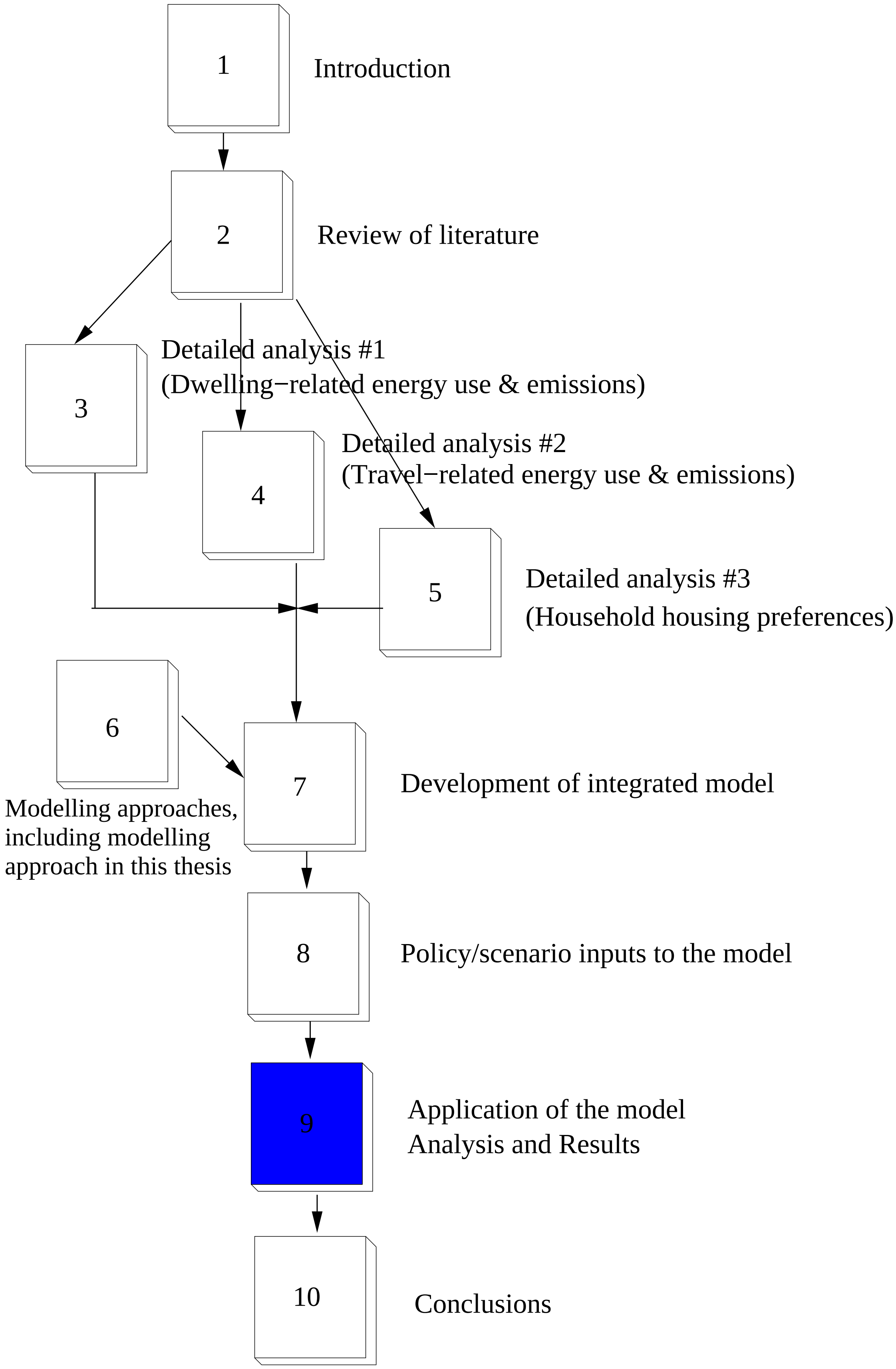


Figure 8.10: Growth centres for new fringe development, and 'spillover' regions to cater for any increase in fringe development.

Chapter 9

Integrated Modelling – Analysis and Results


1
Introduction
2
Review of literature
3
Detailed analysis #1
(Dwelling−related energy use & emissions)
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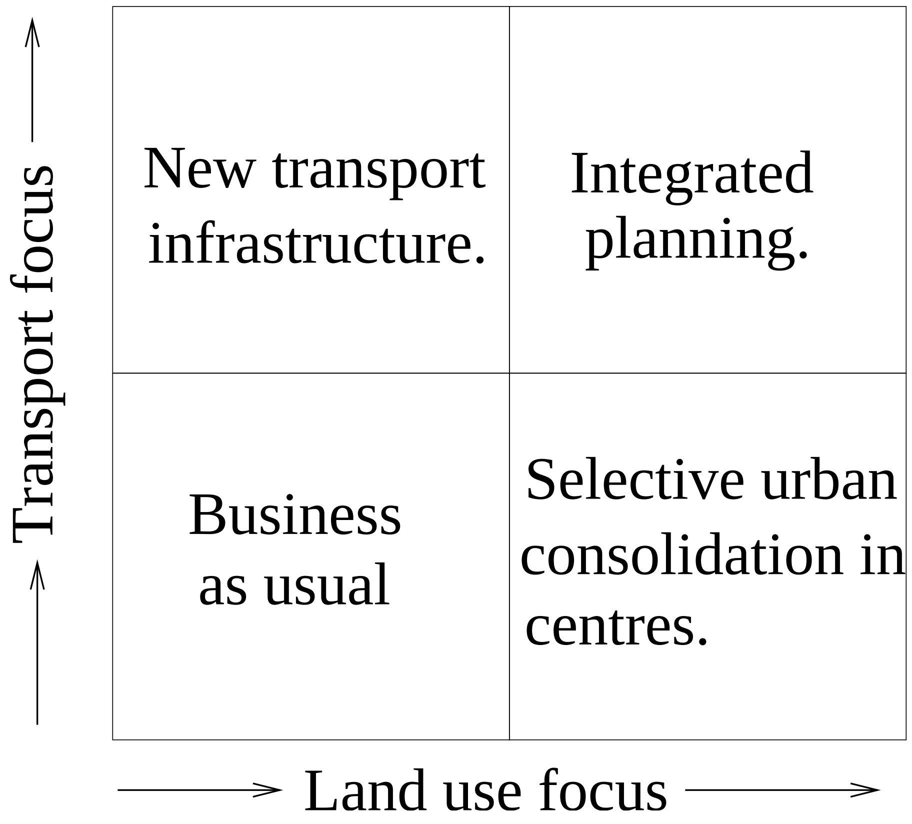


Figure 9.1: Classification of planning policies as horizontal (land-use) centric, or vertical (transport infrastructure centric).

9.1 Introduction

Chapters 7 and 8 have provided a specification of the model used for analysis of different scenarios, and its inputs. I am now in a position to employ that model to evaluate planning scenarios for Sydney. It is important to note that both the baseline scenario used (the Sydney metro-strategy), and the model used to evaluate it, are land-use centric. Referring to the planning policy classification table in Rickwood and Glazebrook (2009) (reproduced here as Figure 9.1), it should be clear to the reader that the planning scenarios evaluated in this chapter are those where the focus in on land use. Scenarios where there is an integrated planning approach cannot be evaluated using the model in its current form, but will result in more significant changes to energy use than the land-use centric scenarios evaluated in this chapter.

As one of the stated aims of the model is to assist in visualising the implications of different policy scenarios, a large number of figures are produced as part of the evaluation and analysis of each scenario. Reproducing all of these figures for each of the scenarios evaluated in this chapter is impractical (there would be hundreds), and so I will only reproduce a large number of the possible figures for the 'baseline' scenario (Section 9.2.1). In other scenarios, I will concentrate on presenting a small number of the most relevant figures which contrast the results for that scenario with the baseline scenario.

The most important limitation of the model used in this analysis is that it does not adequately capture the long-term interaction between land-use and transport. This is a limitation shared with most land-use/transport models, which assume that transport infrastructure influences land use decisions, but do not attempt to project any significant changes to transport infrastructure that result from changes to land use. In reality, increased intra-urban travel between A and B will result in improved transport between A and B. This improved transport could be in the form of additional road capacity, or more frequent bus services, express buses, or a new rail line. These general transport improvements result in city-wide changes to travel times, and so cannot be easily captured with local proxy variables (such as local-area density). In any city with even somewhat responsive transport providers, significant changes to transport infrastructure and service will occur in response to changes in land use. However, the difficulty in anticipating this response causes most land-use/transport modellers to ignore the land-use→transport interaction and consider only the transport→land-use interaction, with transport infrastructure viewed as largely static. This decision is understandable, given that:

1. Transport infrastructure provision decisions are usually made by governments or government-regulated transport bodies, and so do not fit nicely into disaggregate microsimulation models that concentrate on modelling small-scale interactions; and

2. The political nature of large transport infrastructure decisions made by governments or their bodies makes them inherently unpredictable[1].

It is for these reasons that monopolistic government bodies are left out of most microsimulation models. However, regardless of the difficulties, it is unsatisfactory to ignore, completely, land-use→transport feedback; and yet, given the difficulties just mentioned, there is no clear avenue for modelling this feedback. I resolve this dilemma by dividing the scenarios evaluated in this chapter into two Sections (9.2 and 9.3). Section 9.2 takes the usual modelling approach of largely ignoring land-use→transport feedback, while in Section 9.3, I attempt to apply a simple correction to allow for land-use→transport feedback. While the correction applied to the scenarios in Section 9.3 is necessarily simple, this is preferable to reporting results only for the case where the land-use→transport feedback is ignored.

9.1.1 Other metropolitan-scale estimates of the impact of land use on energy use

Before commencing to apply the model to different land-use scenarios, it is worth briefly reviewing some other work that has used simpler methods to estimate the possible effect of land-use policy on energy use. There is very little research on the effect of land use policy on in-dwelling energy use, so most of the work discussed below relates only to transport energy consumption.

Breheny (1995) makes some rudimentary calculations to estimate the effects of long-term planning policy on transport energy. The methods used are very simple, but the results are nonetheless illuminating. Breheny first takes the *lowest* transport energy (in MJ per capita) consumption observed in a number of U.K cities & regions, and calculates that this is 34% lower than the national average. Assuming the cities with the lowest transport energy represent relatively 'well-planned'

[1] Recent developments in Sydney serve as sobering examples, with the last few years seeing the announcement, and subsequent cancellation, of over half-a-dozen major rail infrastructure projects alone.

cities, Breheny suggests that, as a very rough estimate, the best that one can reasonably hope for through planning policy is a 34% reduction in transport energy use. Breheny uses only average energy consumption figures for each region, and so does not control for inter-region differences in income or household structure. However, it is worth noting that the difference between inner and outer London per-capita transport energy consumption is 23%, with lower consumption in denser inner-London, despite higher incomes in inner-London.

Breheny next goes on to point out that inter-city differences in urban structure take many decades (even centuries) to evolve, and given the 'inertia' this gives to each city, claims that changes to planning policy will have an actual effect lower than the 34% initial estimate. Breheny suggests 10 to 15 percent. Given this, Breheny asks:

> If the 'lowest rate' approach would give gains of 34 per cent, it is likely that any more realistic intervention – of, for example, the kinds being proposed by the advocates of the compact city – would yield gains well below this .... Would advocates of the compact city be so forceful if they knew that the likely gains from their proposals might be a modest 10 or 15 per cent energy saving achieved only after many years, and unprecedentedly tough policies?
>
> Breheny (1995, page 95)

While Breheny's point about the 'inertia' of a city's urban structure is valid, it is worthwhile pointing out that changes to land-use, while slow to achieve, have very long-lasting effects. Breheny's analysis is static, and based on summary average statistics only. Breheny's 'optimistic' estimate of the effect of compaction policies (a 34% reduction) is broadly in-line with the inter-city regression analyses by Ewing et al. (2002) and Bento et al. (2003), both of which estimate that there would be a 25% reduction in per-capita vehicle kilometres travelled by moving the same household from a sprawling city (such as Atlanta), to a more compact one (such as Boston). Another recent analysis of 66 U.S. metropolitan areas estimates a slightly smaller independent effect of $\approx 17.5\%$ (Glaeser and Kahn, 2008). This suggests that, within the currently observable range of urban structures in cities in the United States, there is the potential for a 15-25% reduction in transport energy use achievable through changes to urban form and transport infrastructure. This is not to say that there could not be further decreases, unless one takes the marginal view that cities such as Boston represent some not-to-be-improved-upon ideal. It does however, suggest that even quite drastic changes in urban form are unlikely to result in more than a 25% decrease in transport energy use. Such drastic changes are, for many cities, unachievable, even over the span of a few decades, because of the 'inertia' of each city. Even with the most draconian planning policies, for example, Atlanta could not be transformed into a city even resembling Boston in the space of a few decades (Bertaud, 2003).

An alternative method in estimating the potential impact of planning policies is to treat Newman and Kenworthy's graphs of density versus transport energy consumption as a reliable predictor of the expected change in transport energy consumption from an increase in density. Fitting an exponential function through the data in Newman and Kenworthy (1999), for example, suggests that transport-related emissions decrease by 1.9% for each unit increase in density (measured in people per hectare)[2] – see Figure 9.2.

[2]Newman and Kenworthy did not report fitted data results in Newman and Kenworthy (1999). I have fitted a

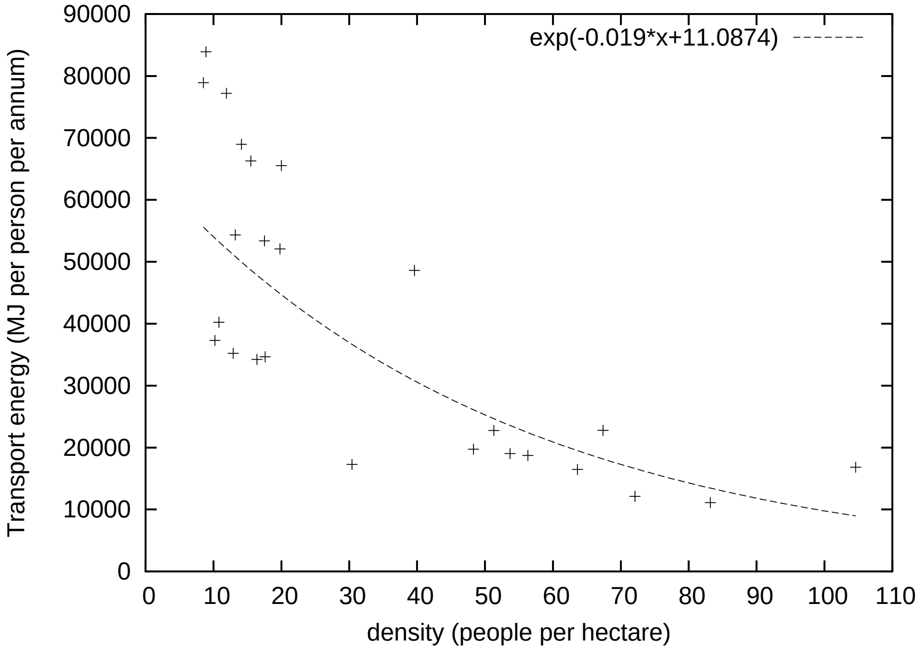


Figure 9.2: Exponential fit of density and transport energy use data in Newman and Kenworthy (1999), suggesting a 1.9% decrease per unit increase in density.

Assuming that a city's transport energy decreases by 1.9% for each unit increase in density, we can calculate the effect of different containment policies. For a city like Sydney, for example, with a population density of around twenty people per hectare[3], if Sydney grew by 33% in population terms[4], and *all* future suburban growth in Sydney occurred in the existing urban area, we could project that Sydney's density would rise to ≈ 26.7 people/ha, with a corresponding 12.7% decrease in transport emissions. This is not to say that larger decreases are not possible with a policy shift towards investment in public transport, merely that in the absence of major policy shifts, one might expect an 12.7% decrease in transport energy use, based on a simple feedback model derived from Newman and Kenworthy's data (Newman and Kenworthy, 1999).

The empirical research suggests that, absent fundamental economic or policy changes, realistic expectations for the effect of planning policy in reducing transport emissions should be in the range 0-35%, with changes over a span of 20-30 years from non-draconian policies more likely to be in the lower half of this range. This is a 'business as usual' estimate – it is possible that coordinated approaches could do better. We would expect, for example, a better result from greatly increased spending on public transport infrastructure, together with selected urban consolidation of residents and jobs, road pricing, and support for car-share schemes. However, it is the 'business as usual' situation with which I concern myself in this thesis, as more defensible estimates can be provided for this case.

line of the form ln(transportenergy) $= a \times$ density $+ b$ to the data in that publication, with Hong Kong excluded. Values for a and b are -0.019 and 11.09, respectively.

[3] Newman and Kenworthy (1999) report Sydney's density as 17.6 people per hectare, but there is no point being precise here, given the age of the estimates in Newman and Kenworthy (1999).

[4] This is the projected increase from 2006 to 2031, the period of interest in this thesis.

I will now present results obtained by applying the integrated urban model (described in Chapters 7 and 8) to various planning scenarios for the city of Sydney. Because of the limitations of the model, I am limited principally to considering only the effect of different housing policies (i.e. the location and type of housing provided), although some of the later scenarios (see Sections 9.4.1-9.4.5) evaluate the effect of other changes, such as an increase to petrol prices and changes to vehicle and appliance energy efficiency.

The reader should note that *all* scenarios cover the period 2006-2031. That is, the final projections in each case are for the year 2031, assuming the policy described by that scenario is followed.

The reader should also take the results for housing preferences in each scenario with a grain of salt. As discussed in more detail in Section 5.9, there are some significant limitations to the housing choice model that should make readers wary of attempts to form firm conclusions about housing satisfaction or dwelling-type preference. In particular, the household preference model used considers most household types to have a strong preference for detached dwelling types, but this may not be the case, for two reasons: firstly, preferences may change over time (something not allowed for in the model); secondly, the preference may not be for detached housing per-se, but instead for neighbourhood qualities currently correlated with detached housing. Please see Chapter 5, and especially Sections 5.6 and 5.9, for a broader discussion.

9.2 Scenarios *without* land-use/transport feedback

The supporting analyses of travel behaviour (Chapter 4) suggest that while characteristics of the local area make a difference to travel behaviour, city-wide factors also make a big difference. For example, the regression analysis of journey-to-work mode choice in Section 4.2.4 suggests that a household living in Sydney is far more likely to travel to work by public transport than a household in (say) Brisbane, *even given identical local area characteristics*. One reason for this difference is that Sydney has a more extensive public transport system, and so, even if the two households enjoy comparable local area public transport services (in terms of frequency), there are fewer destinations reachable (in reasonable time) by public transport in Brisbane, due to the less extensive network. Considering this along with other city-wide factors (such as employment distributions) it is easy to see that, without a detailed city-wide transport model, local area characteristics can only provide partial information about likely travel behaviour. Just as there are clear city-wide differences between Sydney and Brisbane that affect travel behaviour, there are likely to be important differences between planning scenarios for Sydney that are not captured by the travel model developed for this thesis, which relies on proxy variables. One housing land-use scenario, for example, may support extensions and improvements to the public transport network better than another scenario, but this cannot be properly captured by the transport model I use, which does not include any explicit representation of transport networks. The essential limitation is that transport is treated in a passive way. Transport can take on a much more dynamic role in the development and reorganization of cities, but I do not attempt to evaluate such transport-led reorganization. In Section 9.3 (following this section), I re-evaluate the scenarios presented in this section, but with a 'correction' applied to take account of possible land-use→transport feedback.

9.2.1 Scenario 1: baseline

The baseline scenario is based heavily on the Sydney metropolitan strategy (NSW Department of Planning, 2005), and represents a plausible future scenario against which other results for other scenarios are compared.

The model projects that for the baseline scenario in 2031, households will consume, on average, 217 GJ of primary energy per annum, resulting in 13.7 tonnes of greenhouse emissions. The per-capita figures are 91 GJ and 5.8 tonnes. Although the per-household figure represents an 11.4% reduction in per-household total energy use (compared with 2006), this is largely in-line with the projected 10% decrease in household size (from 2.65 to 2.38), so per-capita energy use and greenhouse emissions are largely unchanged. Note that the baseline scenario assumes that both technology and household behaviour are unchanged – these figures do not assume substantial changes to vehicle or appliance efficiency, or to electricity generation technologies. Although these assumptions are unrealistic, they are made because I wish to focus on the effect of urban structure, and holding them constant in this way will better allow this.

I generate *many* results/figures for this baseline scenario in the following sections. I do this for two reasons; firstly, I wish to give the reader an idea of the sorts of measures/figures produced by the model; and secondly, given the baseline scenario is used as a reference point against which results for other scenarios are compared, it is important that the reader is familiar with the baseline results. It is impractical to show such a large number of figures for all other scenarios, so only a few key indicators are shown in scenarios other than the baseline one.

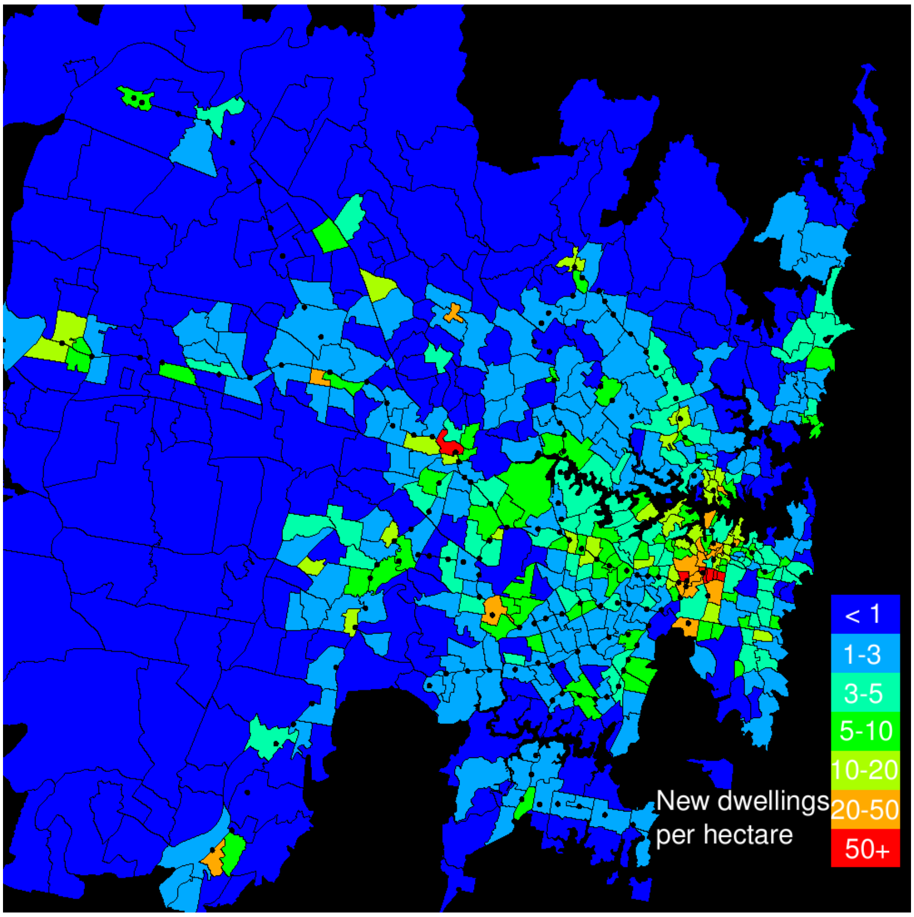


Figure 9.3: New dwellings built per hectare, 2006 to 2031.

Built-environment indicators

The baseline scenario is based on the Sydney metropolitan strategy (NSW Department of Planning, 2005). The general principles underlying the strategy are that development should take place in 'centres' and key 'corridors'. Figure 9.3 shows that a significant amount of new development takes place through redevelopment of the industrial land just south of the CBD, but there is also a great deal of development in other centres such as Parramatta, Bankstown, Dee Why, and Homebush Bay. Of all infill development, only 20% takes place in traditional suburban areas not designated as centres, and the natural consequence of this is that much of the new housing provided will be in the form of higher density dwelling forms such as townhouses and apartments. Figure 9.4 shows the dwelling proportions in 2006 compared to those projected in 2031 for the baseline scenario. Notice the significant increase in the share of higher density dwellings.

Figure 9.5 shows that high-rise apartments are concentrated in those inner-city areas and old industrial areas just south of the CBD expected to undergo significant redevelopment in the coming years. The western centre of Parramatta is the only other area with a majority of housing in the form of high-rise apartments.

Figure 9.6 shows the anticipated change to local area population density between 2006 and

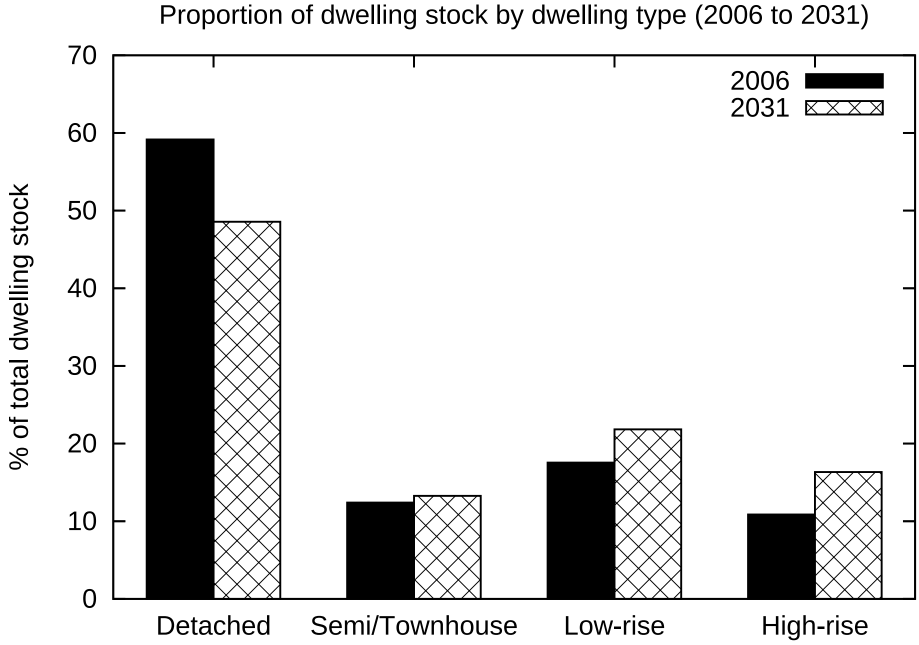


Figure 9.4: Proportion of total dwellings by dwelling type, 2006 and 2031.

2031 in the baseline scenario.

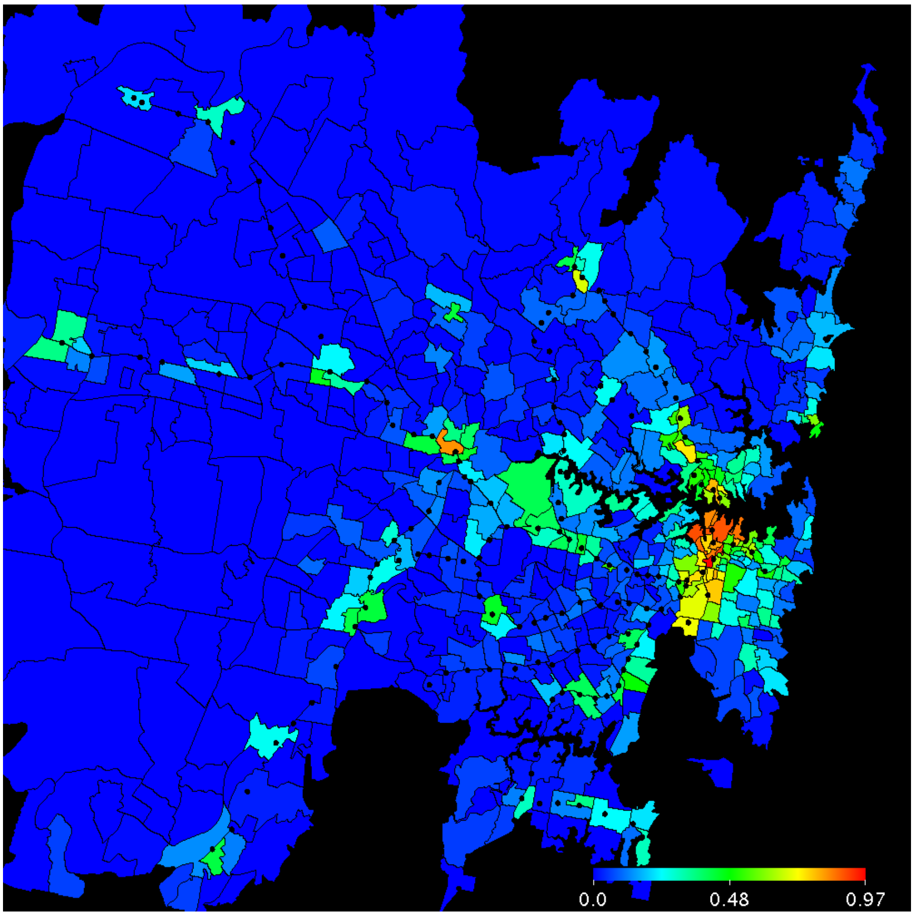
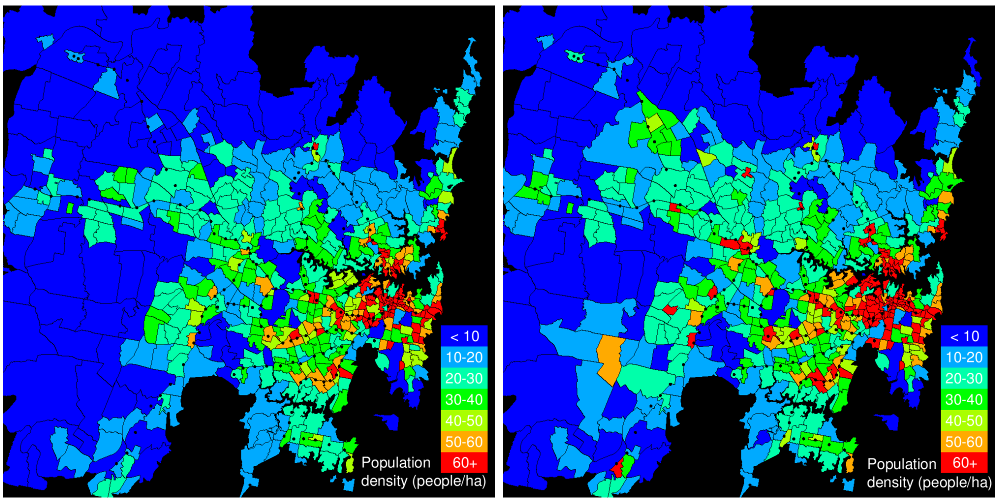


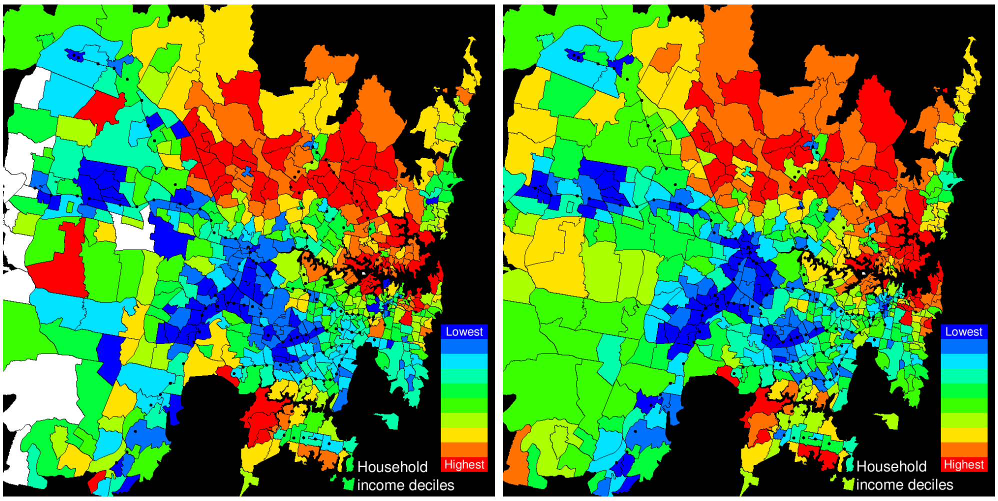
Figure 9.5: Proportion of total dwellings that will be high-rise apartments, by zone.



(a) 2006

(b) 2031

Figure 9.6: Population density in 2006 (from ABS data) and 2031 (projected for baseline scenario).



(a) 2001 (b) 2031

Figure 9.7: Household income deciles in 2001 (from ABS data) and 2031 (projected for baseline scenario).

Demographic and economic indicators

Because the integrated urban model developed for this thesis includes a residential location sub-model, a variety of rich spatial demographic outputs are possible. Figures 9.7 and 9.8 are good examples, showing spatial variation in per-household and per-capita income.

Figure 9.9 shows the spatial variation in satisfaction with housing (calculated as described in Section 5.8). Unsurprisingly, housing satisfaction is lowest in far-western and south-western suburbs of Sydney, traditionally home to Sydney's less affluent households, and areas where unemployment and crime are relatively high (see Bureau of Crime Statistics and Research (2007, 2008)). Satisfaction levels are a good indicator of housing supply constraints, because satisfaction levels near 1.0 (i.e. 100%) imply that other households would like to locate in those areas, but are unable to, as they are outbid by wealthier households for the limited number of dwellings available.

Figure 9.10 shows the projected satisfaction levels (for the baseline scenario) of each of the eight different household types. Housing satisfaction can be further broken down by income bracket within household types, but I do not include any additional figures showing this.

Figures 9.11-9.14 show the anticipated distribution and concentration of each of the eight household types. Just as Figures 9.7 and 9.8 indicate significant income-segregation, Figures 9.11-9.14 indicate significant segregation based on household type. Figure 9.14 contains the starkest illustrations, with single-parent families concentrated around Liverpool (south-west) and Mount-Druitt (west of Parramatta), and 'Other' households concentrated in inner areas with good accessibility. For the reader's interest, Figure 9.15 shows the distribution and concentration of households with children in 2031 for the baseline scenario, and the currently observed distribution. Though outside the scope of this thesis, it would be possible, and interesting, to conduct detailed analysis of the segregation resulting from different housing scenarios.

Figure 9.16 shows the projected number of people per household in the baseline scenario in

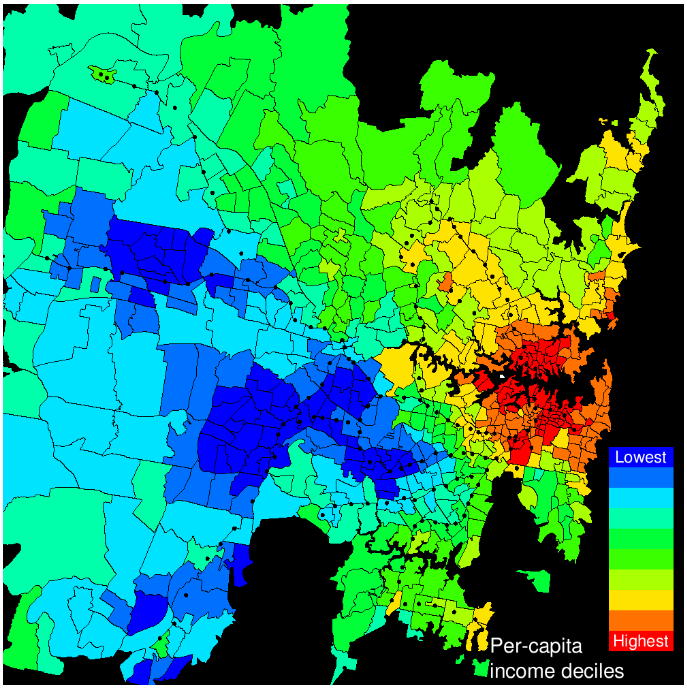


Figure 9.8: Per-capita income deciles in 2031 (projected for baseline scenario).

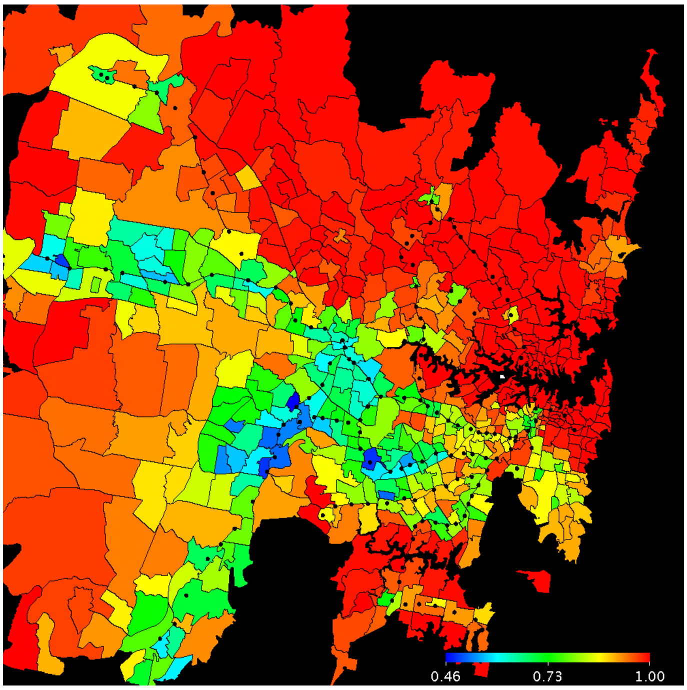


Figure 9.9: Housing satisfaction. Values less than 1.0 indicate that households live in that area not because they choose to, but because they have been displaced from their preferred choice by wealthier households.

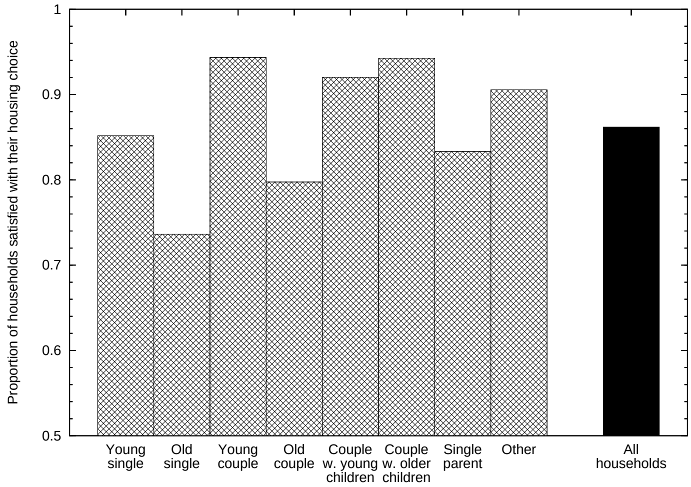
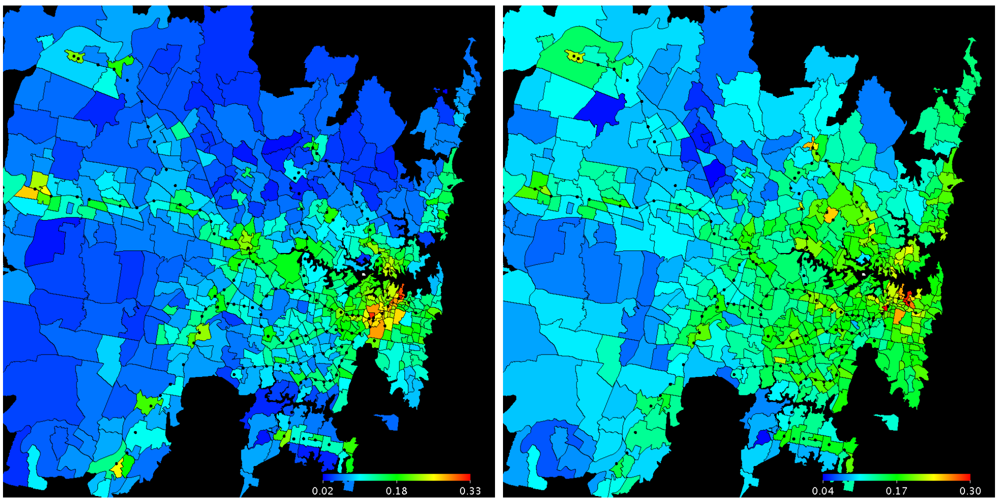


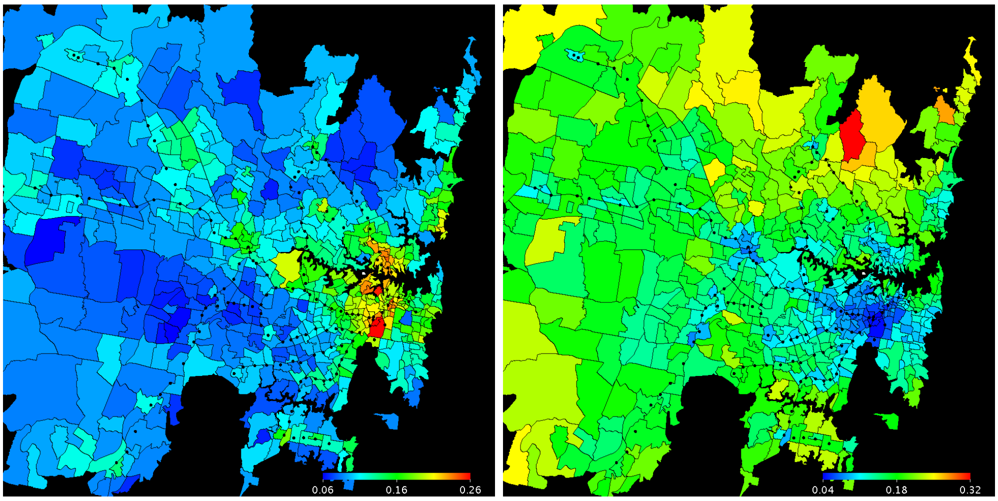
Figure 9.10: Proportion of households satisfied with their housing choice in baseline scenario. Note truncated scale.



(a) Young singles

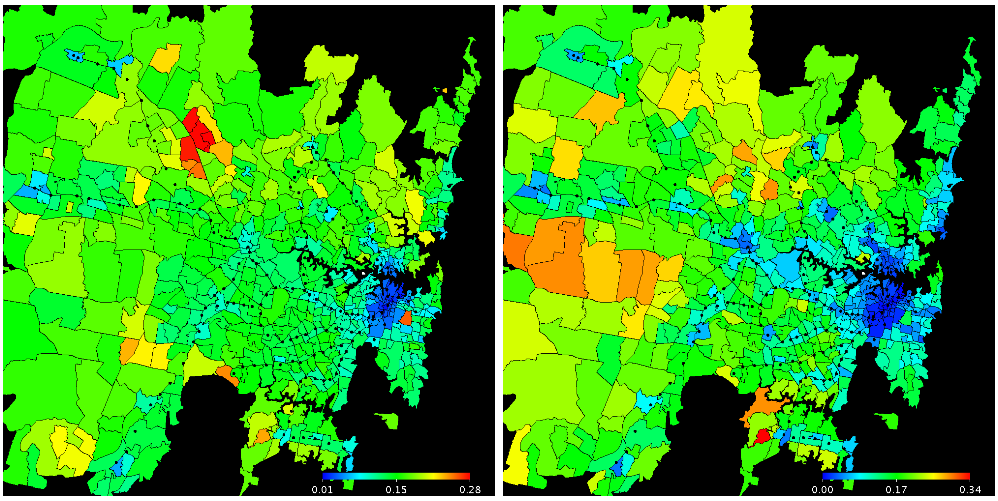
(b) Older singles

Figure 9.11: Proportion of households by household type, by zone.



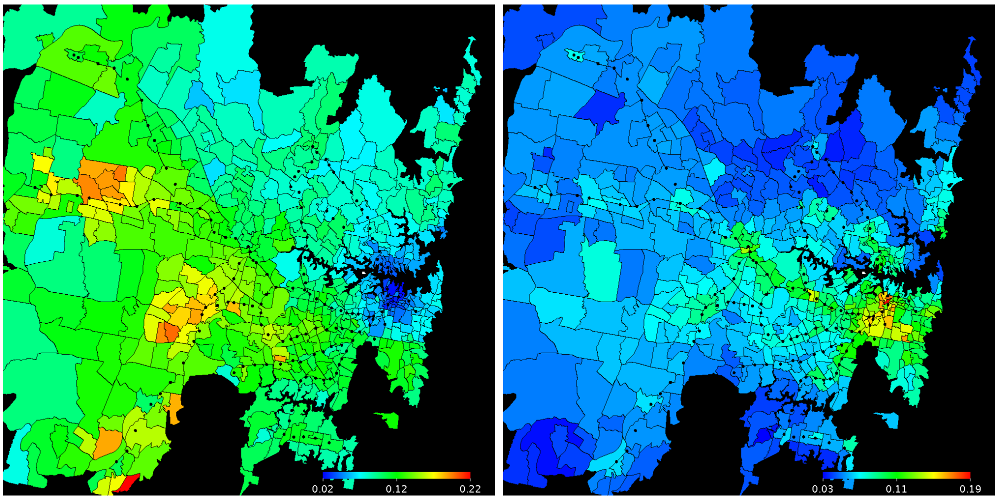
(a) Young couples (b) Older couples

Figure 9.12: Proportion of households by household type, by zone.



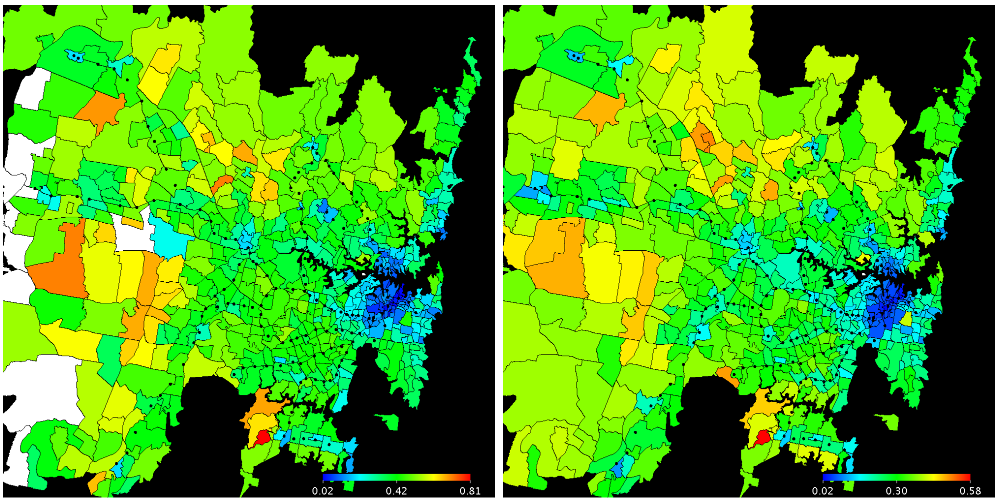
(a) Couples w. young children (b) Couples w. older children

Figure 9.13: Proportion of households by household type, by zone.



(a) Single-parent households (b) Other households

Figure 9.14: Proportion of households by household type, by zone.



(a) 2001 (b) 2031

Figure 9.15: Proportion of households that are couples with children (all ages), by zone, for 2001 and 2031.

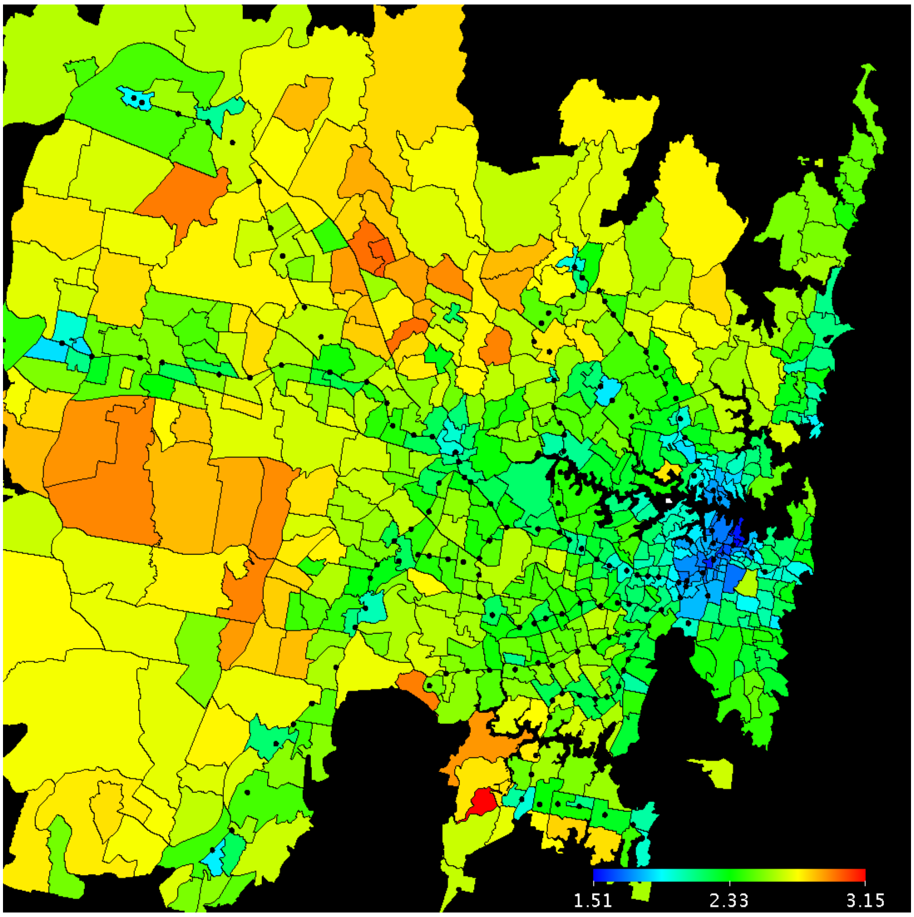


Figure 9.16: Persons per household in 2031, by zone.

2031. Changing demographics mean that city-wide household size will decline from 2.65 to 2.38, and, as the figure shows, many of the smaller household types (i.e. singles and couples without children) are projected to locate in apartments in higher-density centres. The reasons for this are that these households are generally more willing to live in apartments, and more willing to live in higher-density areas (see discussion in Section 5.5.2).

Figure 9.17 shows the projected number of cars per person in the baseline scenario, with per-capita car ownership generally being lower in inner areas and main centres along Sydney's rail network (stations on this network are shown as black dots).

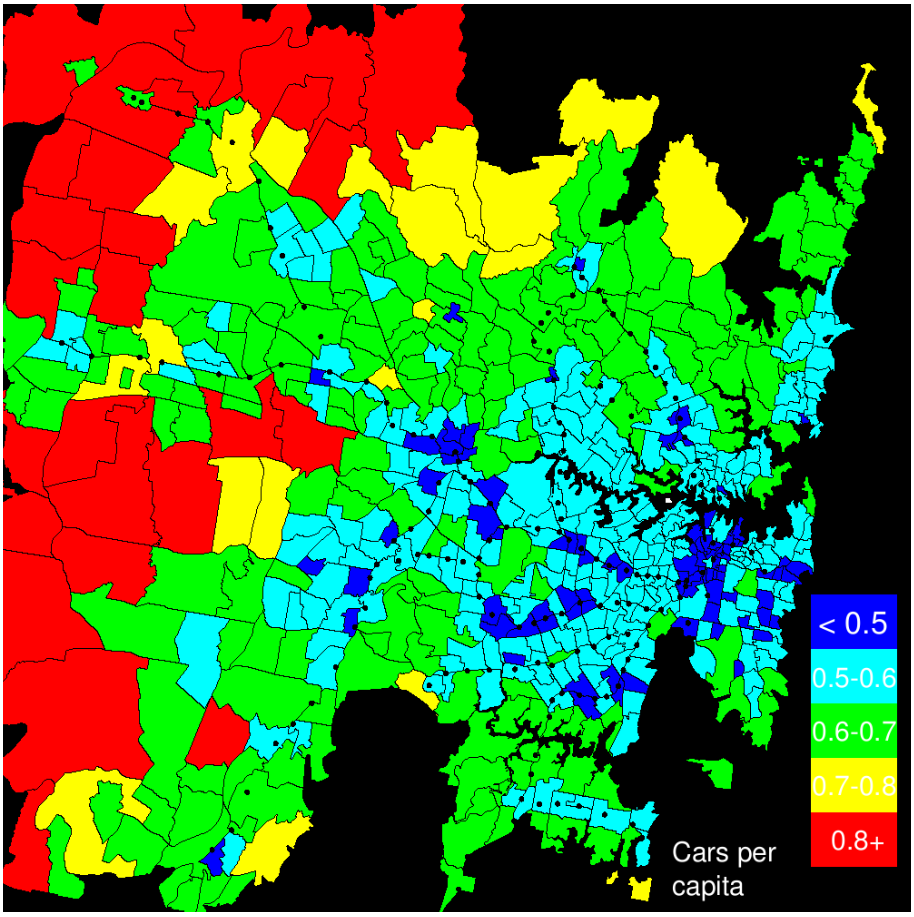


Figure 9.17: Cars per person in 2031, by zone.

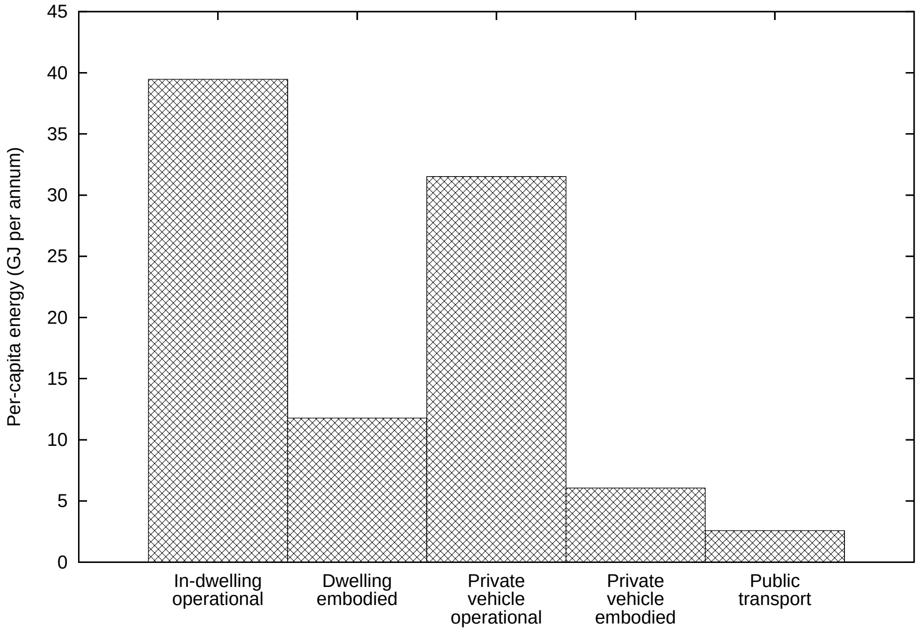
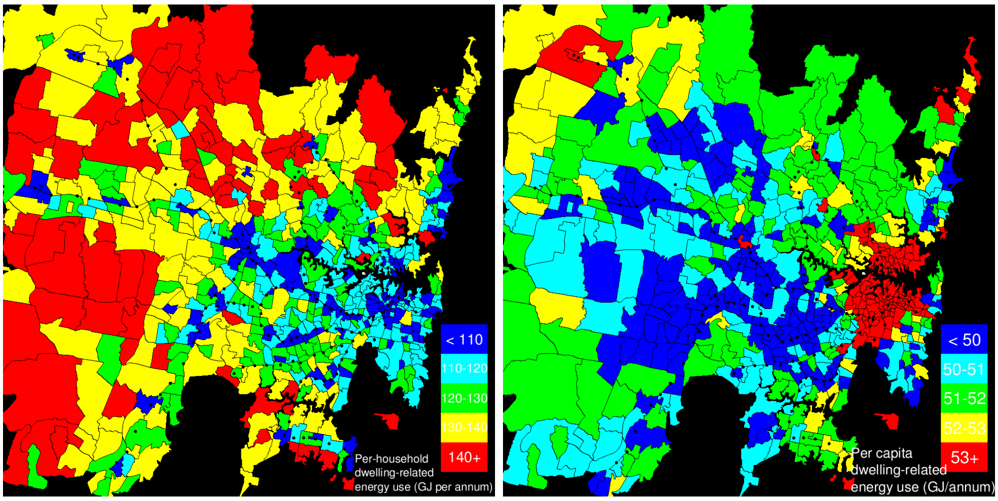


Figure 9.18: Average per-capita primary energy use by category (projected for 2031)

Energy-use indicators

The preceding figures are useful in demonstrating the capabilities of the integrated model developed in this thesis, but generally fall outside the stated focus of this thesis – residential energy use (and related greenhouse emissions). Figure 9.18 shows the projected breakdown (by category) of energy use in 2031 for the baseline scenario. In-dwelling energy use is the largest contributor to total household energy use, with petrol consumption the other main contributor. Embodied energy use is less significant, and energy used by public transport almost a marginal consideration.

Figure 9.19 shows the spatial variation in dwelling-related energy use (i.e. in-dwelling and dwelling embodied), and illustrates the stark difference between per-household and per-capita statistics. Opponents of higher-density living in Australia often choose to report per-capita statistics, but this is misleading. Smaller households do not benefit from the savings that come with shared appliance use in larger households. The household energy use regression model described in Section 3.3, for example, suggests that household in-dwelling energy use increases by only around 20% for each additional inhabitant. Given this, it is unsurprising that inner-city areas, with smaller households (see Figure 9.16), have higher per-capita energy use. In no way does Figure 9.19b suggest that inner-city high-density living is less sustainable than suburban living, merely that there are savings related to appliance sharing in larger households. Short of encouraging more communal living, no clear planning policy implications can be derived from the observation that per-capita energy use is higher in inner-city apartment-dwelling households than in suburban family households. If we accept that household formation and migration are largely outside the control of planners, then knowing that there are efficiency gains from sharing in larger households is not very useful. The real question, from a planning perspective, is what the energy use consequences of different housing policies are, given the number and mix of households likely to be inhabiting the city. The analysis of in-dwelling energy use in Section 3.3 found that energy use was 15-20% lower in apartments (compared to detached dwellings), *all other things equal*, which suggests that higher density housing will result in lower in-dwelling energy use. Combined with the observation that both population density and proximity to the CBD are associated with less automobile travel (see Section 7.3.3), there seems to be a case for policies that limit expansive city growth and encourage additional development in existing areas.



(a) Per household (b) Per person

Figure 9.19: Annual dwelling-related energy use (including embodied) in 2031, by zone.

In contrast to in-dwelling energy use, the overall spatial pattern of per-household transport energy use (shown in Figure 9.21) is very similar to that for per-capita energy use. This suggests that location is the dominating factor determining travel behaviour. Households close to the CBD, and households in higher-density areas along the rail line use less transport energy, due to the shorter distances they travel by private automobile. Figure 9.22 shows the spatial distribution of per-capita public-transport energy use, showing much higher use in inner-city areas and in major centres along the rail line. Note though, that the absolute numbers (in GJ/person) are very small compared to total transport energy use.

Figures 9.23 and 9.24 show total per-household and per-capita energy use for the baseline scenario, and Figure 9.25 shows the proportion of total per-capita energy use related to transport, with those living in the more remote suburbs having transport-related energy use higher than their dwelling-related energy use, while for those in the city and inner suburbs, transport energy consumption comprises around a third of total energy use.

A final figure of interest relating to energy use is Figure 9.26, which shows the amount of energy consumed for each dollar of income. This figure shows clearly that inner-city residents consume less energy, per dollar of income, than those in middle or outer suburbs.

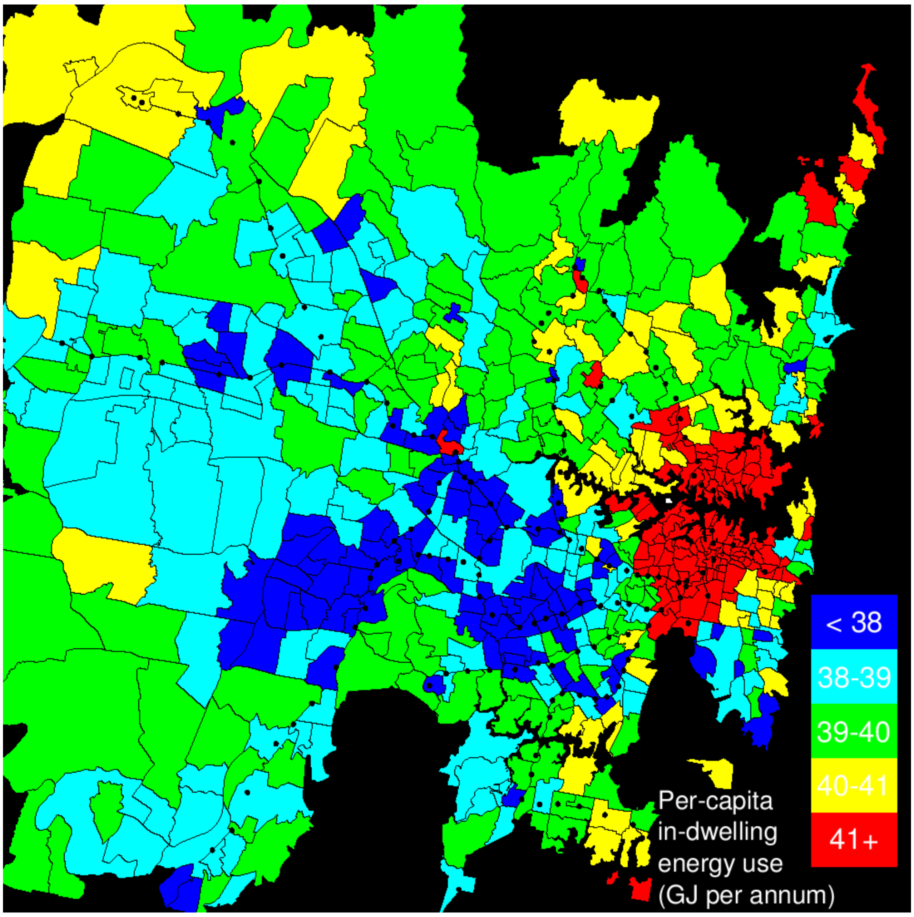
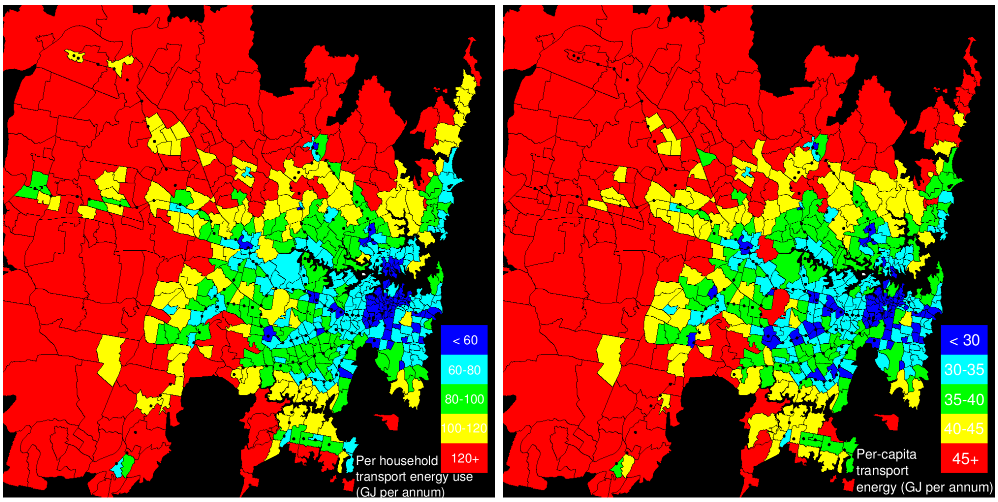


Figure 9.20: Annual in-dwelling energy use per person (excludes embodied) in 2031, by zone.



(a) Per household

(b) Per person

Figure 9.21: Annual personal transport related energy use (including energy embodied in cars) in 2031, by zone.

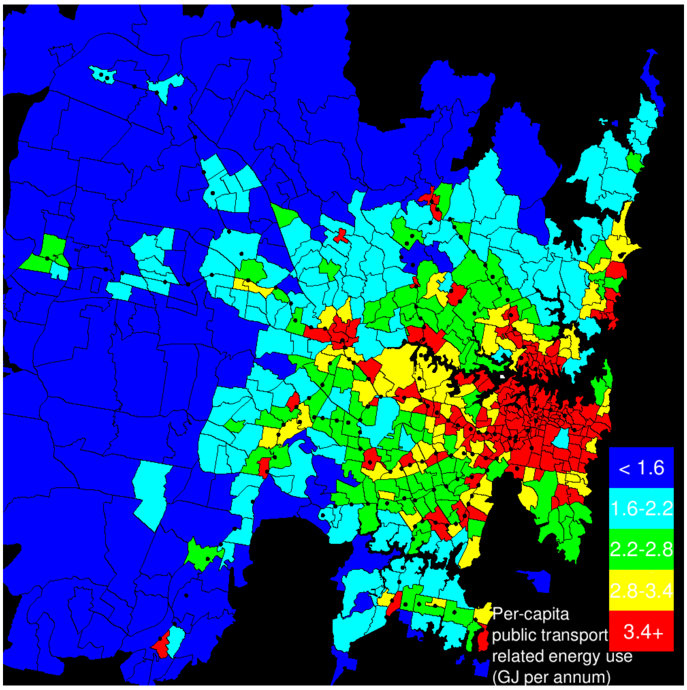


Figure 9.22: Annual public-transport related energy use per person in 2031, by zone.

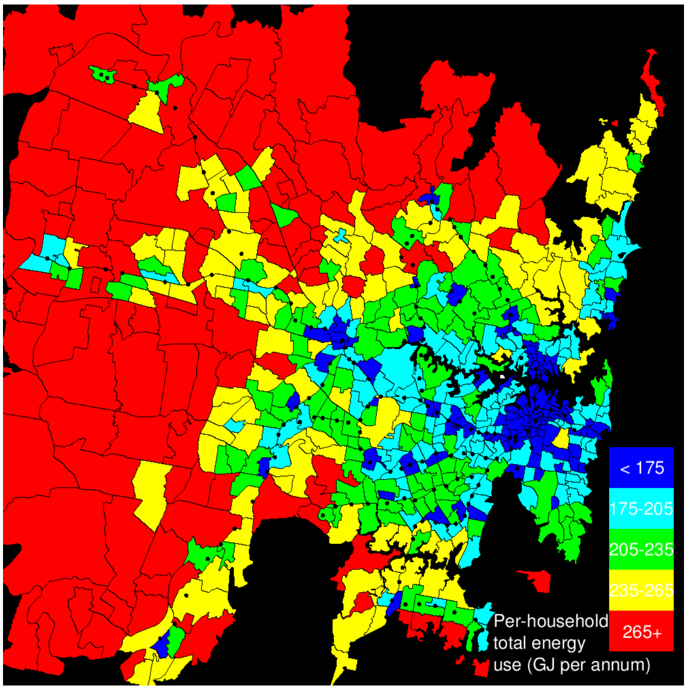


Figure 9.23: Annual per-household energy use (transport and dwelling related, including embodied) in 2031, by zone.

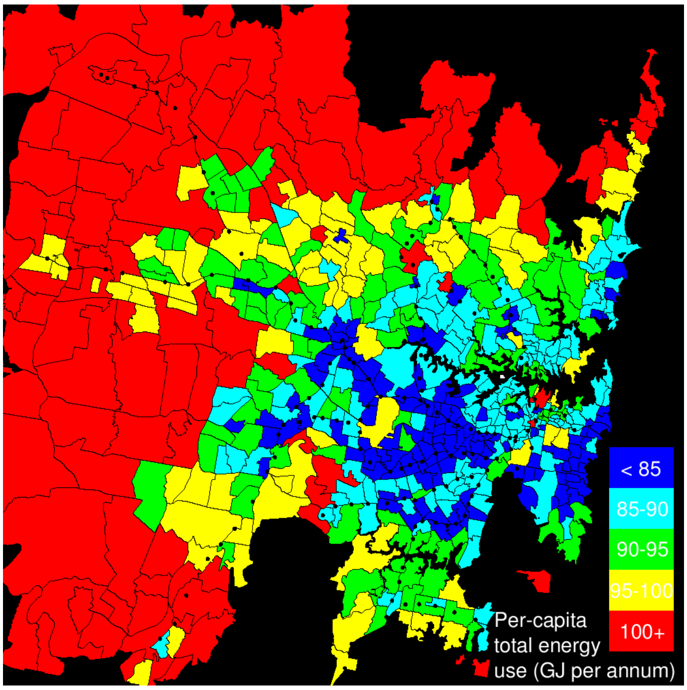


Figure 9.24: Annual per-person energy use (transport and dwelling related, including embodied) in 2031, by zone.

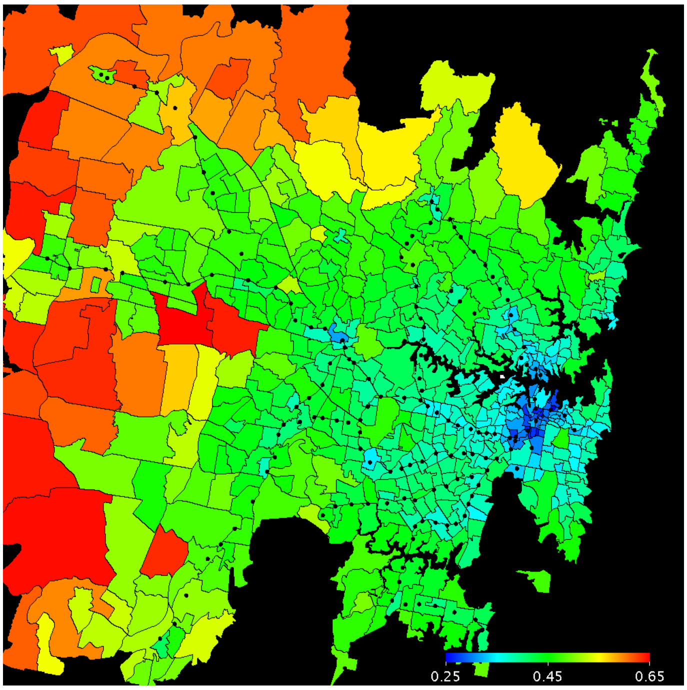


Figure 9.25: Per-capita transport energy as a proportion of total per-capita energy-use.

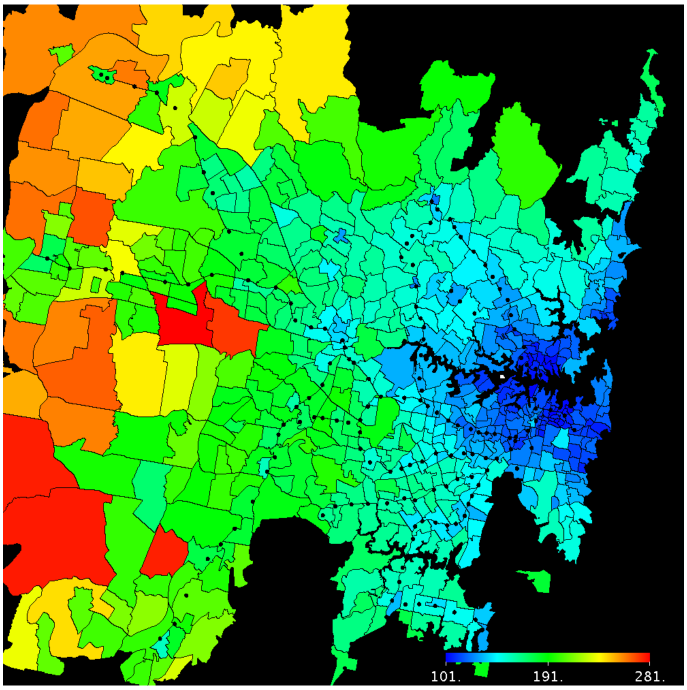


Figure 9.26: MJ of energy used per dollar of income.

Greenhouse indicators

The patterns observed in the baseline scenario are largely replicated if one substitutes greenhouse gas emissions for energy use. Figure 9.27, for example, showing a breakdown of per-capita emissions by end-use is, as one might expect, similar to Figure 9.18. The most notable difference is that the importance of transport is slightly reduced, as in-vehicle energy use (from the burning of petrol) is less greenhouse intensive than in-dwelling energy use, which requires the burning of significant quantities of coal[5].

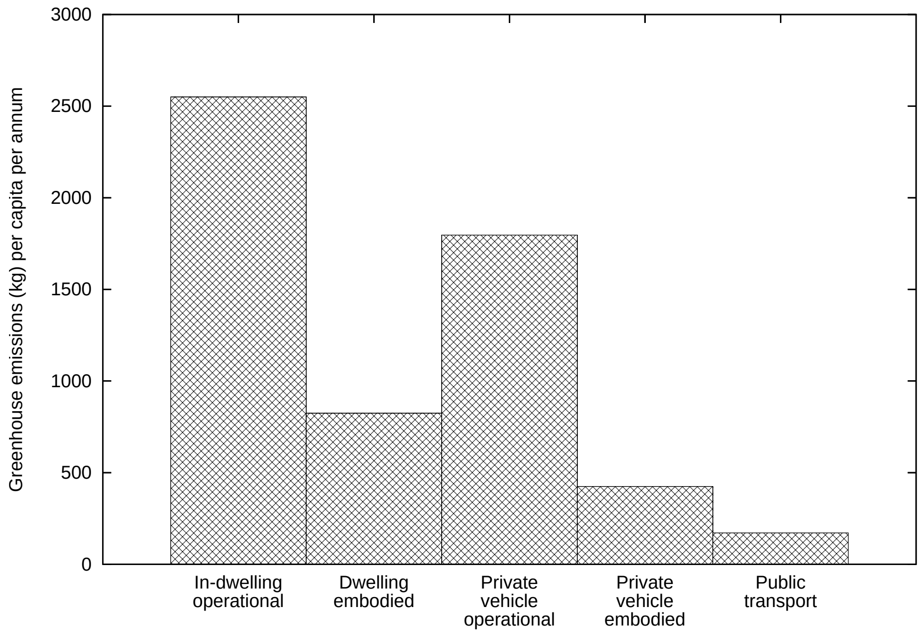


Figure 9.27: Average per-capita greenhouse emissions by category (projected for 2031)

Figure 9.28 shows per-capita emissions resulting from dwelling-related energy use, and Figure 9.29 shows per-capita emissions resulting from transport-related energy use. Figure 9.30 shows total emissions from both dwelling and transport-related energy use.

Figure 9.31, which shows greenhouse emissions per dollar of income, shows a pattern almost identical to that already shown for energy use per dollar (in Figure 9.26), with inner-city residents having a lesser greenhouse impact, per dollar of income, than middle and outer suburban residents.

[5]This may change in the future, if there is a move towards less greenhouse intensive power generation methods.

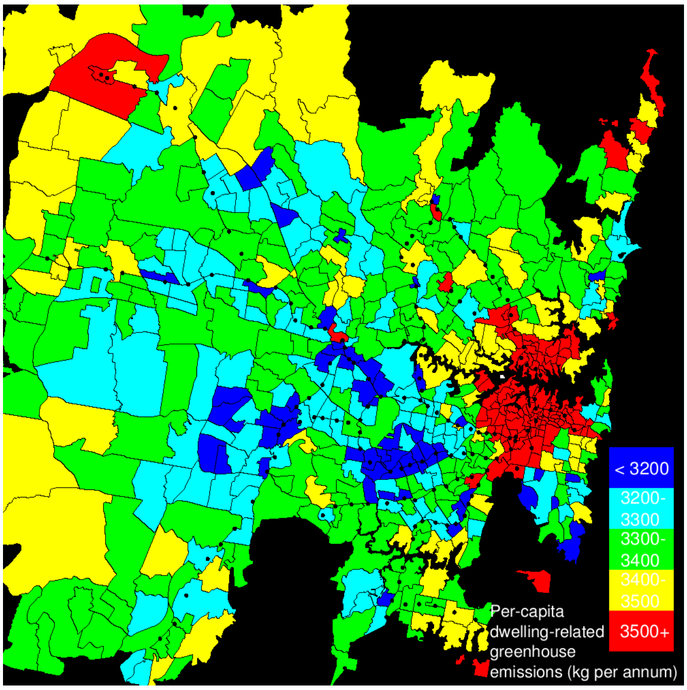


Figure 9.28: Annual dwelling-related emissions per-person (including embodied) in 2031, by zone.

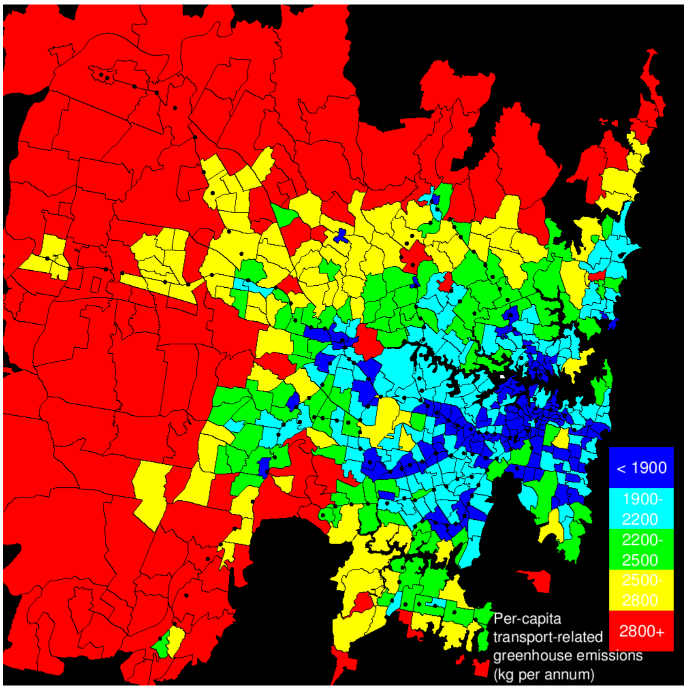


Figure 9.29: Annual personal transport related emissions per person (including emissions embodied in cars) in 2031, by zone.

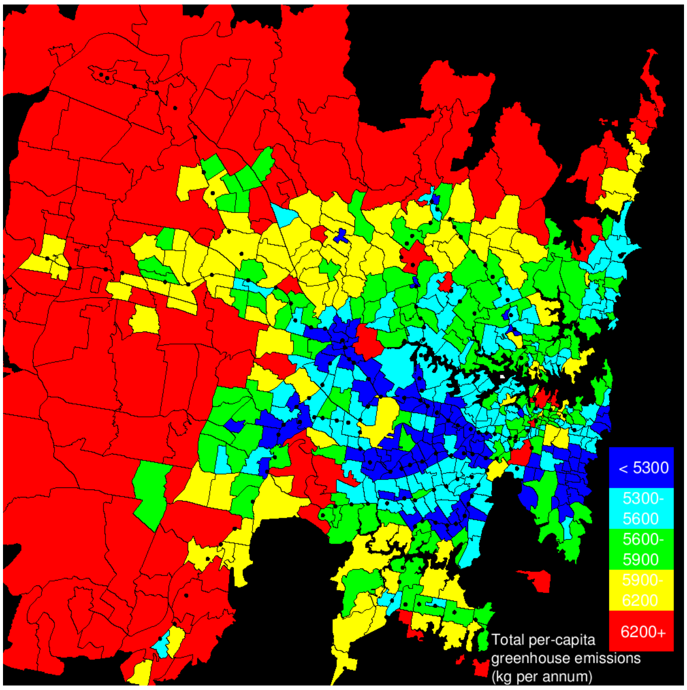


Figure 9.30: Annual emissions per person (including emissions embodied in cars) in 2031, by zone.

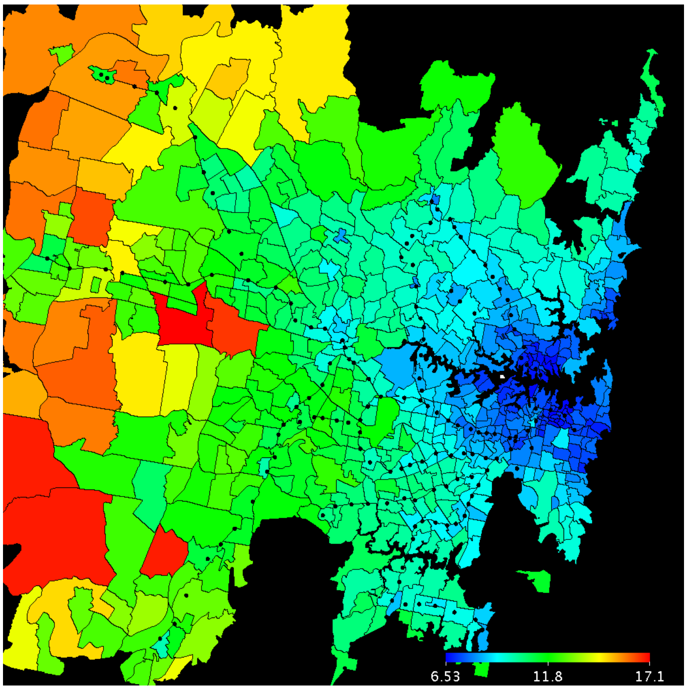


Figure 9.31: Greenhouse emissions (kg) per dollar of income.

Scenarios 2-11

Now that results for the baseline scenario have been presented, ten alternate scenarios are evaluated. Table 9.1 lists those scenarios. Scenarios 2-6 are based on the metro-strategy, but each has a different emphasis on where housing development will occur (i.e. in Centres, Suburbs, or Fringe). Scenarios 7 & 8, while still based on the baseline scenario, represent a move away from the centres/suburbs distinction, with more development instead taking place in inner-suburban and/or inner-city areas. Scenarios 9, 10, & 11 represent radical departures from the metro-strategy.

Scenario #	Centres	Suburbs	Fringe	Notes
1	+0%	+0%	+0%	Baseline
2	+20%	+0%	-40%	
3	+0%	+75%	-40%	
4	+5%	-20%	+0%	
5	-10%	-40%	+40%	
6	-20%	-7%	+40%	
7	NA	NA	-40%	Medium-density inner suburban re-development
8	NA	NA	-40%	High-density CBD development
9	NA	NA	-67%	'Parisian' style development. Like scenario 7, but more pronounced.
10	NA	NA	-67%	'Hong-kong' style development. Like scenario 8, but more pronounced.
11	NA	NA	+150%	'Urban sprawl' style development.

Table 9.1: The scenarios evaluated in this section. Note that scenarios 7-11 are not based around the metrostrategy definition of centres/suburbs, and so changes to the amount of development in centres/suburbs (as defined by the metrostrategy) is not reported for those cases.

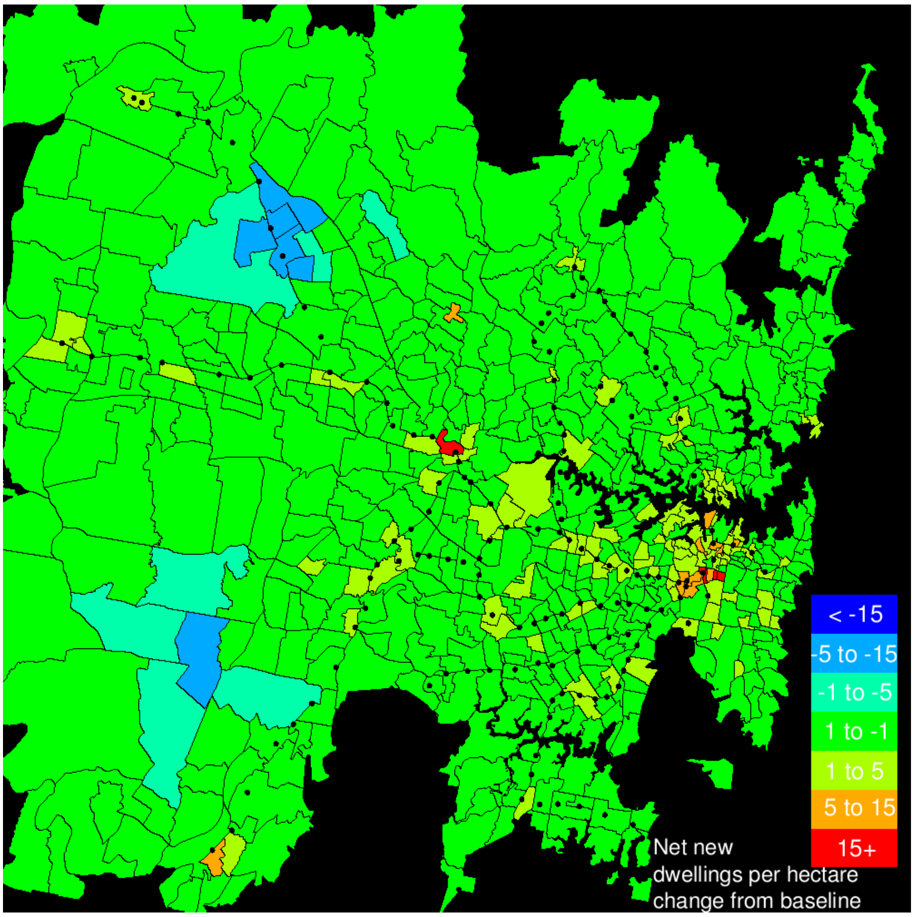


Figure 9.32: Scenario 2: additional dwellings per hectare compared with baseline scenario.

9.2.2 Scenario 2: +20% in centres, +0% in suburbs, -40% on fringe

This scenario is one in which the number of new dwellings provided in centres is 20% greater than in the baseline scenario. This development in centres takes place instead of new fringe development, with 40% fewer new dwellings being built on the urban fringe. Thus, this scenario represents a further strengthening of the 'centres and corridors' approach already adopted in the baseline scenario. Figure 9.32 shows the new development for this scenario, expressed as the number of additional dwellings per hectare built compared to the baseline scenario (refer back to Figure 9.3).

It should come as no surprise that the additional development in centres results in an increase in high-rise apartments, as Figure 9.33 shows.

Figure 9.34 shows the changes in greenhouse emissions projected for this scenario, compared to those in the baseline scenario. We can see that the increased concentration in centres results, as we would expect, in lower private vehicle emissions, and higher public-transport related emissions. Because these scenarios assume no net change in transport technology/efficiency, the reduction in private vehicle emissions must be due in part to a reduction in per-household travel, and in-part to a shift in mode from private vehicle to public transport. Changes in dwelling-related emissions are less pronounced, with small reductions in both embodied and in-dwelling emissions.

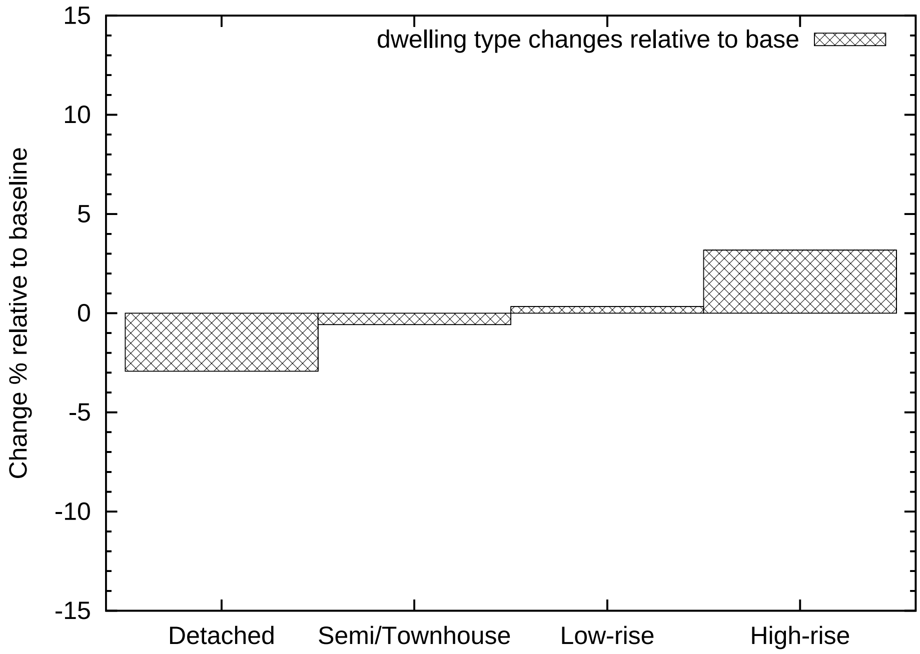


Figure 9.33: Scenario 2: Change in dwelling mix, compared to baseline scenario. Note that these are absolute percentages, so a reported 1% decline indicates that the proportion of all dwellings of that dwelling type is 1% lower.

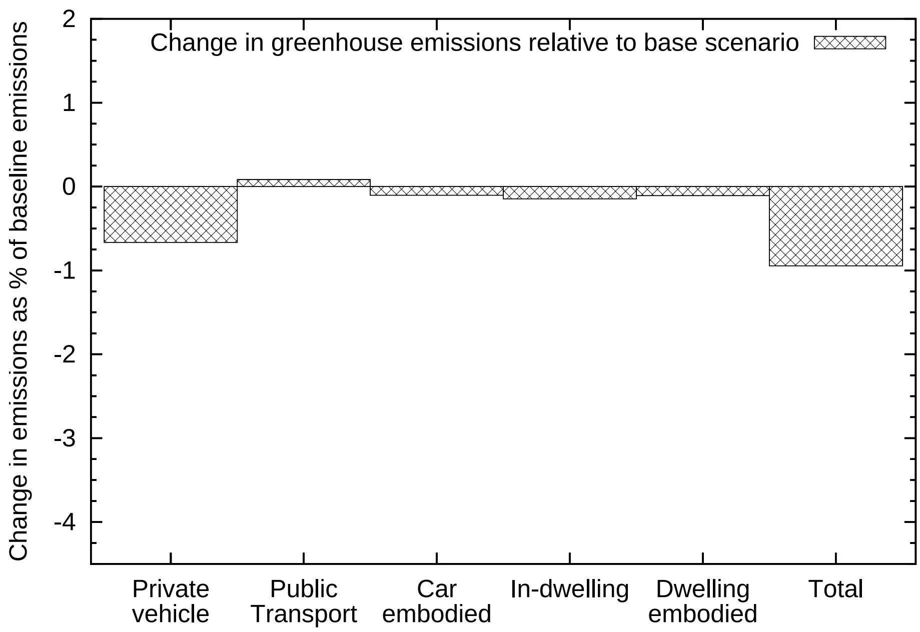


Figure 9.34: Scenario 2: Change in greenhouse emissions, compared to baseline scenario. Note that changes for each end-use are expressed as a percentage of *total* baseline emissions (i.e. from all end uses).

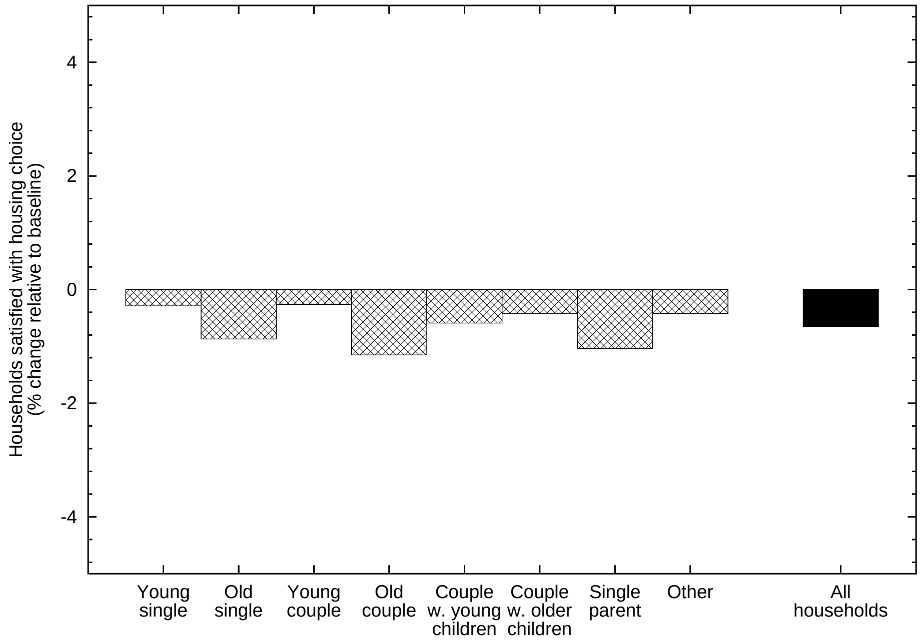


Figure 9.35: Scenario 2: Change in housing satisfaction by household type, compared to baseline scenario. Note that changes are expressed as absolute percentages. So a value reported here of -1% indicates that overall satisfaction levels are 1 percentage point lower for that household type, compared to the baseline scenario.

Figure 9.35 suggests that scenario 2 results in lower housing satisfaction than the baseline scenario, with satisfaction levels lower across all household types. The explanations for this are complex. Because many households prefer detached dwellings, the reduction in the number of detached dwellings on the fringe results in increased competition for in-fill development. This increased competition for housing results in satisfaction levels being lower even among those households that are content with apartment living (i.e. single person households and young couples), although the drop in satisfaction is higher among those households most desirous of traditional suburban detached housing.

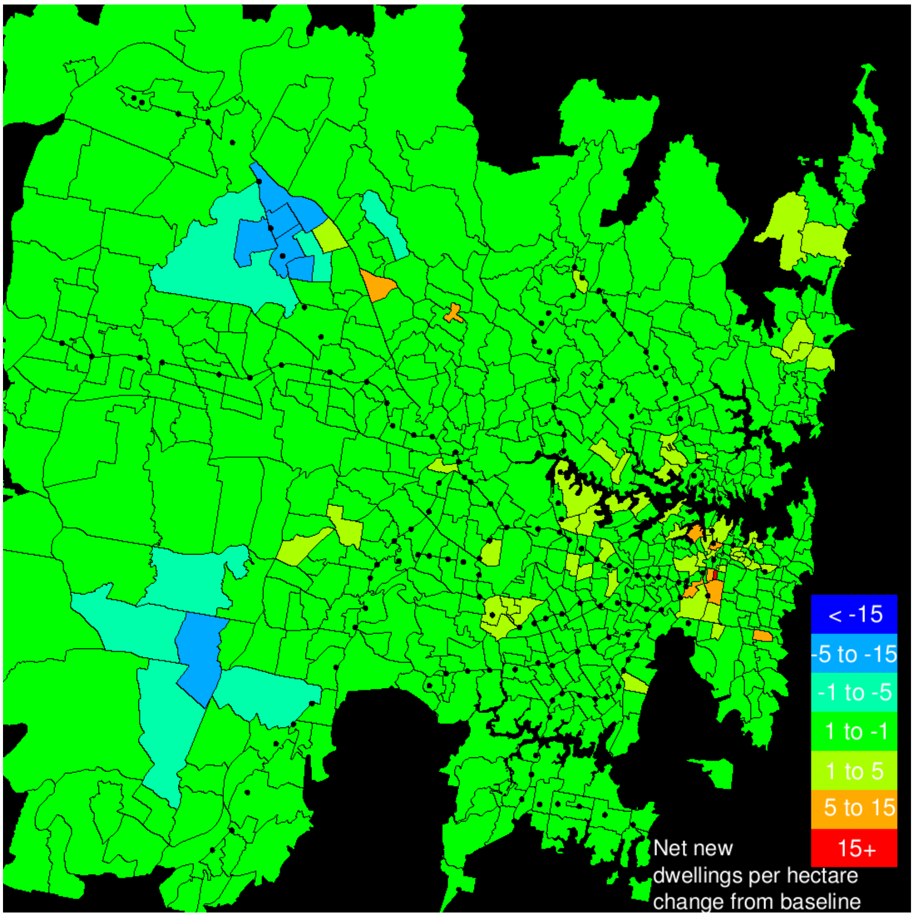


Figure 9.36: Scenario 3: additional new dwellings per hectare compared to baseline scenario.

9.2.3 Scenario 3: +0% in centres, +75% in suburbs, -40% on fringe

This scenario is one in which the number of new dwellings provided in existing suburban areas (i.e. not centres) is 75% greater than in the baseline scenario, with this development taking place in the stead of new fringe development, with 40% fewer new dwellings being built on the urban fringe. Figure 9.36 shows the new development for this scenario, expressed as the number of additional dwellings per hectare built compared to the baseline scenario.

Although suburban areas are traditionally associated with lower-density dwelling forms, the large increase in development (75% additional new dwellings), combined with the limited opportunities for development in suburban areas and land economic factors, result in much of that additional development taking place in the form of high-density apartments, as Figure 9.37 shows. Note however that the increase in high-rise apartments is slightly less than in the case where development is concentrated in 'centres', such as scenario 2.

Figure 9.38 shows that changes to greenhouse emissions in scenario 3 are very similar to those seen for scenario 2. This suggests that the reduction in fringe development is the dominating factor, as this is common across both scenarios. Differences arising from concentrating infill development in centres or in existing suburbs are minor.

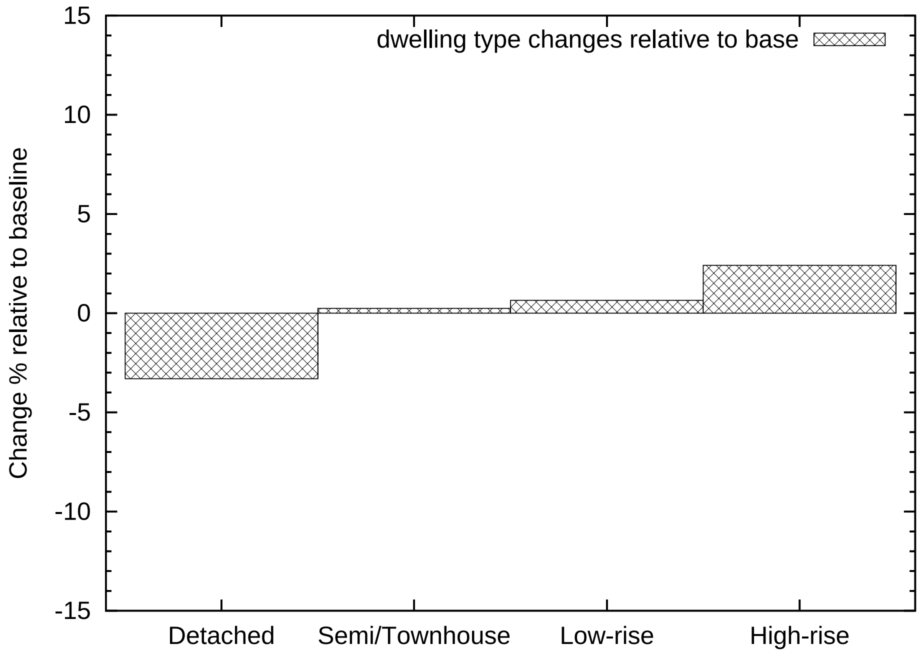


Figure 9.37: Scenario 3: Change in dwelling mix, compared to baseline scenario. Note that these are absolute percentages, so a reported 1% decline indicates that the proportion of all dwellings of that dwelling type is 1% lower.

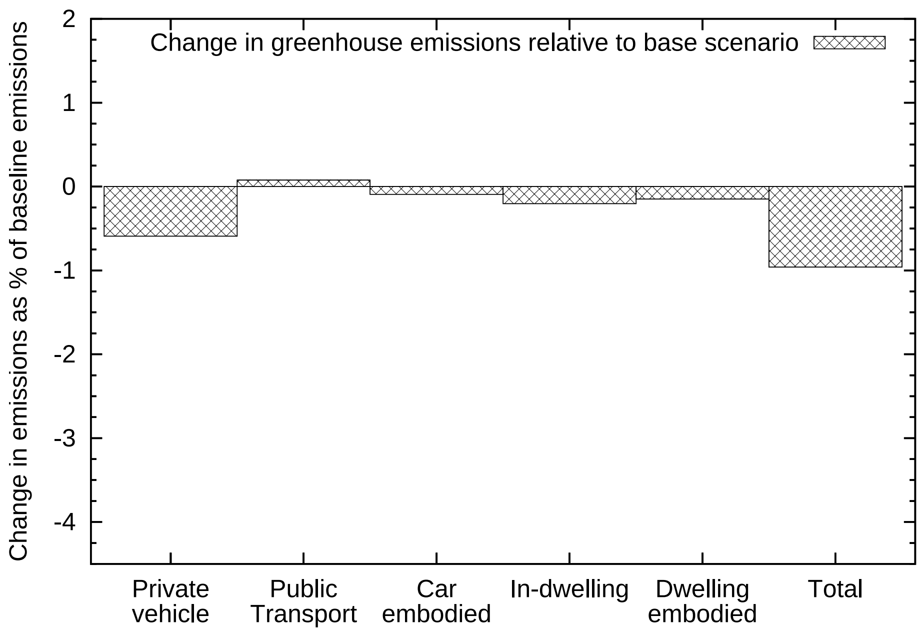


Figure 9.38: Scenario 3: Change in greenhouse emissions, compared to baseline scenario. Note that changes for each end-use are expressed as a percentage of *total* baseline emissions (i.e. from all end uses).

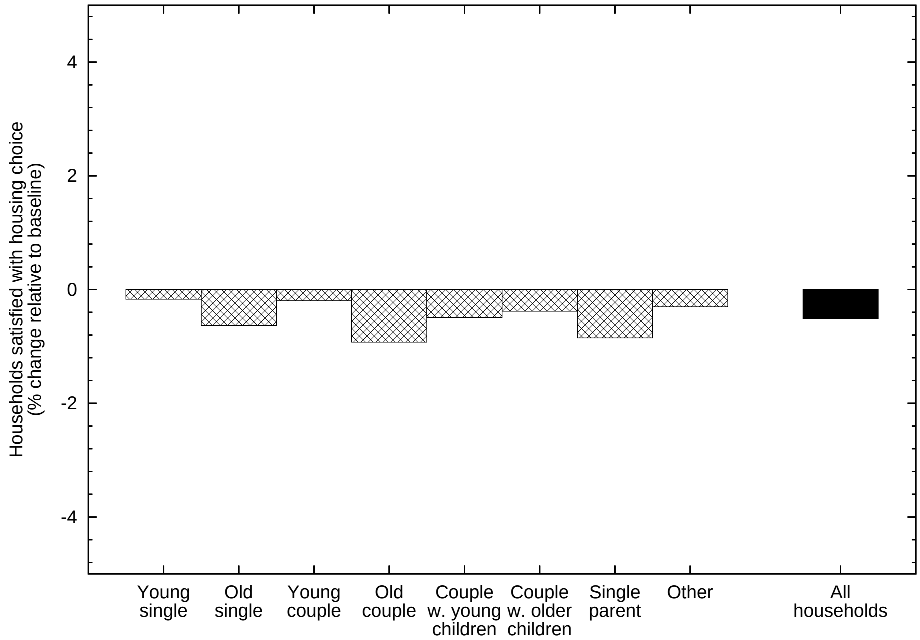


Figure 9.39: Scenario 3: Change in housing satisfaction by household type, compared to baseline scenario. Note that changes are expressed as absolute percentages. So a value reported here of -1% indicates that overall satisfaction levels are 1 percentage point lower for that household type, compared to the baseline scenario.

Like scenario 2, housing satisfaction is lower in total, and across all household groups, compared to the baseline scenario. However, the decreases in satisfaction are less pronounced than in scenario 2, suggesting that the provision of additional housing in suburban areas is preferable to residents than provision of housing in centres.

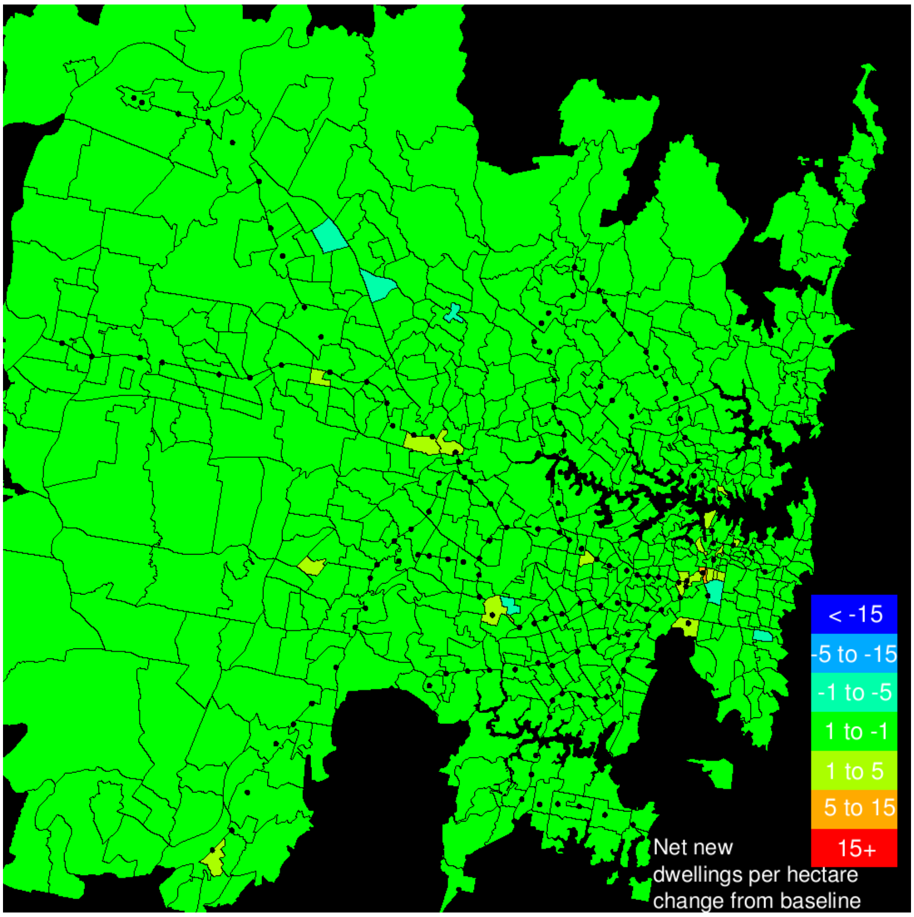


Figure 9.40: Scenario 4: additional new dwellings per hectare compared to baseline scenario.

9.2.4 Scenario 4: +5% in centres, -20% in suburbs, +0% on fringe

This scenario is one in which there is only a small (5%) increase in the number of new dwellings provided in centres, and *fewer* new dwelling constructed in suburban areas, with no change in the number of dwellings released on the fringe. Figure 9.40 shows the new development for this scenario, expressed as the number of additional dwellings per hectare built compared to the baseline scenario.

The change in dwelling mix compared to the baseline scenario is very small, as Figure 9.41 shows, with a slight increase in high-rise dwellings being due to the slight increase in development in centres.

Figure 9.42 shows that there is essentially no change in emissions compared with the baseline scenario. This suggests changes to greenhouse emissions in scenario 3 are very similar to those seen for scenario 2. This provides even more support for the claim that varying the amount of fringe development is more important than redistributing infill development between centres and suburbs.

Figure 9.43 shows that housing satisfaction is almost indistinguishable from that in the baseline scenario.

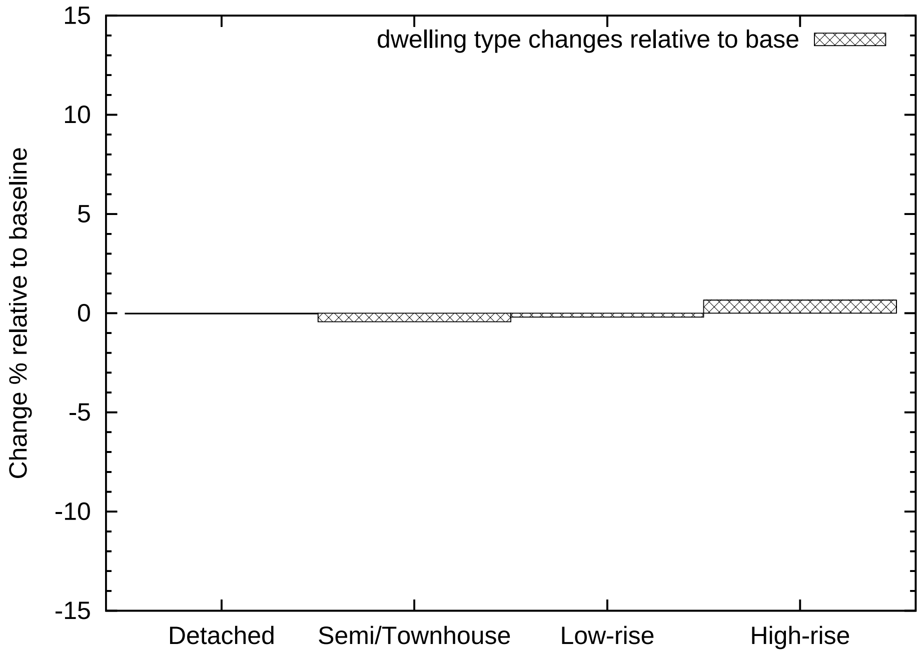


Figure 9.41: Scenario 4: Change in dwelling mix, compared to baseline scenario. Note that these are absolute percentages, so a reported 1% decline indicates that the proportion of all dwellings of that dwelling type is 1% lower.

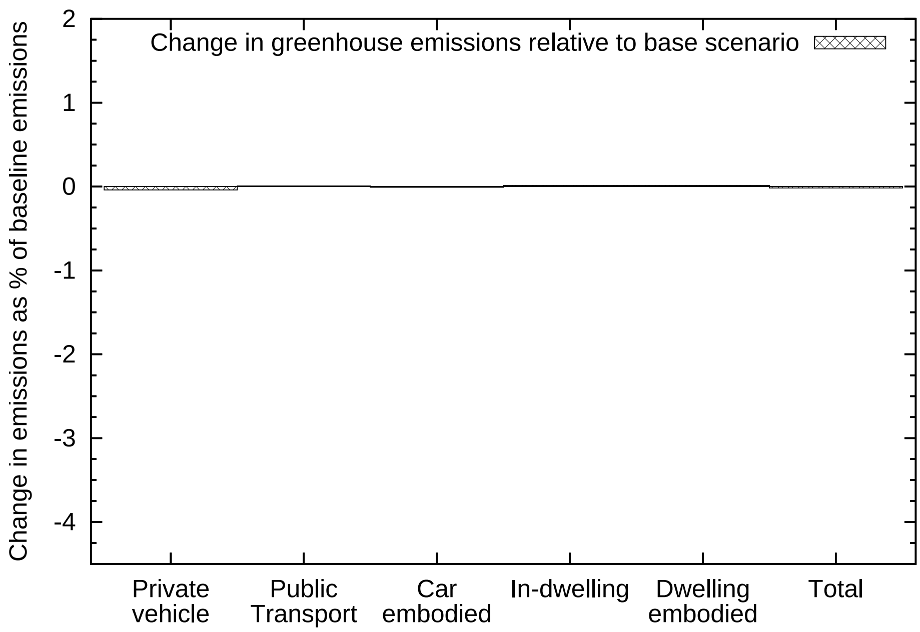


Figure 9.42: Scenario 4: Change in greenhouse emissions, compared to baseline scenario. Note that changes for each end-use are expressed as a percentage of *total* baseline emissions (i.e. from all end uses).

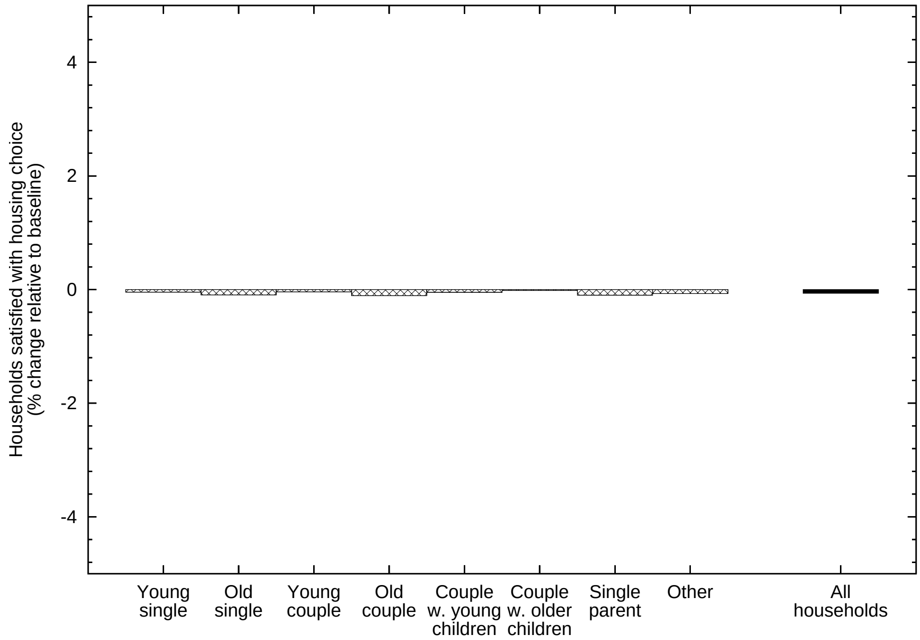


Figure 9.43: Scenario 4: Change in housing satisfaction by household type, compared to baseline scenario. Note that changes are expressed as absolute percentages. So a value reported here of -1% indicates that overall satisfaction levels are 1 percentage point lower for that household type, compared to the baseline scenario.

Analysis of a separate scenario that involved -10% development in centres, +35% development in suburban areas, and +0% development on the fringe resulted in greenhouse emissions almost indistinguishable from those in the baseline scenario. Housing satisfaction was also very similar to that in the baseline scenario, but was slightly better for all households than in both the baseline scenario and scenario 4. Because these results are so similar to those in the baseline scenario, and scenario 4, they are not reported-on in detail. They do serve to further emphasise that shifting infill development between centres and existing suburbs makes little difference to greenhouse emissions, and a slight difference to housing satisfaction (i.e. people prefer suburban redevelopment).

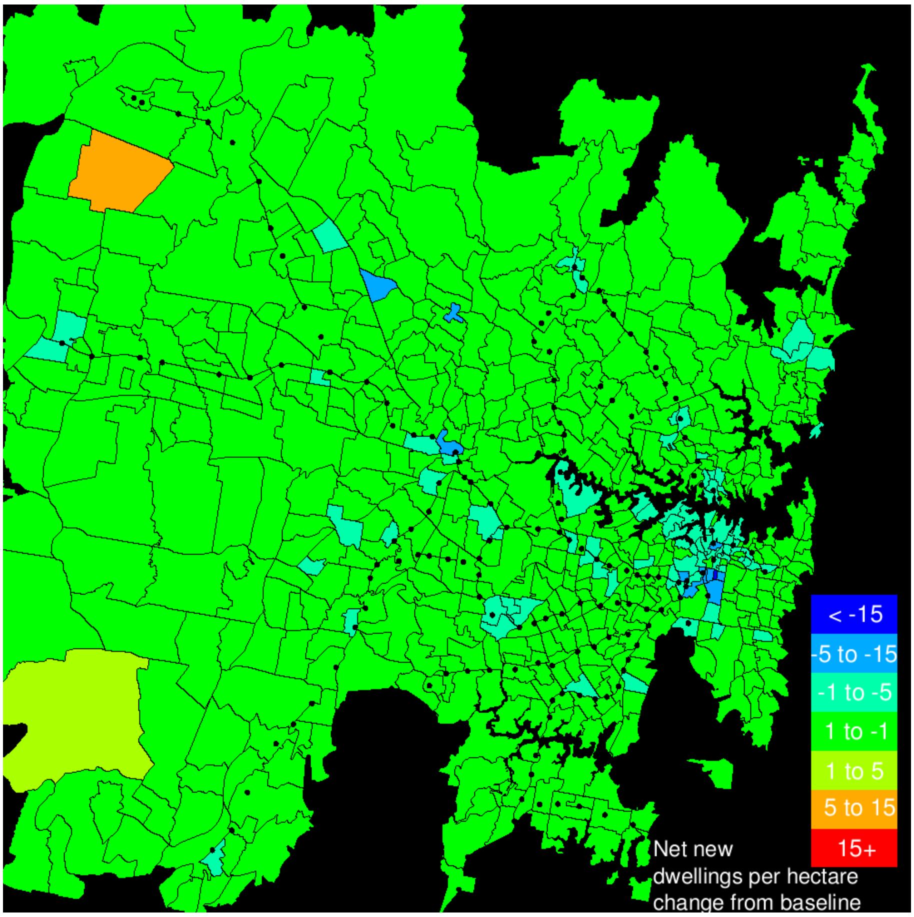


Figure 9.44: Scenario 5: additional new dwellings per hectare compared to baseline scenario.

9.2.5 Scenario 5: -10% in centres, -40% in suburbs, +40% on fringe

To contrast with scenarios 2 and 3, which have decreased fringe development and increased infill development, scenario 5 represents the case where there is slightly (-10%) less new development in centres, and a good deal (-40%) less development in existing suburbs, with these reductions in urban re-development being countered by a substantial (+40%) increase in development on the city fringe. Figure 9.44 shows the new development for this scenario, expressed as the number of additional dwellings per hectare built compared to the baseline scenario.

Figure 9.45 shows that this scenario, unsurprisingly, results in a relative increase in the number of detached dwellings, with decreases in all other dwelling categories.

Figure 9.46 shows that total greenhouse emissions are around 1.6% higher than in the baseline scenario, with increases in all categories except public transport.

Figure 9.47 shows that housing satisfaction is higher overall, and amongst all household types, compared to the baseline scenario. This is likely due to the fact that an increase in fringe development allows those households with a strong preference for detached dwellings to satisfy that preference.

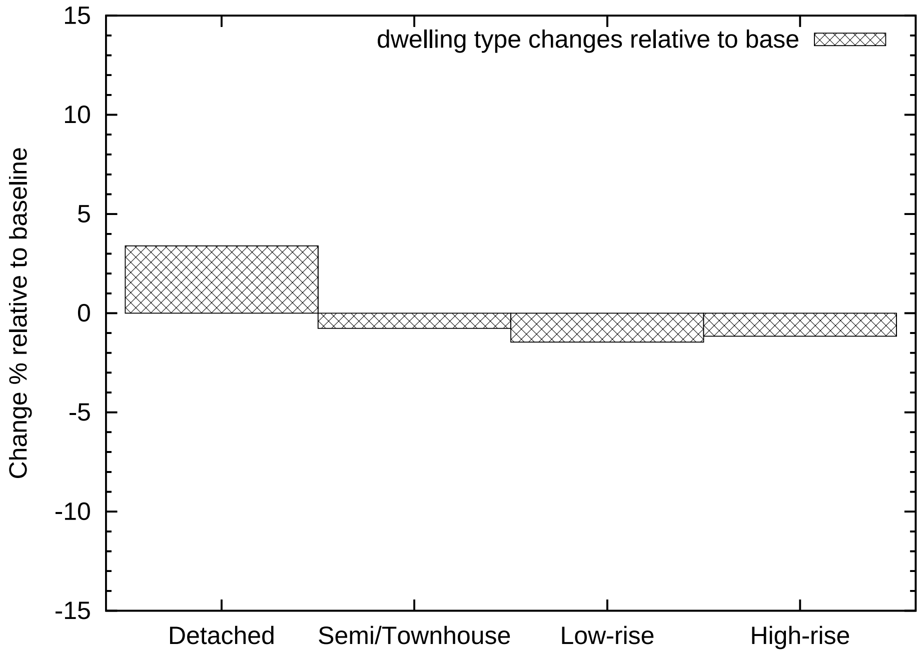


Figure 9.45: Scenario 5: Change in dwelling mix, compared to baseline scenario. Note that these are absolute percentages, so a reported 1% decline indicates that the proportion of all dwellings of that dwelling type is 1% lower.

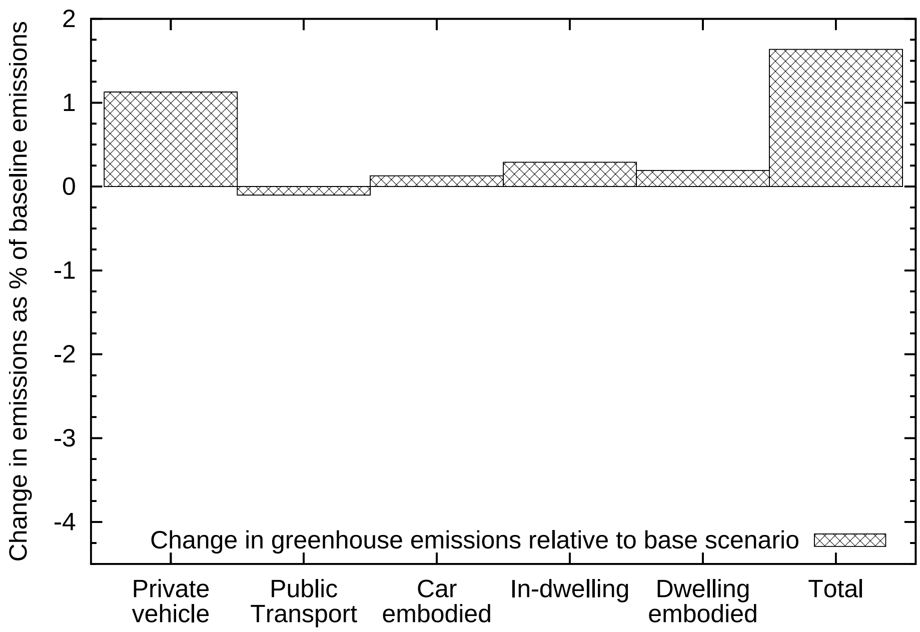


Figure 9.46: Scenario 5: Change in greenhouse emissions, compared to baseline scenario. Note that changes for each end-use are expressed as a percentage of *total* baseline emissions (i.e. from all end uses).

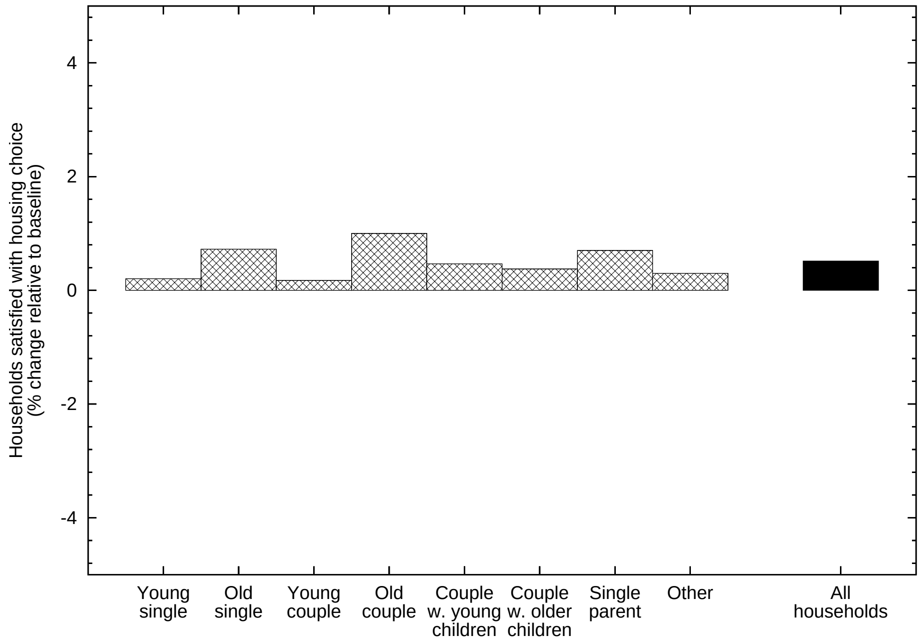


Figure 9.47: Scenario 5: Change in housing satisfaction by household type, compared to baseline scenario. Note that changes are expressed as absolute percentages. So a value reported here of -1% indicates that overall satisfaction levels are 1 percentage point lower for that household type, compared to the baseline scenario.

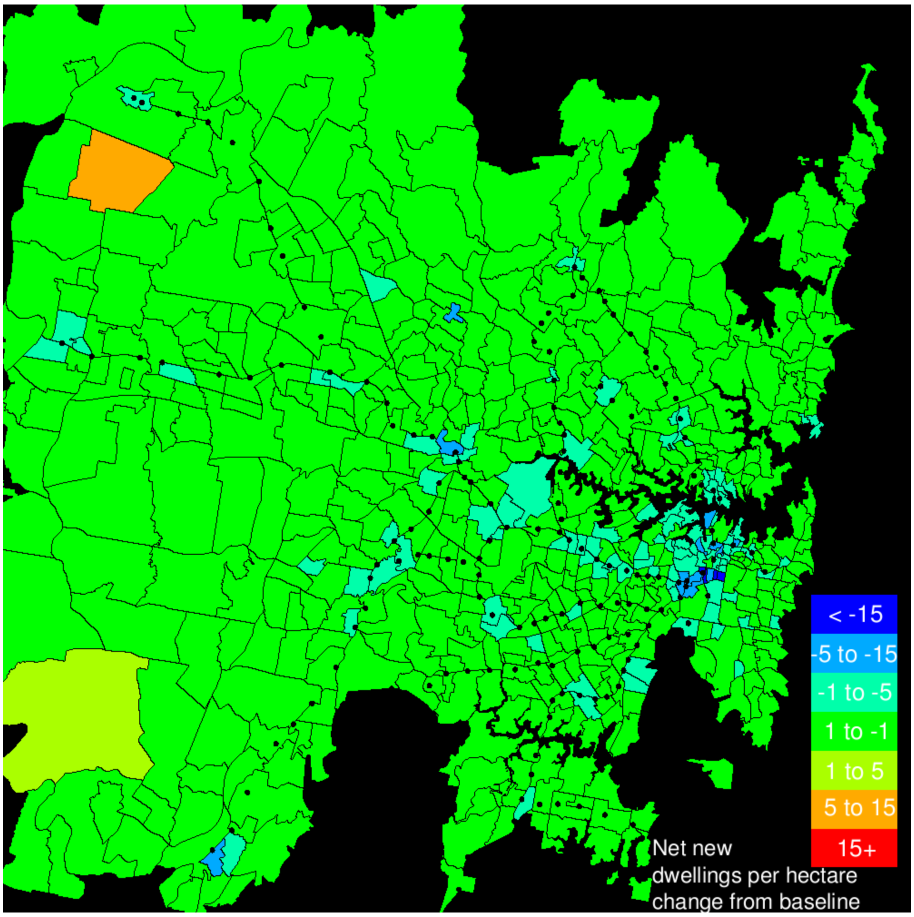


Figure 9.48: Scenario 6: additional new dwellings per hectare compared to baseline scenario.

9.2.6 Scenario 6: -20% in centres, -7% in suburbs, +40% on fringe

Scenario 6 represents a slight adjustment to scenario 5, with some re-development in existing areas shifted from centres to suburban areas. There is still a 40% increase in fringe development. Figure 9.48 shows the new development for this scenario, expressed as the number of additional dwellings per hectare built compared to the baseline scenario.

Like scenario 5, the increased fringe development results in an increase in the amount of detached dwellings, relative to the baseline scenario, with decreases in all other dwelling types (see Figure 9.49).

Figure 9.50 shows that total greenhouse emissions are around 1.8% higher than in the baseline scenario, with increases in all categories except public transport.

Figure 9.51 shows that housing satisfaction is higher overall, and amongst all household types, compared to the baseline scenario. Housing satisfaction is similar, but slightly higher, than in scenario 5, again suggesting that suburban re-development is preferable to re-development of centres.

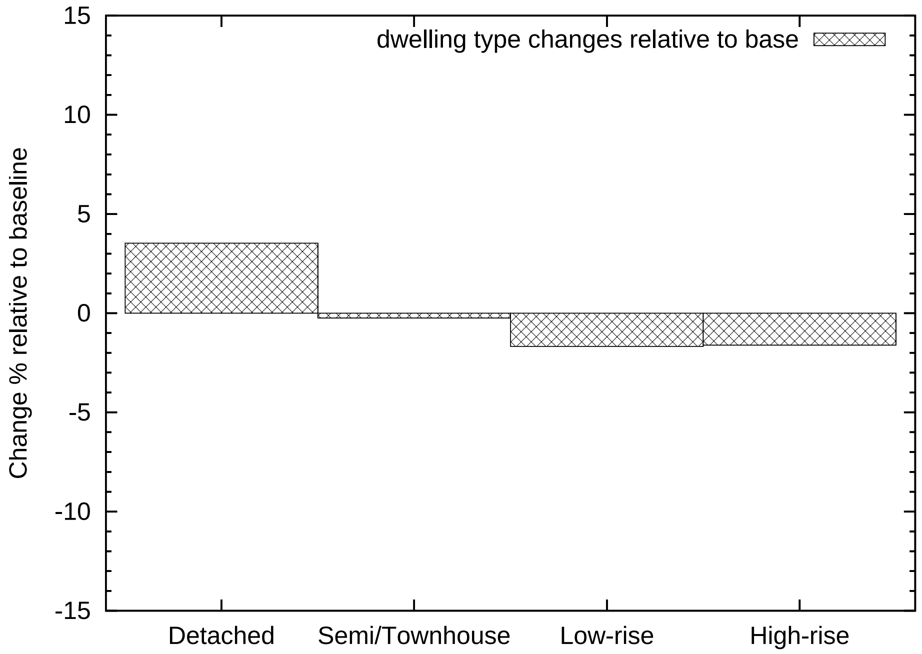


Figure 9.49: Scenario 6: Change in dwelling mix, compared to baseline scenario. Note that these are absolute percentages, so a reported 1% decline indicates that the proportion of all dwellings of that dwelling type is 1% lower.

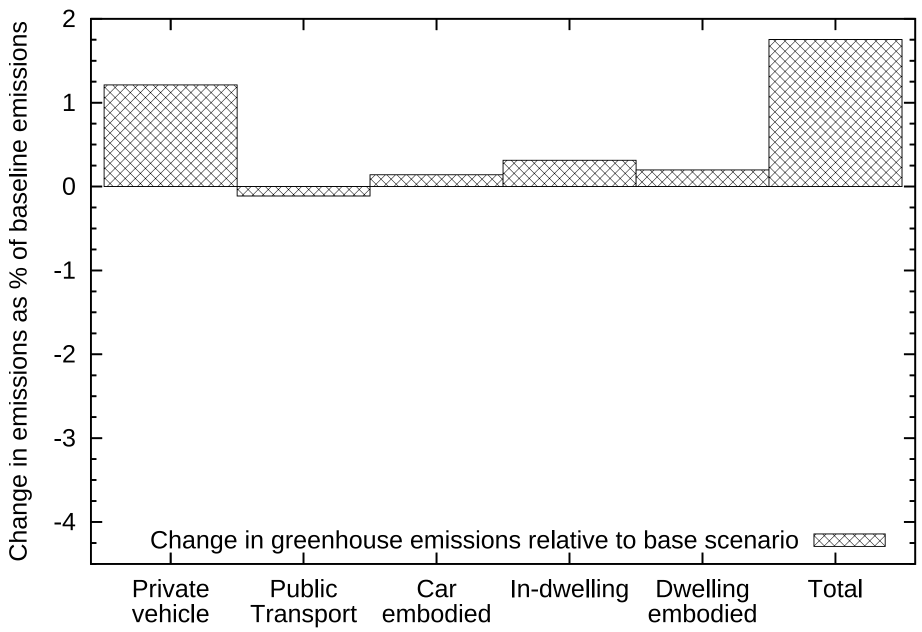


Figure 9.50: Scenario 6: Change in greenhouse emissions, compared to baseline scenario. Note that changes for each end-use are expressed as a percentage of *total* baseline emissions (i.e. from all end uses).

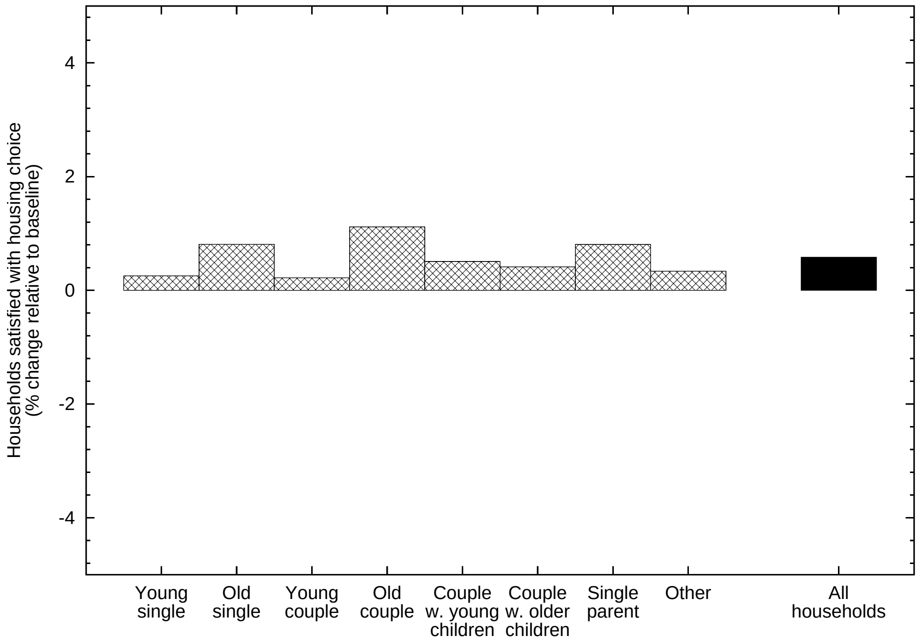


Figure 9.51: Scenario 6: Change in housing satisfaction by household type, compared to baseline scenario. Note that changes are expressed as absolute percentages. So a value reported here of -1% indicates that overall satisfaction levels are 1 percentage point lower for that household type, compared to the baseline scenario.

9.2.7 Scenario 7: 'mildly Parisian re-development' (-40% fringe)

Scenarios 2-6 suggest that it is the amount of fringe development that matters, and that shifting re-development within the existing urban area between centres and suburbs makes relatively little difference to either greenhouse emissions or housing satisfaction. However, centre and suburban areas are defined, for the purposes of these scenarios, by their classification in the Sydney metropolitan strategy. As already discussed, the classifications used in the Sydney metropolitan strategy are quite loose, and this allows, for example, outlying low-density areas near Penrith and Campbelltown to be classified as 'centres' when higher-density areas much closer to the city are classified 'suburban'. This flexibility allows the metro-strategy to claim that 80% of in-fill development will take place in centres, even though much of the in-fill development will take place is areas far distant from the CBD. There is a noticeable emphasis, in the metropolitan strategy, on development in 'centres', with the implicit assumption that proximity to a centre (however loosely defined) is more important than proximity to *the* centre[6]. Consider, for example, the following statements from the metro-strategy:

> The Metropolitan Development Program (MDP) distinguishes housing near transit nodes, which are either within 800 metres of a rail station or 400 metres of high frequency bus services in the morning peak.

NSW Department of Planning (2005, page 131)

> Concentrating activities in centres has substantial environmental benefits by reducing travel times, pollution, congestion and car dependence, protecting the character of existing suburbs and supporting public transport. Public transport networks and other Government investment in services are concentrated in existing centres. Hence, strengthening the centres makes better use of existing infrastructure services already in place.

NSW Department of Planning (2005, page 104)

This last statement may be true, but when centres are defined loosely, and sub-regional dwelling targets are such that the western regions are specified as the destination for much new development, the inevitable consequence is that a significant amount of development will take place in minor centres that are distant from the CBD, and not well linked in with the public transport network. Figure 9.52, which the reader has already seen (as Figure 8.6), illustrates this well, with over 50% of centre re-development occurring in 'towns and villages' – essentially minor centres. Furthermore, although 20% of re-development is targeted to take place in 'Global Sydney and Regional Centres', much of this is assumed to take place in regional centres like Penrith and Liverpool, that are either far-distant from the CBD (Liverpool), or right on the fringe of Sydney's urban boundary (Penrith). In short, the regional dwelling targets and centre definitions in the metro-strategy result in *distributed centralization*, and much less concentrated development than if centres were defined by land values, or employment density, or population density, or any other objective measure. With

[6]Even technical analysis by the NSW ministry of transport shows a tendency to focus on *proximity to transit*, rather than *access provided by transit*. The travel model in Corpuz et al. (2006), for example, includes measures of proximity to a centre, and proximity to a high-frequency public transport service, but doesn't include any general accessibility measures.

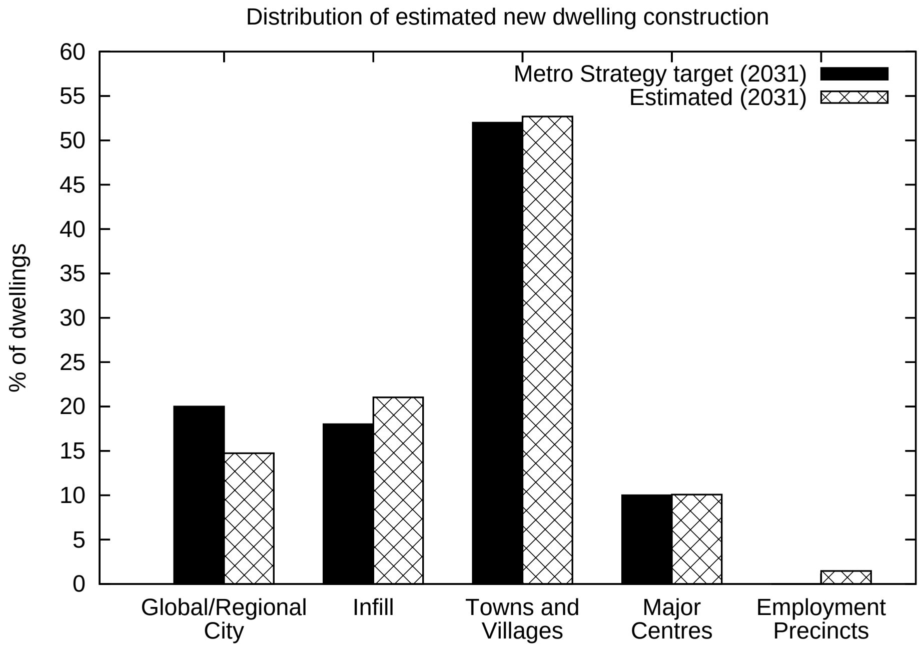


Figure 9.52: New infill dwelling construction by neighbourhood classification (2006 to 2031). Compares the proportions projected in the Sydney Metro-strategy (NSW Department of Planning, 2005), versus those estimated by the author for the baseline scenario.

this being the case, it is worth-while considering some scenarios where a little more re-development occurs in the denser, more central areas of Sydney (regardless of how they are classified in the metropolitan strategy). Scenario 7 is the first of these, and is dubbed (somewhat tongue-in-cheek) 'Parisian', because development is more concentrated in the inner suburbs and centres, but there is much less high-rise development. Instead, re-development takes place through the demolition of existing detached dwelling stock, to be replaced by medium-density dwelling types such as townhouses or low-rise apartments. Although a significant amount of re-development is shifted to centres and suburbs closer to the CBD for scenario 7, it is still in large part based on the metropolitan strategy. More radical departures from the metropolitan strategy are analyzed in scenarios 9 & 10. To keep scenario 7 comparable with scenarios 2 and 3, scenario 7 assumes a 40% reduction in the amount of fringe development. Thus, scenario 7 differs from scenarios 2 and 3 only in the intra-urban distribution of new dwellings. Figure 9.53 shows the number of additional dwellings per hectare built compared with the baseline scenario (scenario 1).

Figure 9.54 shows that, like scenarios 2 and 3, there are fewer detached dwellings than in the baseline scenario, due to the reduced development on the urban fringe. However, unlike scenarios 2 and 3, the additional re-development in existing areas takes place in the form of medium-density dwelling types, and so there is also a reduction in the amount of high-rise development.

Figure 9.55 shows that total greenhouse emissions are 2% lower than in the baseline scenario, with decreases in all categories except public transport, which rises 3% (due to substitution of public transport provided mobility for private vehicle provided mobility).

Figure 9.56 shows that housing satisfaction is lower both overall, and amongst all household types, compared to the baseline scenario. However, satisfaction is higher than in both the other

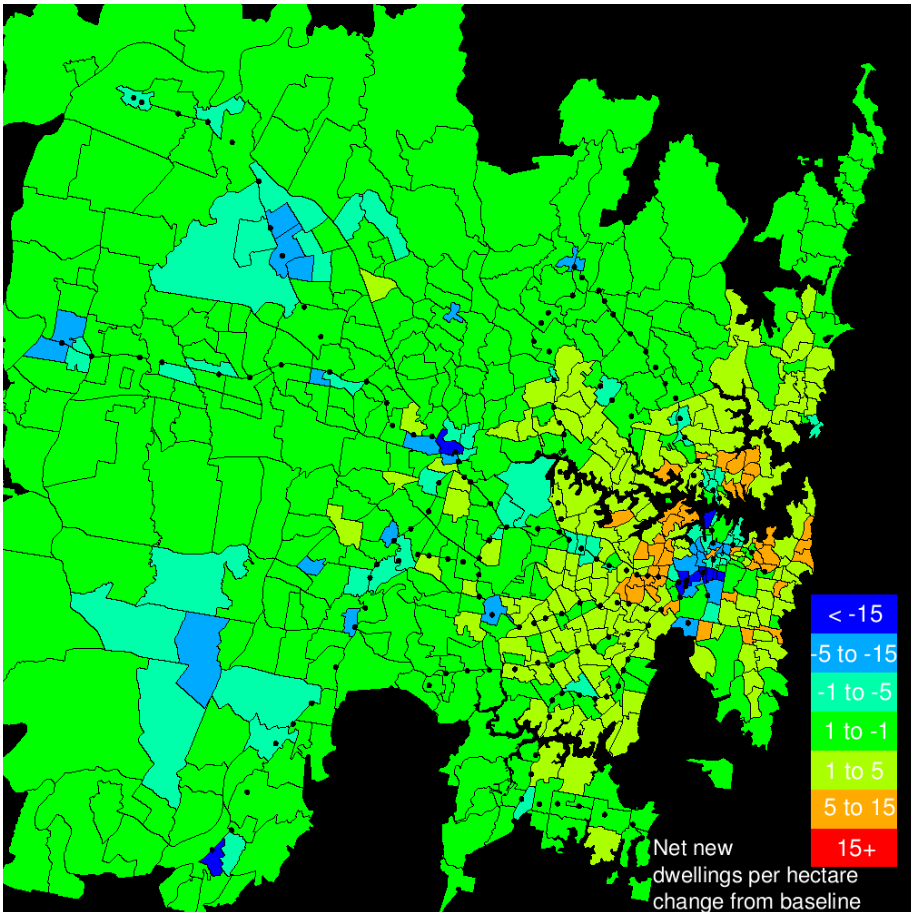


Figure 9.53: Scenario 7: additional new dwellings per hectare compared to baseline scenario.

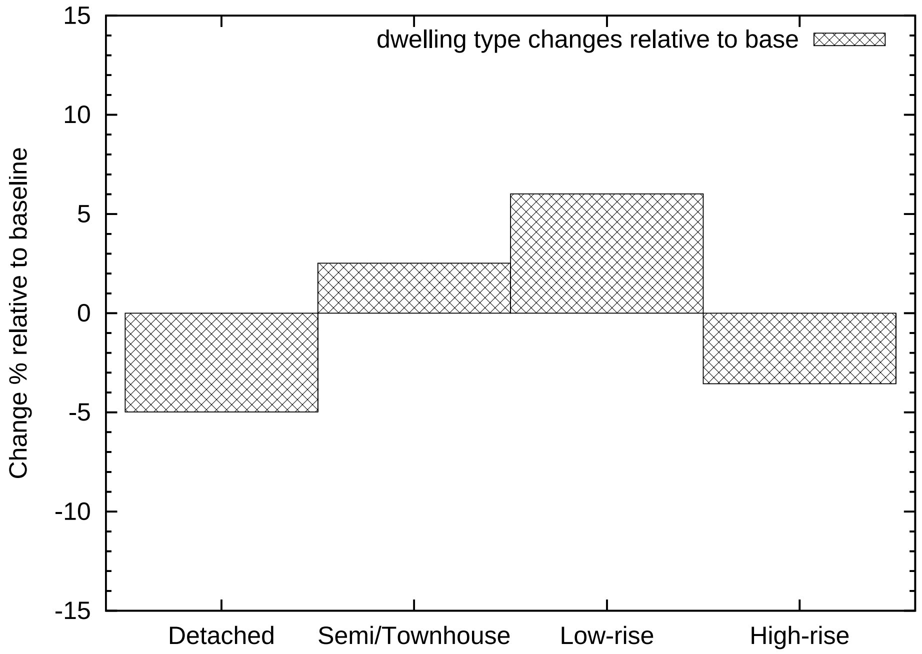


Figure 9.54: Scenario 7: Change in dwelling mix, compared to baseline scenario. Note that these are absolute percentages, so a reported 1% decline indicates that the proportion of all dwellings of that dwelling type is 1% lower.

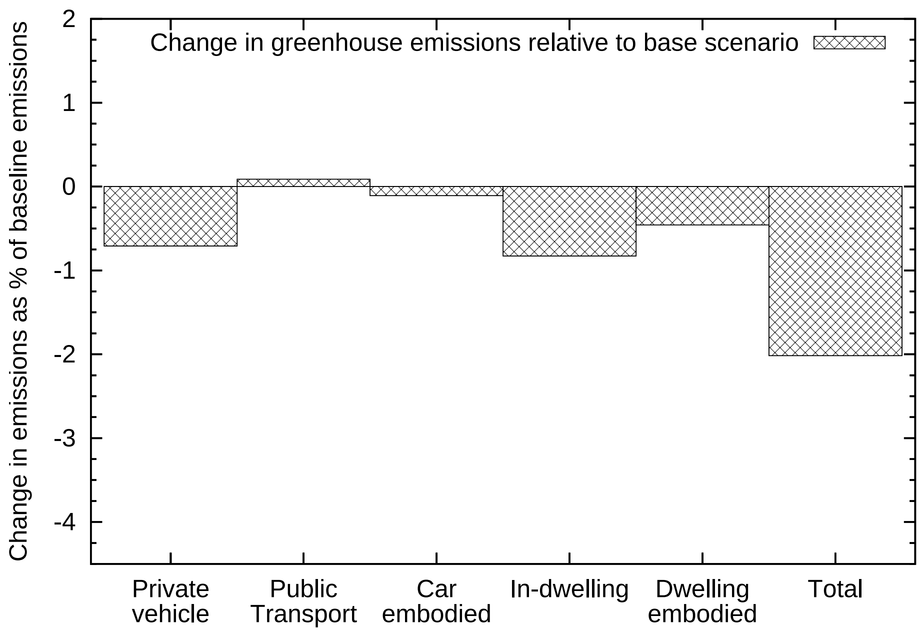


Figure 9.55: Scenario 7: Change in greenhouse emissions, compared to baseline scenario. Note that changes for each end-use are expressed as a percentage of *total* baseline emissions (i.e. from all end uses).

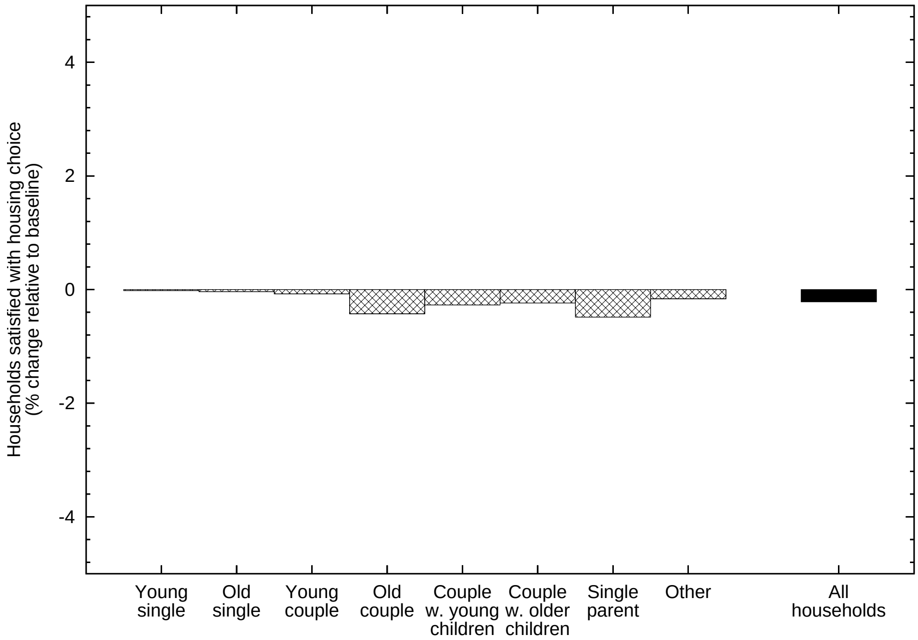


Figure 9.56: Scenario 7: Change in housing satisfaction by household type, compared to baseline scenario. Note that changes are expressed as absolute percentages. So a value reported here of -1% indicates that overall satisfaction levels are 1 percentage point lower for that household type, compared to the baseline scenario.

scenarios with 40% less fringe development (i.e. scenarios 2 & 3).

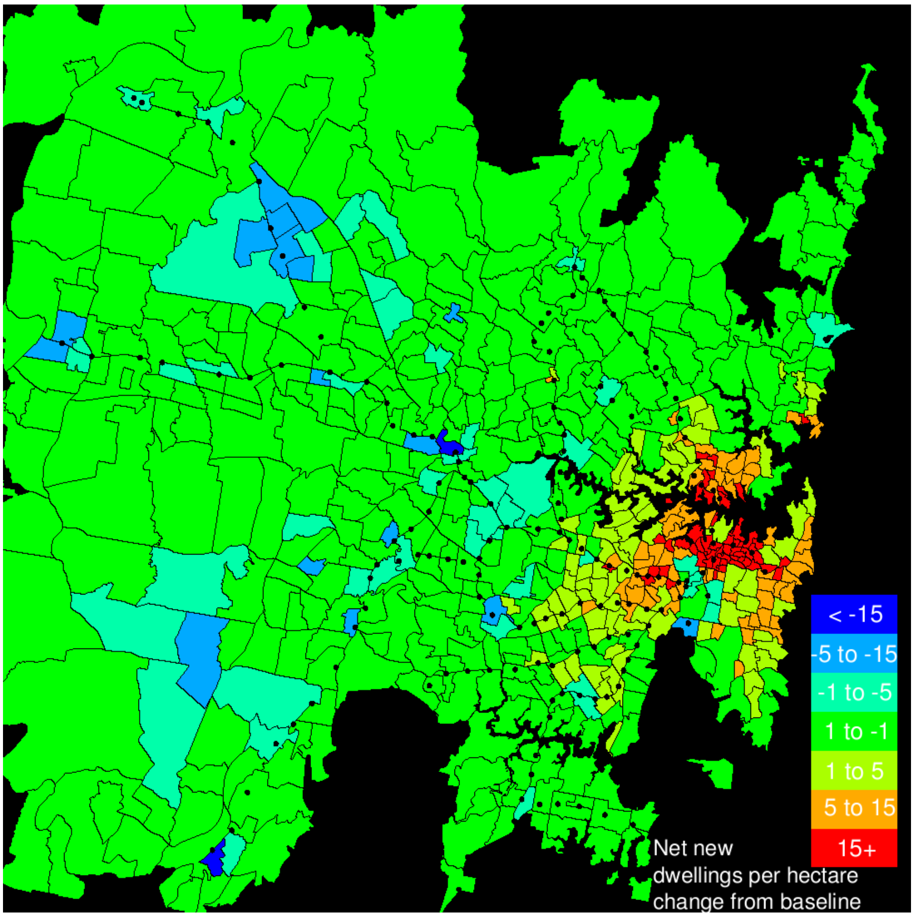


Figure 9.57: Scenario 8: additional new dwellings per hectare compared to baseline scenario.

9.2.8 Scenario 8: 'high-rise re-development' (-40% fringe)

Scenario 8 is still based on Sydney's metropolitan strategy, but, like scenario 7, some of the re-development in the more distant centres and suburbs takes place closer to the CBD. Unlike scenario 7, however, where this re-development occurred in the form of medium density dwelling forms (i.e. semi-detached/townhouse and low-rise apartments), almost all of the shifted re-development takes place in the form of high-rise apartments. Figure 9.57 shows the number of additional dwellings per hectare built compared with the baseline scenario.

Figure 9.58 shows the large shift towards high-rise apartments that takes place in this scenario. Because the number of new dwellings built on the fringe is 40% less than in the baseline strategy, there is still a net decrease in the number of detached dwellings available, but note that this decrease is less than in any of the other scenarios that have 40% less fringe development. This is because scenario 8, with its strong focus on developing high-rise apartments in the CBD and other major centres, results in less demolition of existing detached housing stock.

Figure 9.59 shows that total greenhouse emissions are around 0.8% lower than in the baseline scenario, with a large decrease in private vehicle emissions being offset by higher dwelling-related emissions. Public-transport related emissions also rise markedly in percentage terms, but this

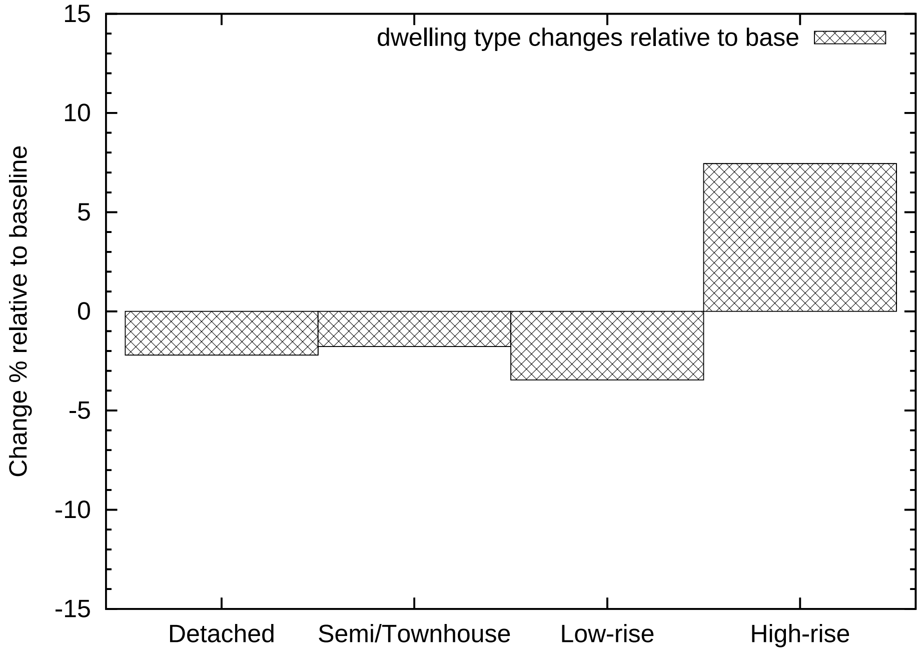


Figure 9.58: Scenario 8: Change in dwelling mix, compared to baseline scenario. Note that these are absolute percentages, so a reported 1% decline indicates that the proportion of all dwellings of that dwelling type is 1% lower.

is off a very low base. The increase in embodied energy is understandable, given that much of the high-rise development is taking place instead of low-rise apartment development. This also explains the increase in in-dwelling energy use, as it is an assumption of the model that energy use is one-third higher in high-rise apartments than in low-rise apartments (see Section 7.4.1).

The focus on high-rise inner-city redevelopment also makes scenario 8 the first scenario to result in a split between the housing satisfaction levels of different household types, as Figure 9.60 shows. Lone person households are happier with the housing provided, compared to the baseline scenario. Such households are not averse to apartment living, and young lone households in particular place greater value on proximity than on suburban amenity. Young couples without children show satisfaction levels similar to those in the baseline scenario, while the other 5 household types are all less satisfied with the focus on high-density high-rise living. The overall satisfaction level (i.e. weighted by household numbers across all household groups) is lower than in the baseline scenario, but, with the exception of scenario 7 ('mildly Parisian re-development'), housing satisfaction is higher than in any other scenario with 40% less fringe development. These results, and the satisfaction results from scenario 7, suggest that there may be alternatives to the metropolitan strategy that result in higher levels of community satisfaction.

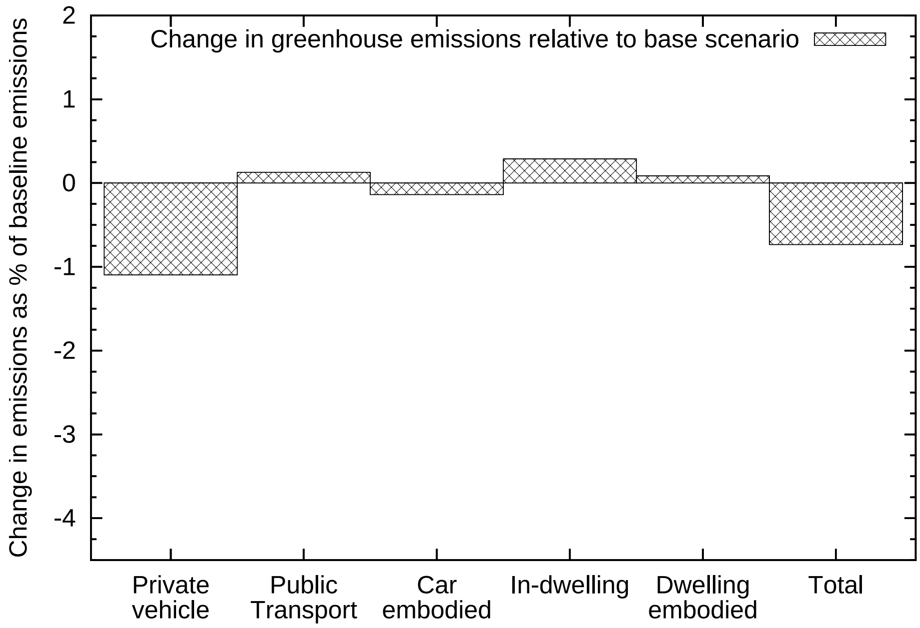


Figure 9.59: Scenario 8: Change in greenhouse emissions, compared to baseline scenario. Note that changes for each end-use are expressed as a percentage of *total* baseline emissions (i.e. from all end uses).

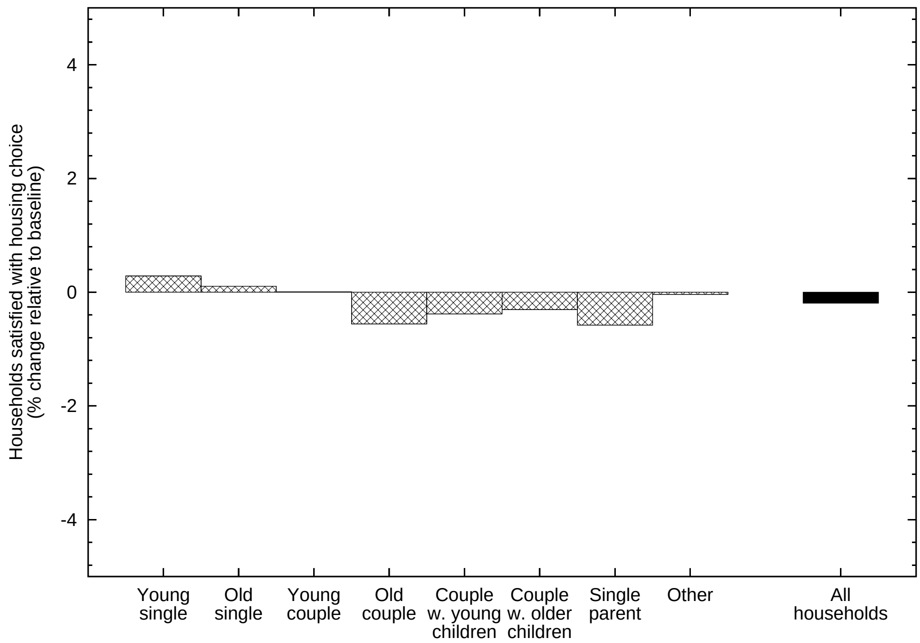


Figure 9.60: Scenario 8: Change in housing satisfaction by household type, compared to baseline scenario. Note that changes are expressed as absolute percentages. So a value reported here of -1% indicates that overall satisfaction levels are 1 percentage point lower for that household type, compared to the baseline scenario.

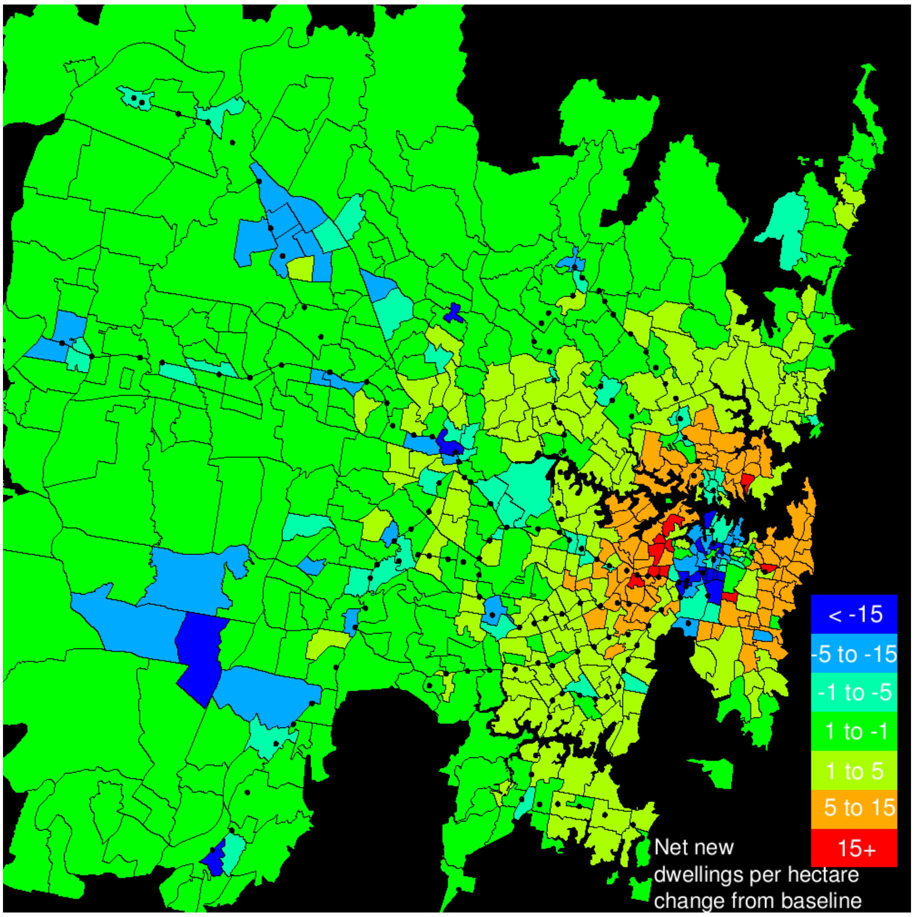
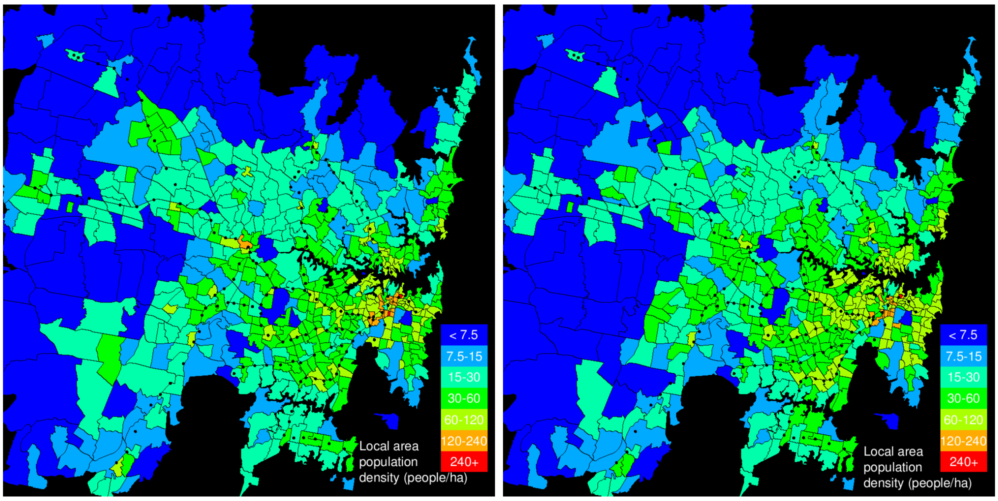


Figure 9.61: Scenario 9: additional new dwellings per hectare compared to baseline scenario.

9.2.9 Scenario 9: 'Parisian re-development' (-67% fringe)

Although scenarios 7 and 8 represent larger diversions from Sydney's metropolitan strategy than any of scenarios 2 through 6, they are both still based, fundamentally, on the metropolitan strategy. Thus, while scenario 7 shifts some of the more far-flung redevelopment to the inner suburbs, a good deal of development planned (in the metro-strategy) for those areas still occurs. Scenario 9 represents the first scenario that is a major deviation from the baseline scenario. It is also a scenario that, given the practical and political constraints placed on the planning process, will never come to pass. Despite this, it is a useful thought experiment, to further develop our understanding of the potential impact of different approaches.

Scenario 9 is similar to scenario 7, but represents a much stronger focus on inner-suburban re-development than does scenario 7. There is also less fringe development than in any other scenario evaluated thus far. Figure 9.61 shows the number of additional dwellings per hectare built compared with the baseline scenario. However, because scenario 9 represents a significant deviation from the baseline scenario, this Figure is less informative than for other scenarios, and so an additional figure is included (Figure 9.62), which shows contrasting population density figures for the baseline scenario and scenario 9.



(a) Baseline

(b) Scenario 9

Figure 9.62: Scenario 9: contrasting population density figures for baseline scenario and scenario 9.

Figure 9.63 shows the large shift towards low-rise apartments (and, to a lesser extent, terrace/-townhouse/semi-detached dwellings) that takes place in this scenario, with large decreases in detached dwellings (due to less fringe release, and more inner-suburban re-development), and high-rise apartments.

Figure 9.64 shows that total greenhouse emissions are around 4% lower than in the baseline scenario – by far the largest decrease for any scenario so far. Significant decreases in emissions can be found in all categories except public transport.

Housing satisfaction is lower for all households groups, as Figure 9.65 shows, but satisfaction levels are quite close to the baseline scenario levels, and are *better* than scenarios 2 and 3, even though there is even less fringe development than in those cases.

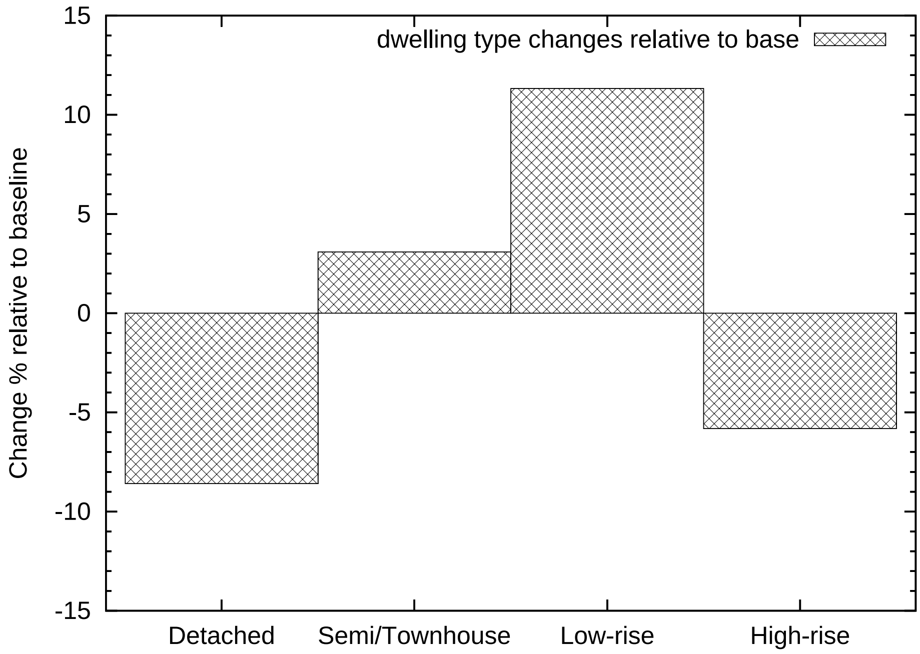


Figure 9.63: Scenario 9: Change in dwelling mix, compared to baseline scenario. Note that these are absolute percentages, so a reported 1% decline indicates that the proportion of all dwellings of that dwelling type is 1% lower.

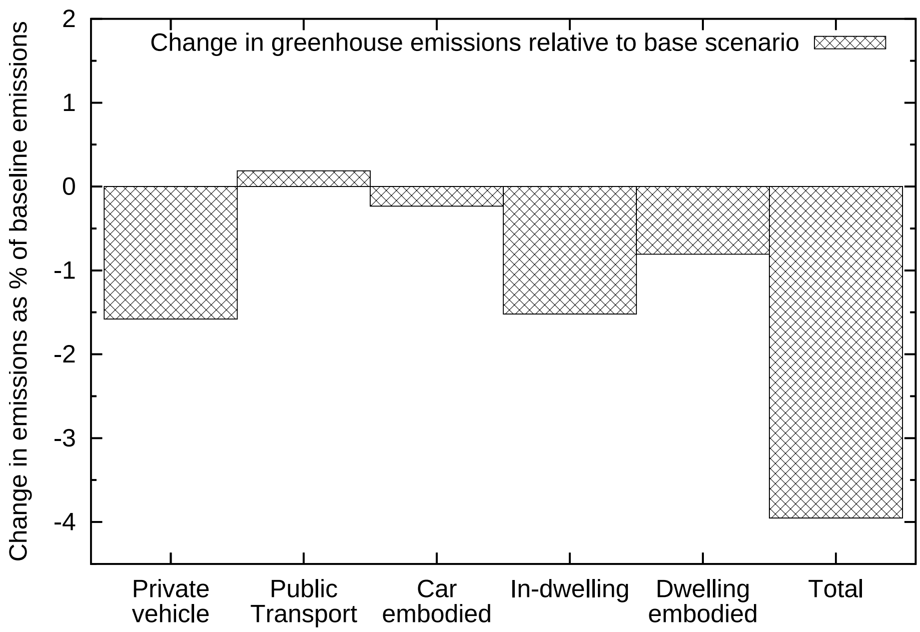


Figure 9.64: Scenario 9: Change in greenhouse emissions, compared to baseline scenario. Note that changes for each end-use are expressed as a percentage of *total* baseline emissions (i.e. from all end uses).

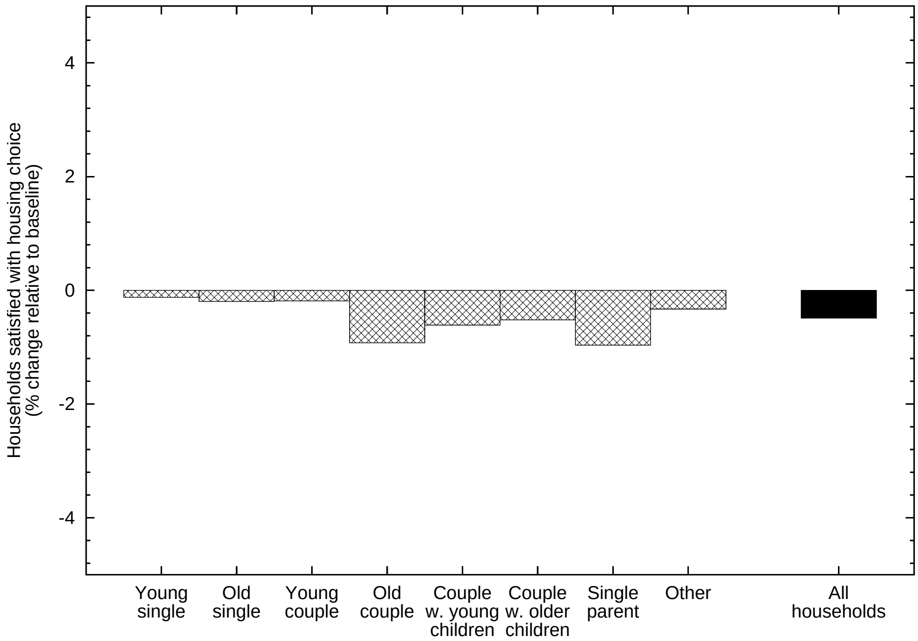


Figure 9.65: Scenario 9: Change in housing satisfaction by household type, compared to baseline scenario. Note that changes are expressed as absolute percentages. So a value reported here of -1% indicates that overall satisfaction levels are 1 percentage point lower for that household type, compared to the baseline scenario.

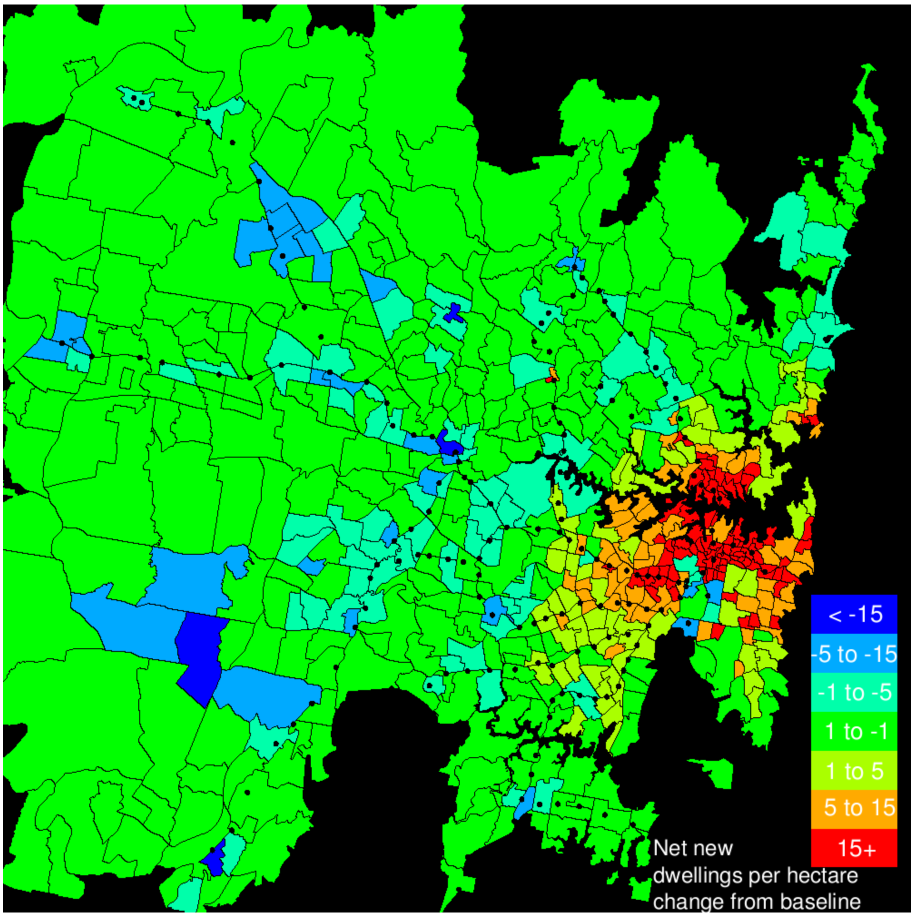


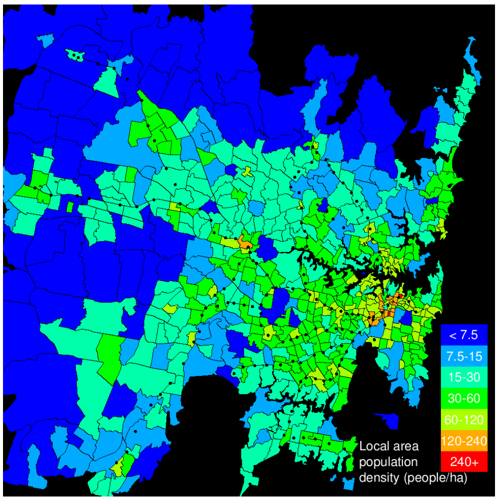
Figure 9.66: Scenario 10: additional new dwellings per hectare compared to baseline scenario.

9.2.10 Scenario 10: 'Hong-Kong style re-development' (-67% fringe)

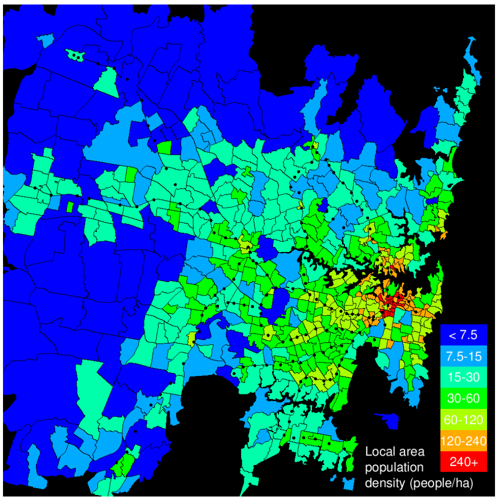
Scenario 10, like scenario 9, represents a major deviation from the baseline scenario. Unlike scenario 9, in which the focus was on the re-development of inner-suburban detached housing into low-rise apartments and townhouses/terraces, the focus is on re-development of inner-city areas. These areas, because they contain no detached dwellings, can only accommodate additional residential dwellings if those dwellings are constructed in the form of high-rise apartments. Thus, this scenario is dubbed the 'Hong Kong' scenario, and represents an extension of the policy direction already evaluated in scenario 8.

Figure 9.66 shows the number of additional dwellings per hectare built compared with the baseline scenario. Figure 9.67 shows contrasting population density figures for the baseline scenario and scenario 10.

Figure 9.68 shows the very large shift towards high-rise apartments that takes place in scenario 10. Note also that although there is a large reduction in fringe development (as in scenario 9), the focus on the building of high-rise apartments in the city core means that detached suburban homes are spared from demolition and redevelopment, with only a small reduction in the proportion of detached dwellings, compared to scenario 9.



(a) Baseline



(b) Scenario 10

Figure 9.67: Scenario 10: contrasting population density figures for baseline scenario and scenario 10.

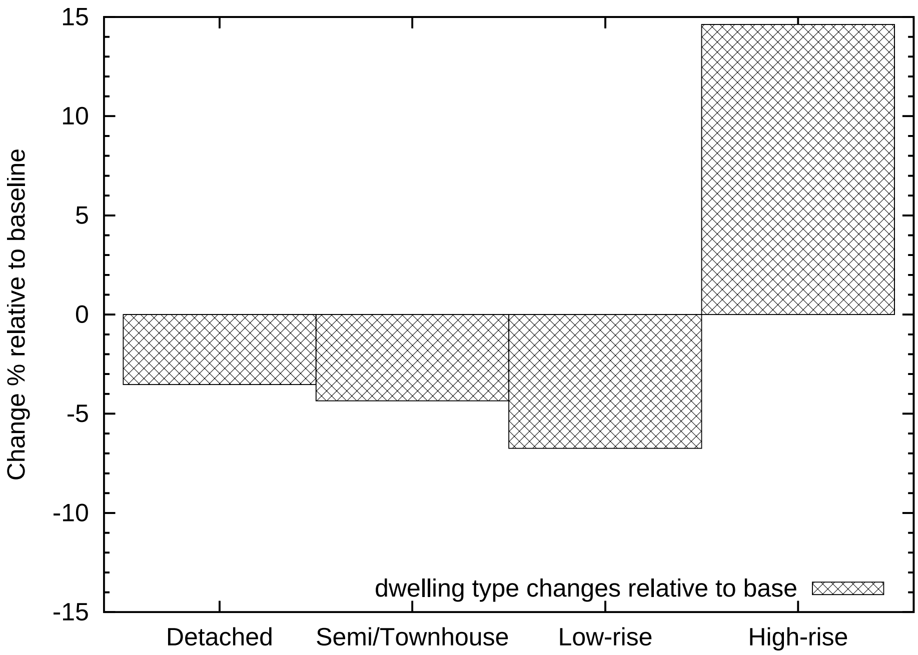


Figure 9.68: Scenario 10: Change in dwelling mix, compared to baseline scenario. Note that these are absolute percentages, so a reported 1% decline indicates that the proportion of all dwellings of that dwelling type is 1% lower.

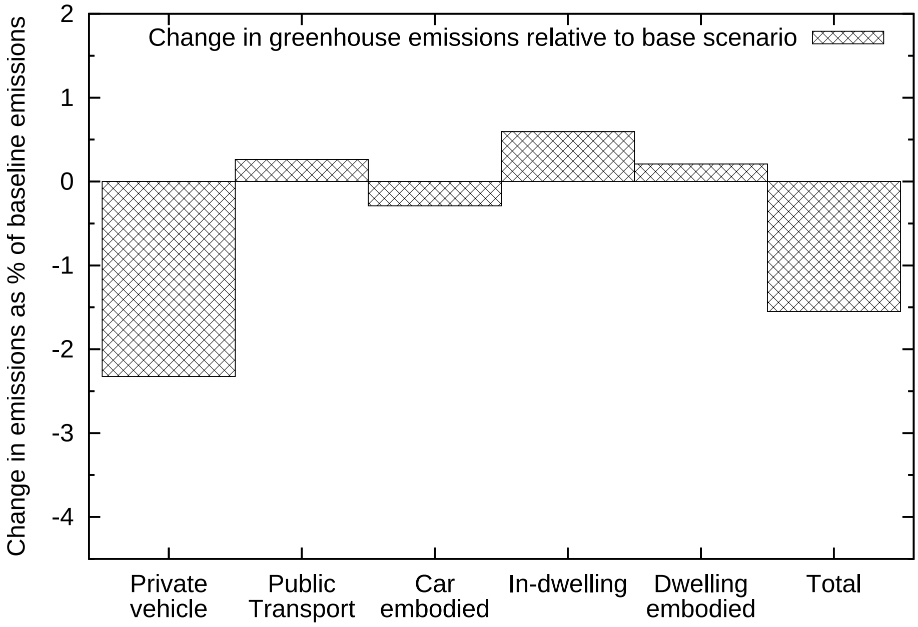


Figure 9.69: Scenario 10: Change in greenhouse emissions, compared to baseline scenario. Note that changes for each end-use are expressed as a percentage of *total* baseline emissions (i.e. from all end uses).

Figure 9.69 shows that total greenhouse emissions are around 1.5% lower than in the baseline scenario. There is a very large decrease in the energy associated with private auto-mobiles (embodied and operational), with this partly offset by increases in dwelling-related emissions.

Like scenario 8 (of which scenario 10 is a more extreme version), lone person households and young couples that are more comfortable with high-rise apartment living show an increase in housing satisfaction (relative to the baseline scenario), whereas other households are less satisfied. The overall effect is a moderate decrease is total satisfaction, compared to the baseline scenario.

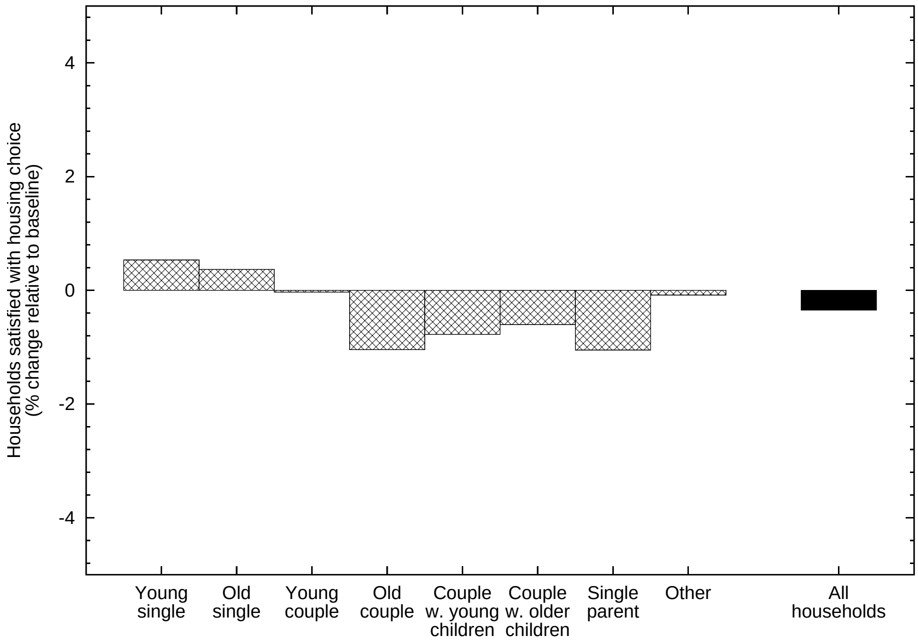


Figure 9.70: Scenario 10: Change in housing satisfaction by household type, compared to baseline scenario. Note that changes are expressed as absolute percentages. So a value reported here of -1% indicates that overall satisfaction levels are 1 percentage point lower for that household type, compared to the baseline scenario.

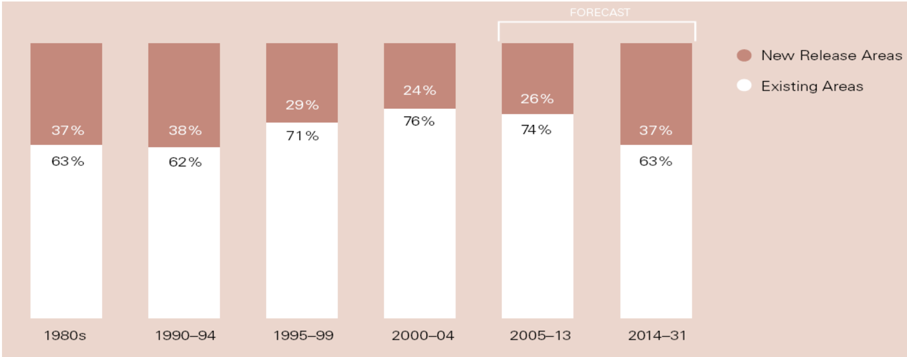


Figure 9.71: Land release and infill development proportions, from the 1980s to 2015 (projected). Source: NSW Department of Planning (2005)

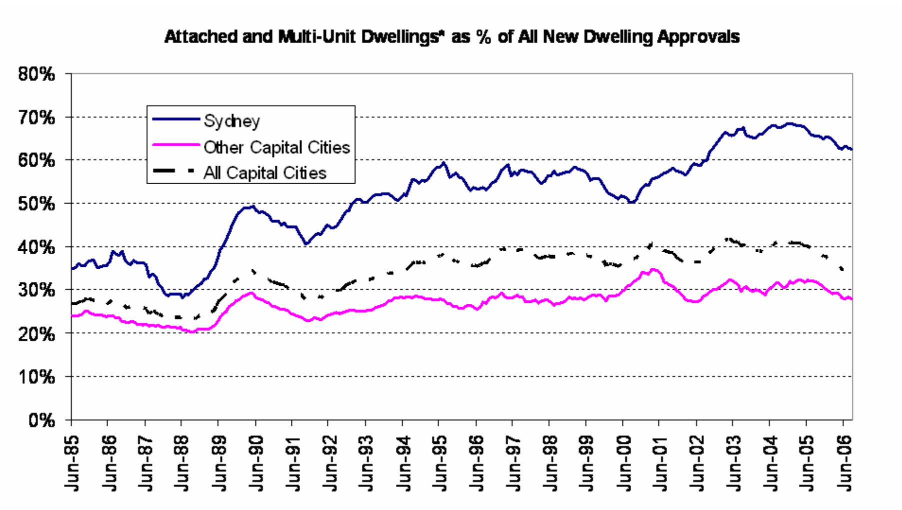


Figure 9.72: Historical rates of attached housing construction in Australian cities.

9.2.11 Scenario 11: 'Urban sprawl' (+150% fringe)

Scenario 11 represents the case where the majority of new housing is provided in the form of detached dwellings on newly released land on the urban fringe. This has been the method traditionally employed in many of Australia's cities, but new housing is increasingly being provided through redevelopment of existing urban areas, rather than through new land release. This trend is most pronounced in Sydney (see Figures 9.71 and 9.72).

Scenario 11 is an attempt to find out what would happen if Sydney returned to the model of providing the majority of new housing via the development of newly released land on the urban fringe. In this scenario, 25% of newly constructed housing (between 2006 and 2031) takes place through urban re-development, with the other 75% taking place on newly released land. Figure 9.73 shows the number of additional dwellings per hectare built compared with the baseline scenario, and Figure 9.74 shows the expected population density for scenario 11, compared to the baseline scenario.

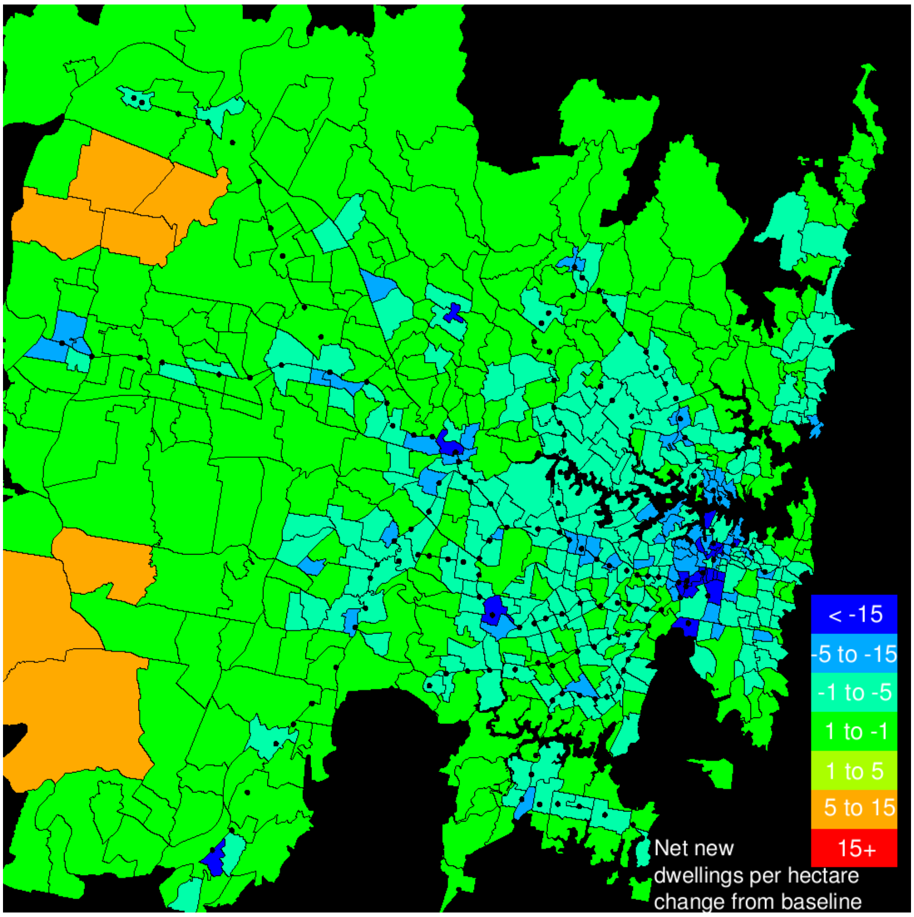
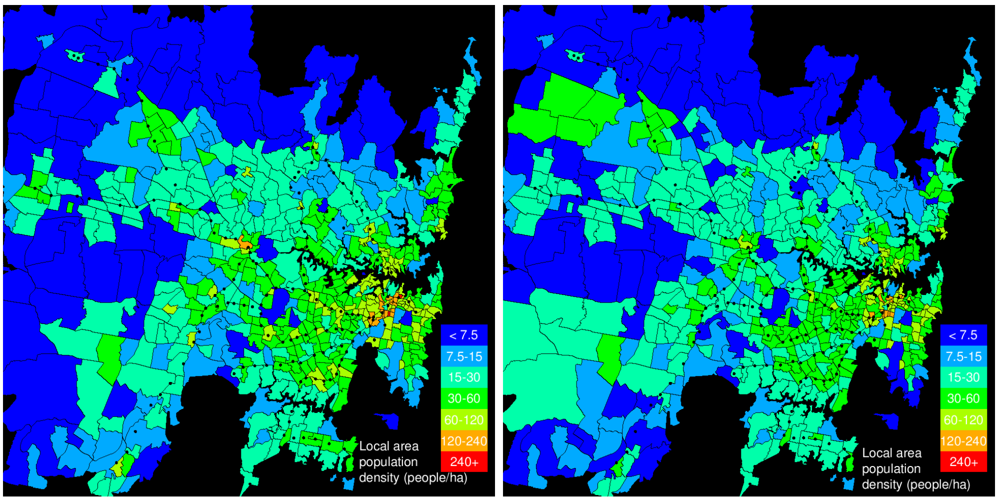


Figure 9.73: Scenario 11: additional new dwellings per hectare compared to baseline scenario.



(a) Baseline

(b) Scenario 11

Figure 9.74: Scenario 11: contrasting population density figures for baseline scenario and scenario 11.

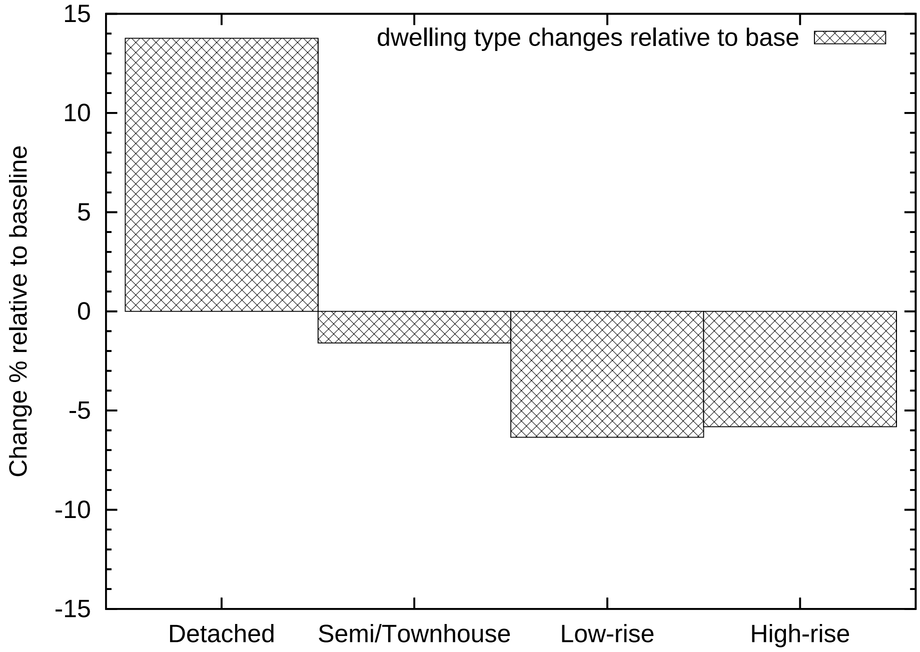


Figure 9.75: Scenario 11: Change in dwelling mix, compared to baseline scenario. Note that these are absolute percentages, so a reported 1% decline indicates that the proportion of all dwellings of that dwelling type is 1% lower.

Figure 9.75 shows the very large shift towards detached dwellings that takes place in scenario 11.

Figure 9.76 shows that per-household greenhouse emissions are 6% higher than in the baseline scenario – by far the highest of all scenarios analyzed thus far. Emissions increase in every category except public-transport, but the largest contributor is the increase in emissions from private vehicle travel. Note that the scale in Figure 9.76 is different to the scale used in other scenarios.

Scenario 11 results in the most dramatic increases in housing satisfaction of any other scenario, as Figure 9.77 shows. Housing satisfaction levels increase for *all* household types, even those who prefer apartment living. This suggests that in other scenarios, there is large unmet demand for detached dwellings, and releasing additional land on the fringe lifts housing satisfaction by directly satisfying the preferences of large numbers of family households, and thereby indirectly reducing competition for well located housing in more accessible areas (preferred by non-family households).

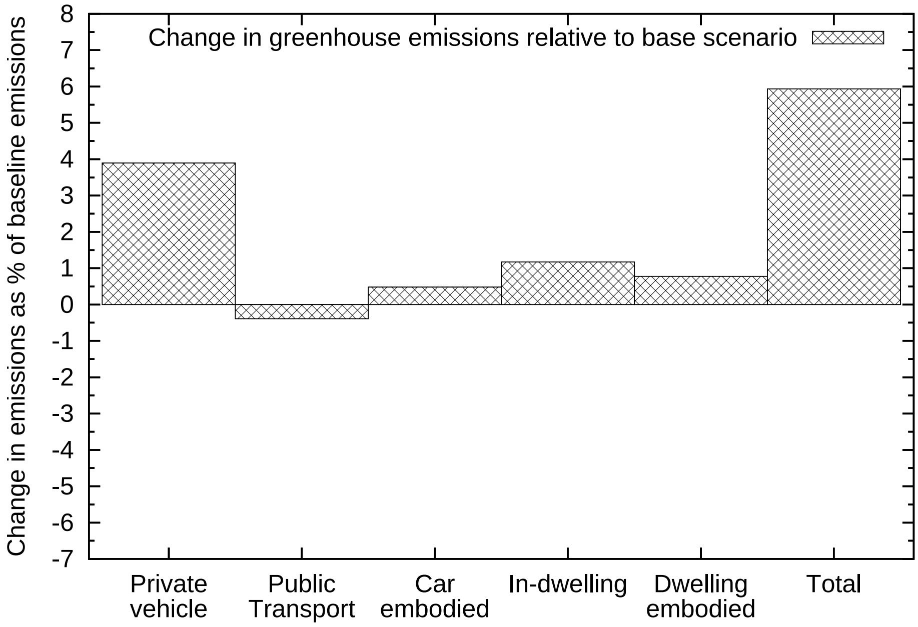


Figure 9.76: Scenario 11: Change in greenhouse emissions, compared to baseline scenario. Note that changes for each end-use are expressed as a percentage of *total* baseline emissions (i.e. from all end uses). *Note that the scale used is different to that used for previous scenarios, as changes to emissions are greater.*

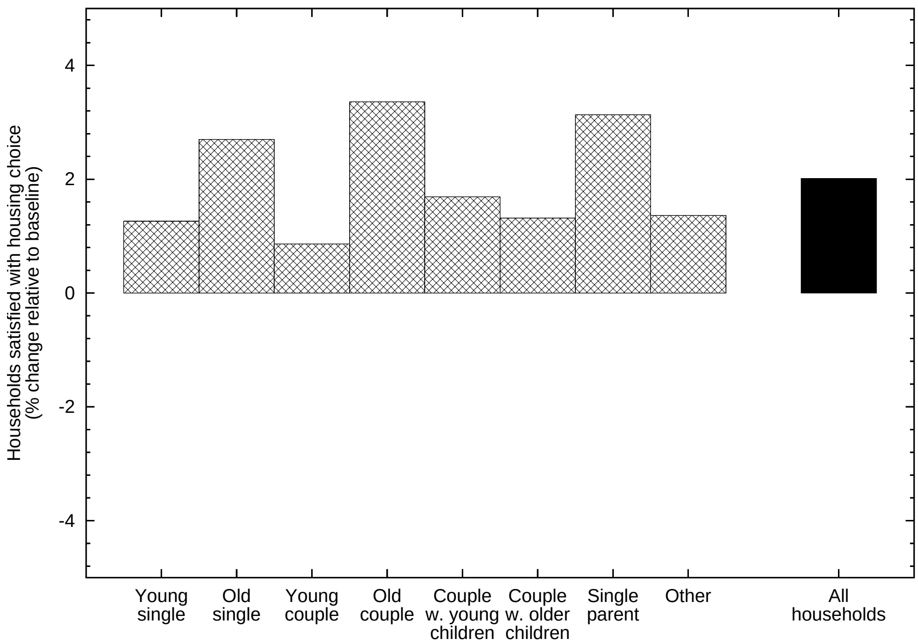


Figure 9.77: Scenario 11: Change in housing satisfaction by household type, compared to baseline scenario. Note that changes are expressed as absolute percentages. So a value reported here of -1% indicates that overall satisfaction levels are 1 percentage point lower for that household type, compared to the baseline scenario.

9.3 Scenarios *with* land-use/transport feedback

Suppose we wish to know the effect of location on a household's travel behaviour. We can use cross-sectional data to observe that households close to the city centre, or households close to a major rail interchange, own fewer cars, and travel less distance, than an equivalent household on the urban fringe. An analysis along these lines allows us to estimate the *marginal* effect of moving a household from one location to another. This does *not* allow us, however, to estimate the effect of moving a large number of households, for two reasons. Firstly it is not necessarily the case that the overall effect will be the sum of the marginal effects for each household, because large changes may render the original (marginal) estimate invalid. Secondly, and more importantly, marginal analyses of the effect of location on travel behaviour ignore the effect that a household has on the travel behaviour of other households. While the marginal effect *on other households* of moving a single household is negligible, this is *not* the case when moving large number of households. An example may make things clearer. Suppose that, as a result of planning policy, a particular urban centre becomes home to a large number of additional households, and this makes congestion worse in the roads near the centre, parking becomes more difficult, and the local transport authority provides better public transport to service the centre. The impact of these changes is felt not only by the new residents of the local area, nor even by the new and existing residents of the local area, but by *all* households in the metropolitan area. *Everyone* will now find it more difficult to drive to and park at this location, and easier to catch public transport. For changes on a larger scale, this effect intensifies. Increasing employment and population density in a few selected urban centres may allow for the expansion of the existing rail network to those centres. This affects not just residents of those centres, but all residents travelling to those centres. Concentrating only on estimating marginal effects of urban structure and location on individual households will result in systematic underestimation of the long-term effect of urban structure on travel behaviour.

Having pointed out, in the preceding paragraph, the importance of taking into account the city-wide effects of different planning policies, I now re-analyze the scenarios analyzed in Section 9.2, but with a correction to capture these city-wide effects. To do this properly would require both a detailed transport model *and* a model capable of estimating at least the likely transport infrastructure & service response for each scenario. This is a formidable task, given the vagaries involved in transport policy formulation, and for this reason, no transport model (or integrated land-use/transport model) attempts this. Instead of accepting that the task is too difficult, however, I prefer to make an attempt. Just because it is difficult to model long term city-wide effects does not mean that the most appropriate response is to ignore them, as I have done in the analysis in Section 9.2.

My method for estimating city-wide effects is to calculate total (i.e. city-wide) population density for the city of Sydney in 2031 for each scenario, and assume that each unit increase in aggregate population density (people per hectare) results in a 1% reduction in per-household vehicle travel. The value of 1% is chosen by simple inspection of an exponential curve fitted to the data of density and per-capita private vehicle energy use in Newman and Kenworthy (1999). A adjustment is then made to correct for the fact that the densities reported in Newman and Kenworthy (1999) tend to be lower than those I calculate for Sydney[7]. The value obtained after

[7]The Sydney urban region I use is not the same as the Sydney Statistical Division used in Newman and

this process is closer to a 1.5% decrease in transport energy per unit increase in density, but I prefer to be conservative and assume 1%, for two reasons. Firstly, the transport model I use will capture some of the effects of increased density; and secondly, I prefer to establish a firm lower bound on the effect of housing policy rather than a more speculative estimate of what may be possible. The approach I use is simple. Developing a more realistic model is something beyond the scope of this thesis, and is a matter for further research.

Because all the scenarios re-analyzed in this section have already been analyzed in Section 9.2, the commentary and reporting for each scenario is much less comprehensive than in Section 9.2. In particular, figures showing the mix of dwelling types, the spatial distribution of new dwelling construction, and housing satisfaction are not reproduced, as they are identical to those in Section 9.2, and so only changes to greenhouse emissions are shown.

In all cases, I have also adjusted the parameter relating to in-dwelling energy use in high-rise apartments such that energy use is assumed to be 16.5% higher in high rise apartments than in low-rise apartments, rather than the 33% assumed in the scenarios in Section 9.2. The reader may remember that there was considerable uncertainty about this parameter (see Section 7.4.1), and I would like to consider a range of scenarios where in-dwelling energy use in high-rise is only moderately higher than in low-rise.

Kenworthy (1999).

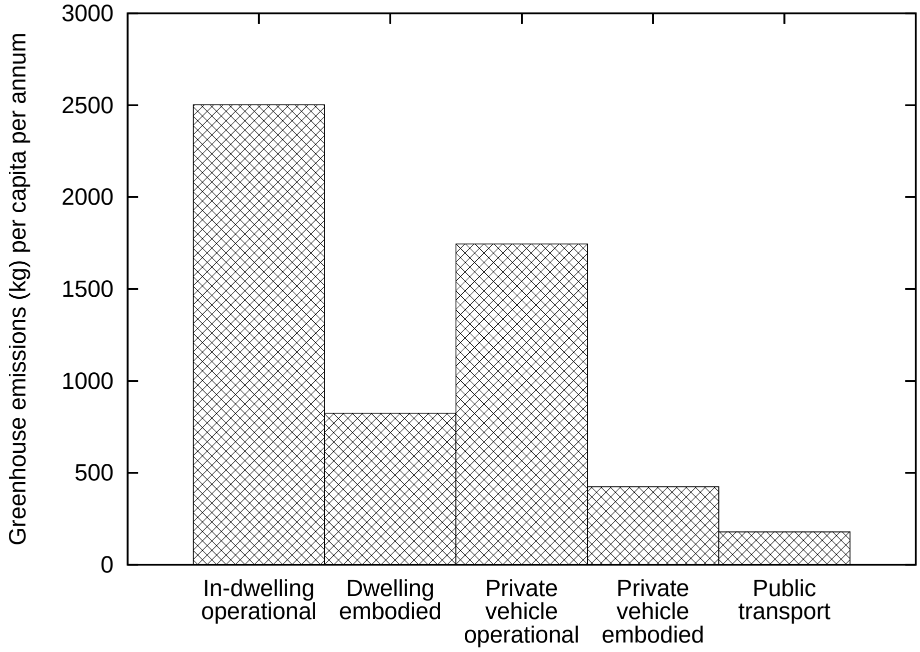


Figure 9.78: Average per-capita greenhouse emissions by category (projected for 2031) for baseline scenario with simple land-use→transport feedback.

9.3.1 Scenario 1a: baseline

Figure 9.78 shows projected per-capita emissions for the baseline scenario when a simple land-use→transport feedback correction is applied. These numbers differ very little from those in Figure 9.27, with a small reduction in emissions from private vehicle travel ($\approx$ 50 kg per capita per year). There is also a small reduction in emissions related to in-dwelling energy use ($\approx$ 50 kg per capita per year), because of the assumption of slightly more energy efficient high-rise apartments. The result is that *total* per-capita emissions for the baseline scenario are 1.7% lower with city-wide land-use/transport feedback than without.

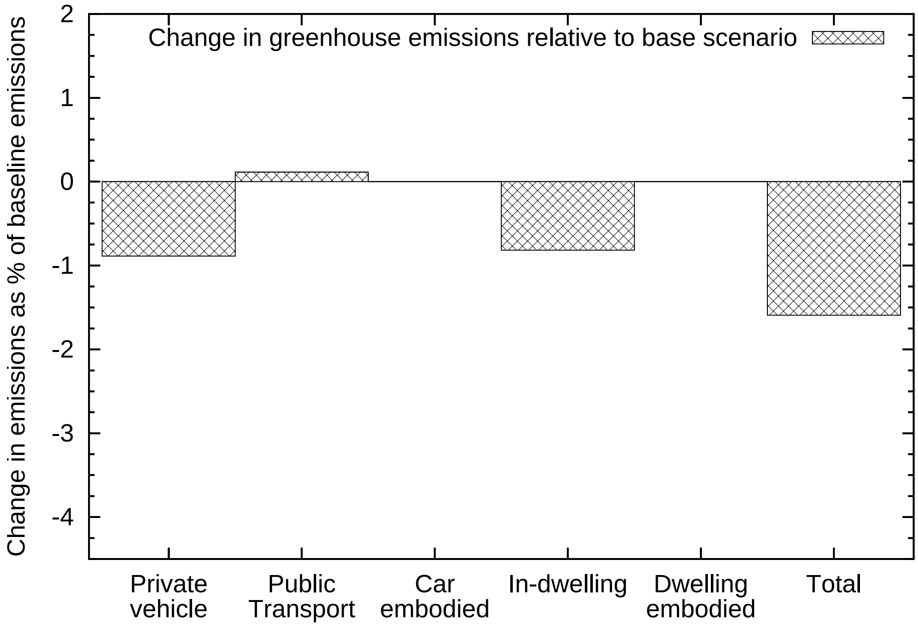
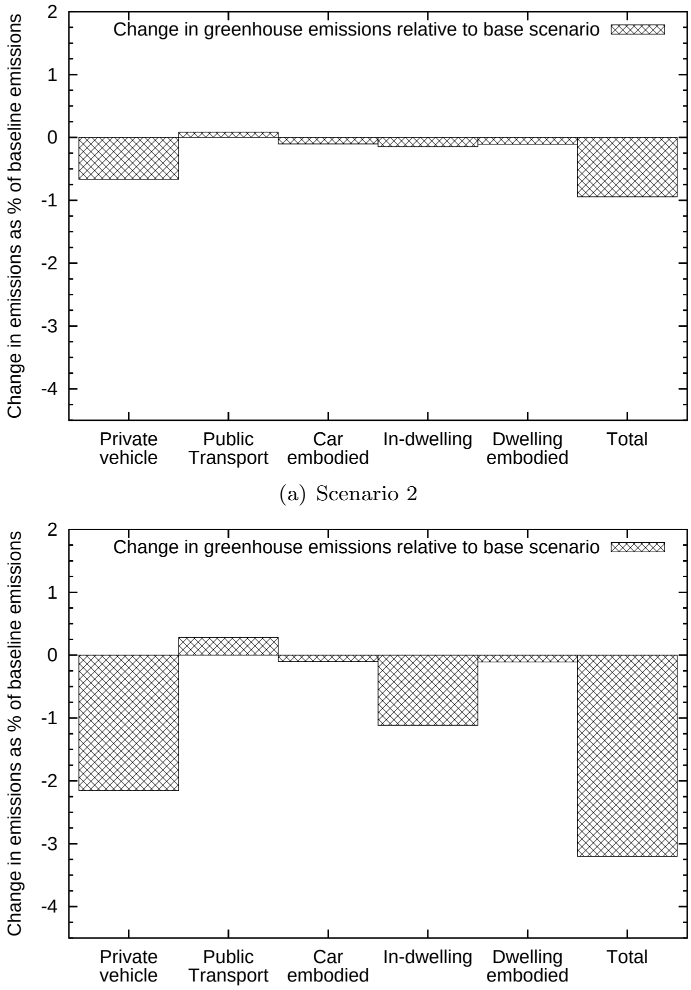


Figure 9.79: Scenario 1a: Change in greenhouse emissions, compared to baseline scenario without land-use→transport feedback (i.e. Scenario 1).

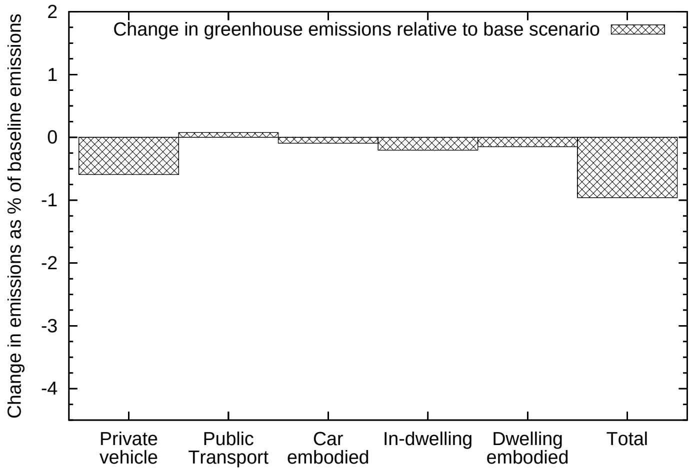


(b) Scenario 2a

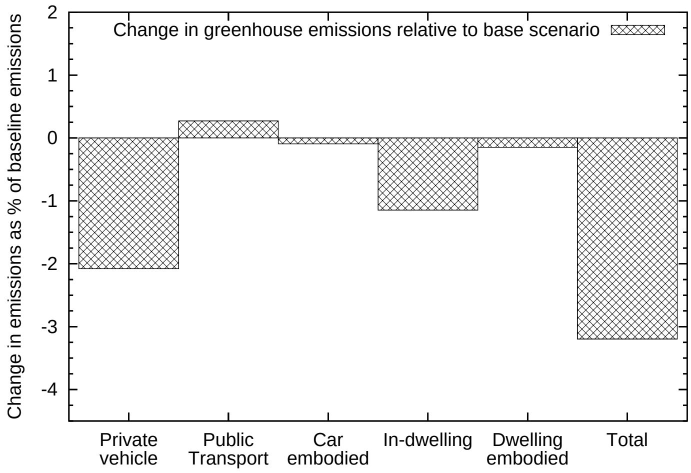
Figure 9.80: Scenario 2a: Change in greenhouse emissions, compared to baseline scenario 1a, and to the case where no land-use/transport feedback is assumed (i.e. Scenario 2).

9.3.2 Scenario 2a: +20% in centres, +0% in suburbs, -40% on fringe

Figure 9.80 shows the change in greenhouse emissions for scenario 2a, compared to the baseline scenario (scenario 1). The change in emissions for scenario 2 (i.e. without land-use feedback) is also reproduced here so that the reader can see what difference including land-use→transport feedback makes. We see that, because Scenario 2 involves a significant reduction in green-field development (compared to the baseline), the inclusion of a land-use→transport feedback reduces private vehicle emissions by significantly more than the case where no such feedback is included.



(a) Scenario 3



(b) Scenario 3a

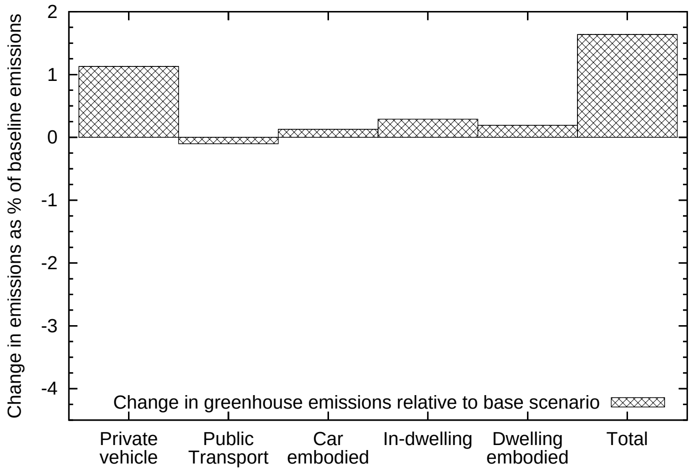
Figure 9.81: Scenario 3a: Change in greenhouse emissions, compared to baseline scenario 1a, and to the case where no land-use/transport feedback is assumed (i.e. Scenario 3).

9.3.3 Scenario 3a: +0% in centres, +75% in suburbs, -40% on fringe

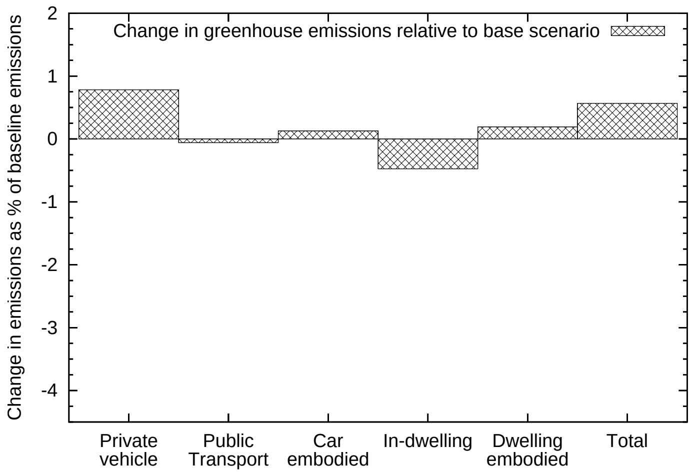
Figure 9.81 shows the change in greenhouse emissions for scenario 3a, compared to the baseline scenario (scenario 1). The change in emissions for scenario 3 (i.e. without land-use feedback) is also reproduced here so that the reader can see what difference including land-use→transport feedback makes. We see that, because scenario 3 involves a significant reduction in green-field development (compared to the baseline), the inclusion of a land-use→transport feedback reduces private vehicle emissions by significantly more than the case where no such feedback is included.

9.3.4 Scenario 4a: +5% in centres, -20% in suburbs, +0% on fringe

Because scenario 4 was found to differ so little from the baseline scenario (see Section 9.2.4), it was not re-evaluated with land-use/transport feedback.



(a) Scenario 5



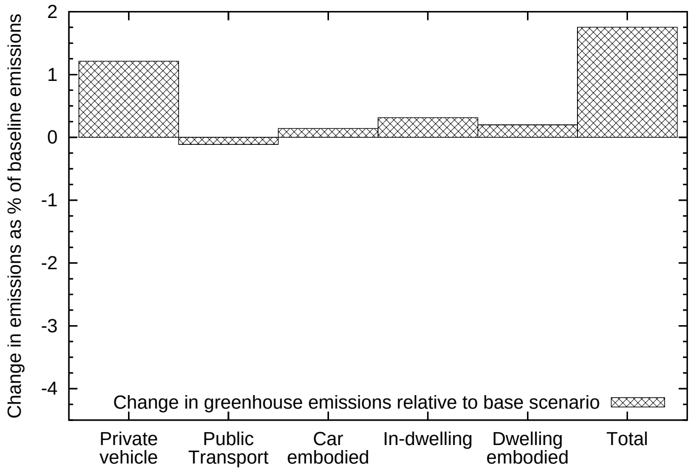
(b) Scenario 5a

Figure 9.82: Scenario 5a: Change in greenhouse emissions, compared to baseline scenario 1a, and to the case where no land-use/transport feedback is assumed (i.e. scenario 5).

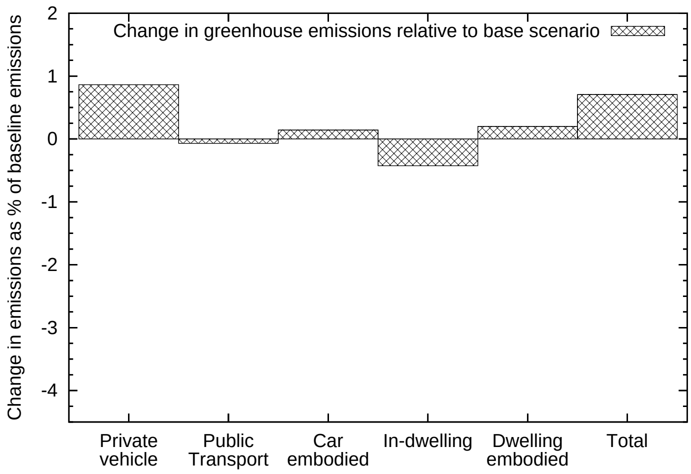
9.3.5 Scenario 5a: -10% in centres, -40% in suburbs, +40% on fringe

Figure 9.82 shows the change in greenhouse emissions for scenario 5a, compared to the baseline scenario (scenario 1). Because of the additional fringe development in scenario 5 (compared to the baseline), city-wide population density increases less than in the baseline scenario[8], and because there is no significant change in aggregate density, transport-related emissions are very similar to the case where no land-use→ feedback is included (i.e. scenario 5).

[8] Aggregate density still increases marginally, compared to 2006, but markedly less than in the baseline scenario.



(a) Scenario 6



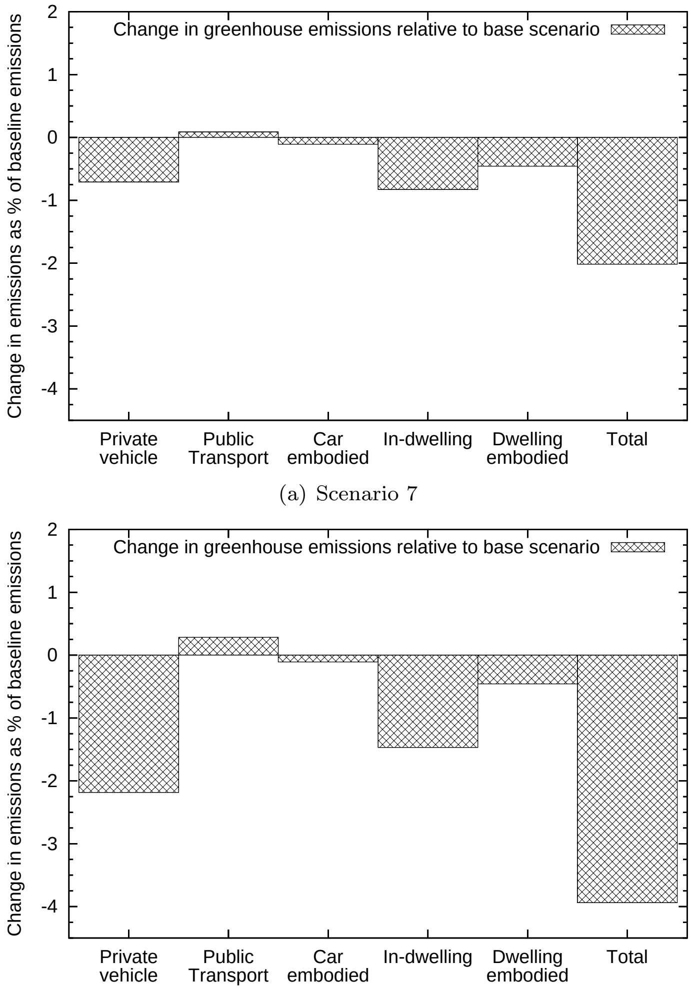
(b) Scenario 6a

Figure 9.83: Scenario 6a: Change in greenhouse emissions, compared to baseline scenario 1a, and to the case where no land-use/transport feedback is assumed (i.e. scenario 6).

9.3.6 Scenario 6a: -20% in centres, -7% in suburbs, +40% on fringe

Figure 9.83 shows the change in greenhouse emissions for scenario 6a, compared to the baseline scenario (scenario 1). Because of the additional fringe development in scenario 6 (compared to the baseline), city-wide population density increases less than in the baseline scenario[9], and because there is no significant change in aggregate density, transport-related emissions are very similar to the case where no land-use→feedback is included (i.e. scenario 6).

[9]Aggregate density still increases marginally, compared to 2006, but markedly less than in the baseline scenario.



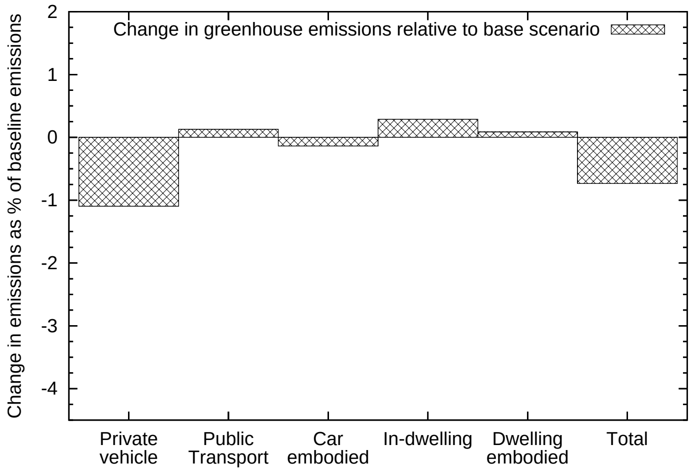
(a) Scenario 7

(b) Scenario 7a

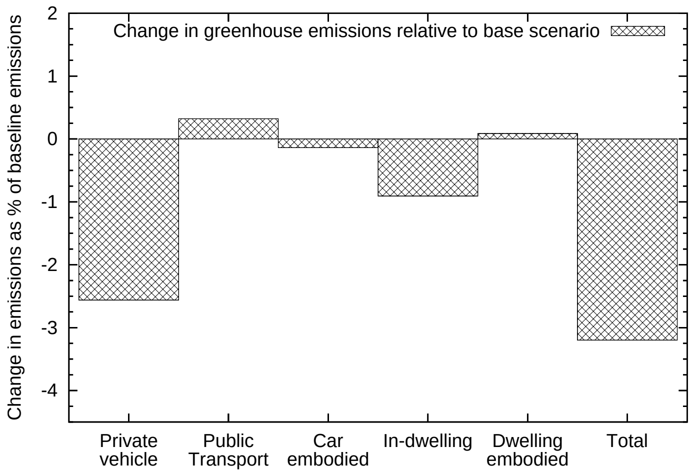
Figure 9.84: Scenario 7a: Change in greenhouse emissions, compared to baseline scenario 1a, and to the case where no land-use/transport feedback is assumed (i.e. scenario 7).

9.3.7 Scenario 7a: 'mildly Parisian re-development' (-40% fringe)

Scenario 7, the reader may recall, represents the first departure from the general planning framework laid out in the Sydney metropolitan strategy. Instead of concentrating on the distinction between 'centre', 'suburban', and 'fringe' development, scenario 7 has development close to the city core (CBD), but only a limited number of high-rise dwellings. The end result is a significant increase in low-rise dwellings in the inner-suburbs close to the city CBD. Figure 9.84 shows the change in greenhouse emissions for scenario 7a, compared to the baseline scenario (scenario 1).



(a) Scenario 8

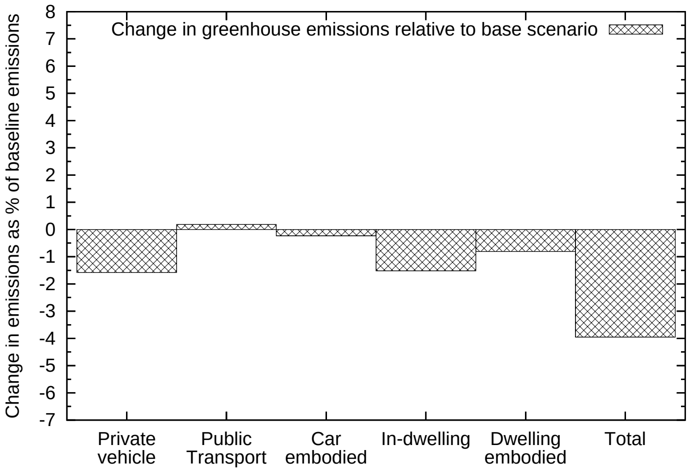


(b) Scenario 8a

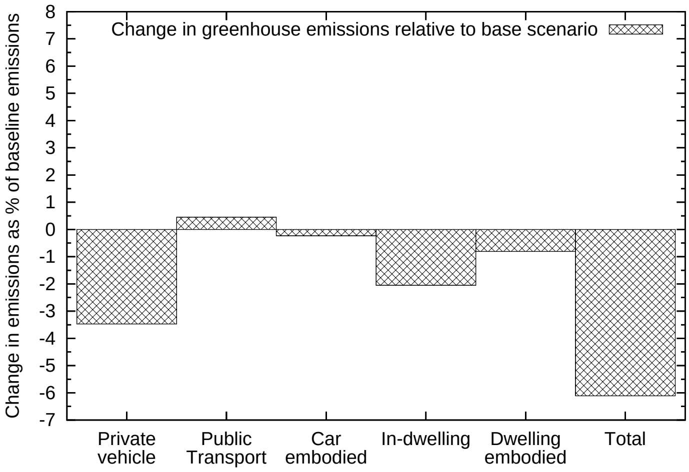
Figure 9.85: Scenario 8a: Change in greenhouse emissions, compared to baseline scenario 1a, and to the case where no land-use/transport feedback is assumed (i.e. scenario 8).

9.3.8 Scenario 8a: 'high-rise re-development' (-40% fringe)

The reader may recall that scenario 8, like scenario 7, sees a concentration of development near the city core. Unlike scenario 7, however, scenario 8 accomplishes this concentration through the building of high-rise apartment towers. Figure 9.85 shows the change in greenhouse emissions for scenario 8a, compared to the baseline scenario (scenario 1).



(a) Scenario 9

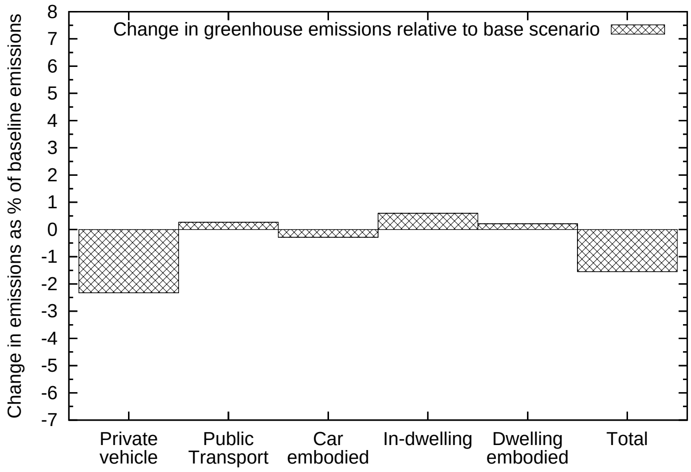


(b) Scenario 9a

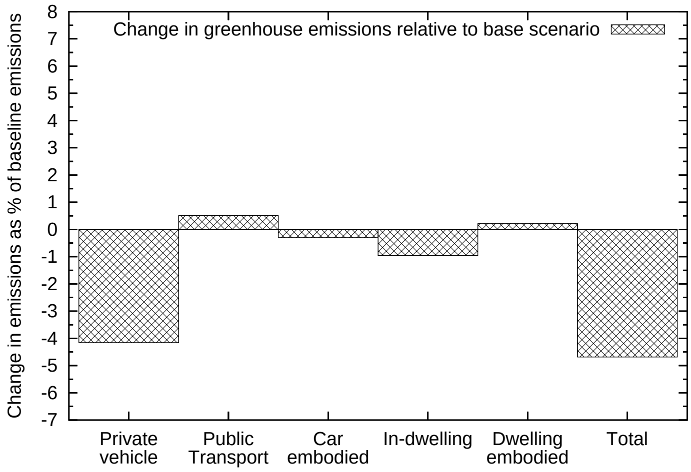
Figure 9.86: Scenario 9a: Change in greenhouse emissions, compared to baseline scenario 1a, and to the case where no land-use/transport feedback is assumed (i.e. scenario 9). *Note that the scale for this figure is different to that used for scenarios 1a-8a.*

9.3.9 Scenario 9a: 'Parisian re-development' (-67% fringe)

Scenario 9 is a more extreme version of scenario 7. Figure 9.86 shows the change in greenhouse emissions for scenario 9a, compared to the baseline scenario (scenario 1).



(a) Scenario 10

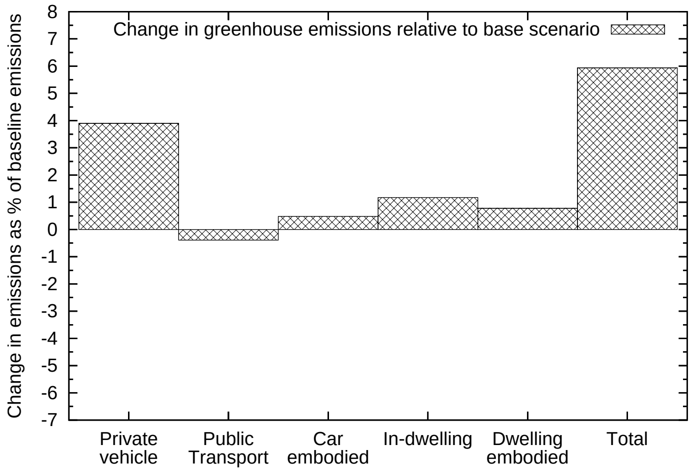


(b) Scenario 10a

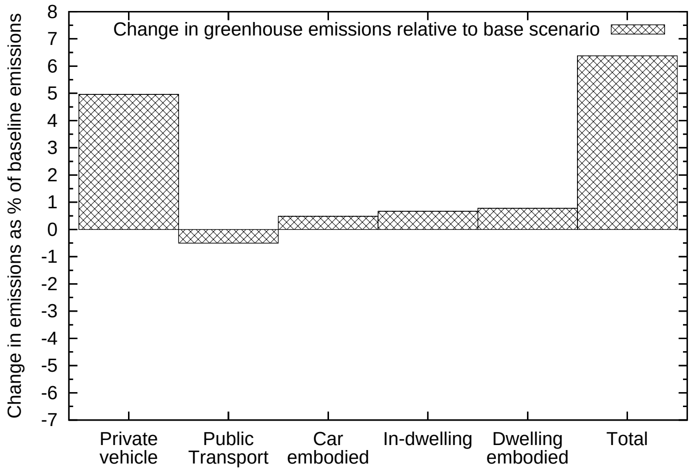
Figure 9.87: Scenario 10a: Change in greenhouse emissions, compared to baseline scenario 1a, and to the case where no land-use/transport feedback is assumed (i.e. scenario 10). *Note that the scale for this figure is different to that used for scenarios 1a-8a.*

9.3.10 Scenario 10a: 'Hong-Kong style re-development' (-67% fringe)

Scenario 10 is a more extreme version of scenario 8. Figure 9.87 shows the change in greenhouse emissions for scenario 10a, compared to the baseline scenario (scenario 1).



(a) Scenario 11



(b) Scenario 11a

Figure 9.88: Scenario 11a: Change in greenhouse emissions, compared to baseline scenario 1a, and to the case where no land-use/transport feedback is assumed (i.e. scenario 11). *Note that the scale for this figure is different to that used for scenarios 1a-8a.*

9.3.11 Scenario 11a: 'Urban sprawl' (+150% fringe)

Scenario 11 represents the case where the majority (three-quarters) of new development takes place by expansion on the urban fringe. This is the *only* scenario that results in a net decrease in aggregate population density for Sydney, and so is the only scenario where greenhouse emissions are *higher* when land-use→transport feedback is taken into account. Figure 9.88 shows the change in greenhouse emissions for scenario 11a, compared to the baseline scenario (scenario 1).

9.4 Miscellaneous scenarios/analyses

The evaluation of scenarios 1-11 (and 1a-11a) form the bulk of this chapter, and are the principal analyses which contribute to help answer the third thesis question ("How does housing location policy influence aggregate dwelling-related and transport-related household energy use?"). In those scenarios, the focus was on evaluating the effect of different land-use planning scenarios on residential energy and greenhouse emissions. Other factors were deliberately held constant, to facilitate this investigation. The following sections evaluate a few alternate scenarios, where different assumptions are made. Section 9.4.1 examines the effect of very high petrol costs on residential property prices and household incomes. Sections 9.4.2-9.4.5 consider the combined greenhouse savings possible through non-planning measures, such as improvements to vehicle and appliance efficiency.

9.4.1 Peak oil

The brief analysis in this section illustrates how the model can be used for investigations/analyses on topics *other* than energy-use/greenhouse emissions. Let us assume for the moment that oil production has peaked, or will peak in the early 21st century. As a consequence, I estimate that petrol increases in wage-adjusted terms[10], to \$3.6 per litre. This is based on current petrol prices of \$1.2 per litre (approximately correct at time of writing), an assumption of 3.5% nominal wage growth (with 2.5% of this CPI inflation), and 8% per annum growth in nominal petrol prices. The 8% growth rate for petrol prices is consistent with an assumption of a peak in oil production in the early 21st century, and is based on the assumption that, if oil production peaks, then the price of oil will rise at the discount rate of oil producers.

What effect would this have? This is a complex question, as clearly there would be widespread responses to such large increases in real prices. We would expect, for example, that people would change behaviour by reducing their discretionary travel, would shift to more efficient vehicles, and would be more inclined to travel on public transport. We would expect governments to respond by increasing spending on public transport infrastructure. As a consequence of all of this, we would expect land prices to increase in areas with good accessibility (i.e. that did not require much driving to reach destinations), especially those areas with good accessibility by public transport. Trying to account for all the possible changes is too difficult to attempt in a brief analysis here, but it is still worthwhile in conducting a simpler analysis. Let us consider instead what would happen to dwelling prices as a result of a relatively sudden increase in petrol prices (from \$1.2 to \$3.6), where there was little time for adjustment. I estimate the effect on dwelling prices in the following way:

1. Expected 'normal' vehicle kilometres travelled is calculated for each household, using the VKT model described in Section 7.3.3.
2. This is translated into petrol consumption assuming vehicle efficiency of 8.8 litres per 100 kilometres[11].
3. With petrol increasing from \$1.2 to \$3.6 per litre, the additional cost of this petrol is calculated (i.e. \$2.4 times the quantity of petrol).
4. The *average* additional petrol cost is calculated for each zone, by averaging across all households in the zone.
5. It is assumed that households will reduce their expenditure on housing in each zone by an amount equal to the average additional cost. That is, if travel costs rise by \$100 per week, households are willing to pay \$100 dollars per week less to live in that zone.
6. The discounted cash-flow model for property developed in Rickwood and Karantonis (2007) is used to calculate the decrease in net present value resulting from the decreased cash-flow of the property.

[10] i.e. I use annual rate of nominal wage growth as a deflator, to get back to 'real' 2006 dollars.

[11] This allows for a slight increase in vehicle efficiency, but does not assume any significant change to the vehicle fleet, such as widespread shift to smaller cars, because the point of this scenario is to see the effect if Sydney is unprepared for peak oil.

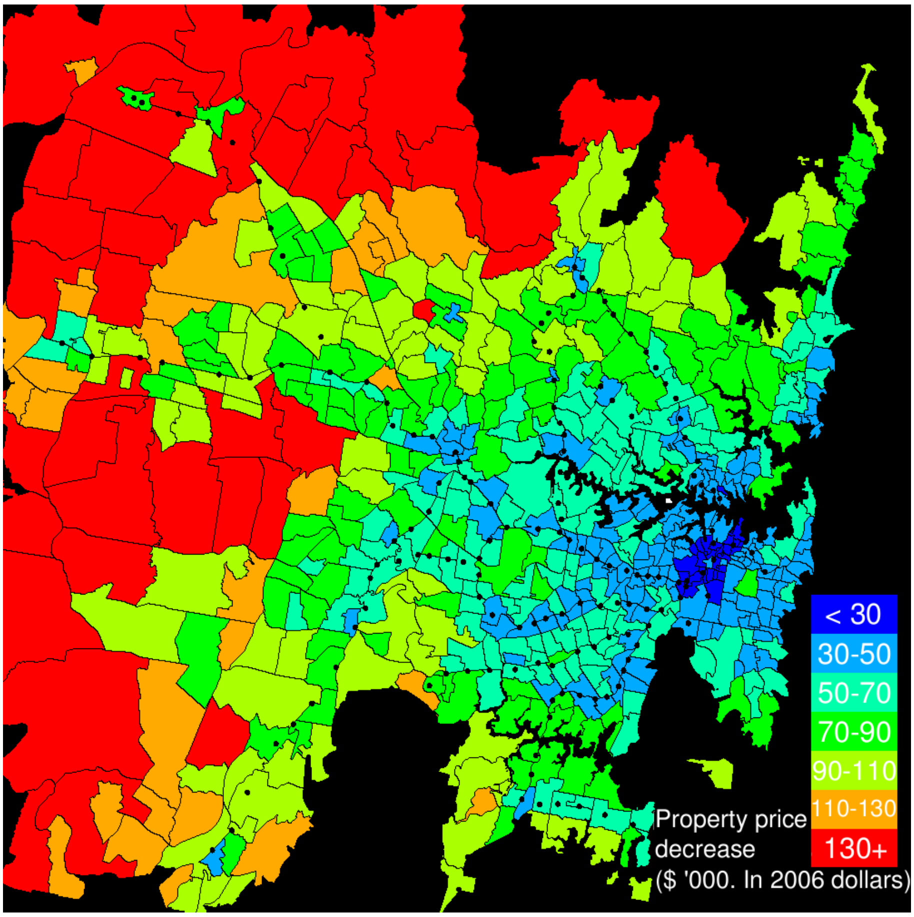


Figure 9.89: Decrease in property prices (in 2006 dollars) resulting from a tripling in real petrol prices, assuming a fixed housing/transport budget.

Figure 9.89 shows the drop in price for housing in each zone calculated by this method. Figure 9.90 reports this drop in terms of a multiple of the mean household income of residents in each zone. Figure 9.91 shows the additional cost of petrol (assuming no change to behaviour) as a proportion of mean household income, and shows the same pattern as Figure 9.90 because housing prices are assumed to drop by an amount proportional to the increase in transport costs.

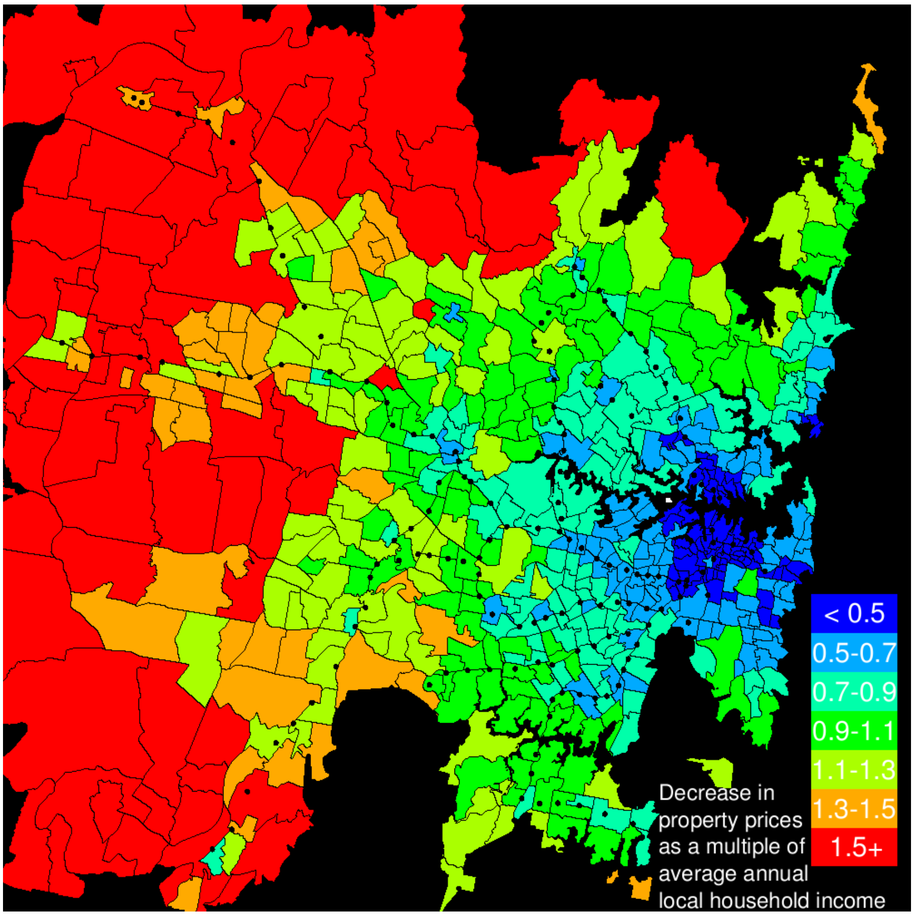


Figure 9.90: Decrease in property prices resulting from a tripling in real petrol prices, expressed as a proportion of local household income.

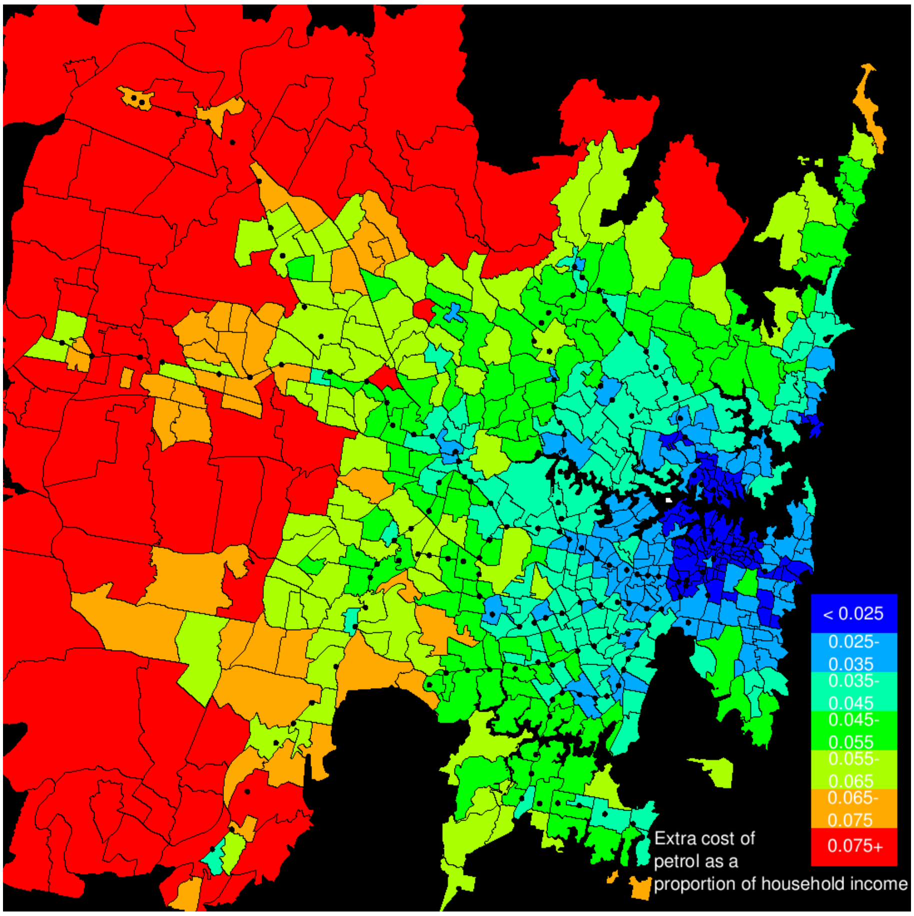


Figure 9.91: Proportion of local household income required to cover petrol after a tripling in real petrol prices.

9.4.2 Scenario 13: Multi-pronged approach, weak response

Total reduction in greenhouse emissions achievable: 14.7%

This scenario is the same, in land-use terms, as the baseline scenario (scenario 1), but assumes that private vehicles are 12% more fuel efficient (a trend of 0.5% per year), and that there is a 25% decrease in per-household greenhouse emissions due to in-dwelling energy use. Both of these decreases are relatively modest. The 0.5% per-year improvement in vehicle energy efficiency is the trend observed in the data reported in Australian Greenhouse Office (2007, page 28) over the period 1991-2005. The 25% decrease in per-household in-dwelling energy use is easily achievable in both new and existing dwellings through the installation of a solar hot-water heating system, or an instantaneous water-heating system (replacing the currently near-ubiquitous storage tank systems).

It is important to note that, in this scenario, and in scenarios 14 & 15 (to follow), I assume no 'rebound' effects from these efficiency gains. That is, I assume that households do *not* choose to drive more, or use more appliances, in response to the energy savings achieved through efficiency. It should be noted that this is a useful assumptions for simplifying calculations, but is unlikely to hold in practice. Historically, technical improvements in vehicle fuel efficiency have been largely consumed through increased vehicle weight and use of air-conditioning, and one might expect this trend to continue. In order to ensure that efficiency gains do translate directly into reductions in fuel consumption, it would likely be necessary to increase fuel excise to offset possible rebounds from efficiency savings.

Figure 9.92 shows the decrease in greenhouse emissions achievable through modest efficiency gains. This represents a 14.7% reduction in total emissions compared to the baseline scenario. I have considered only efficiency gains for private vehicle travel and in-dwelling energy use because these two sources alone make up three-quarters of total household emissions.

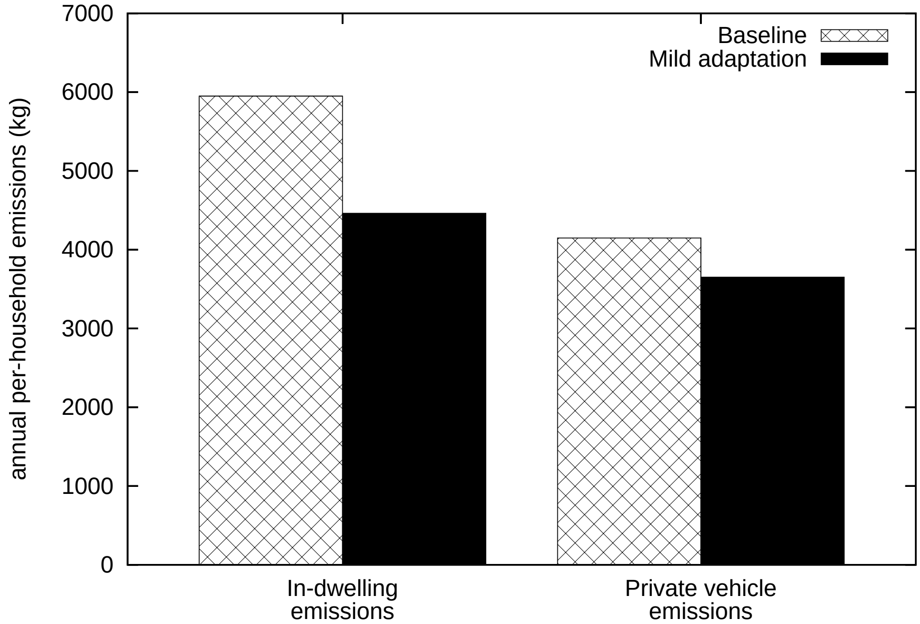


Figure 9.92: Reduction in emissions from in-dwelling and private transport energy use, assuming mild efficiency gains.

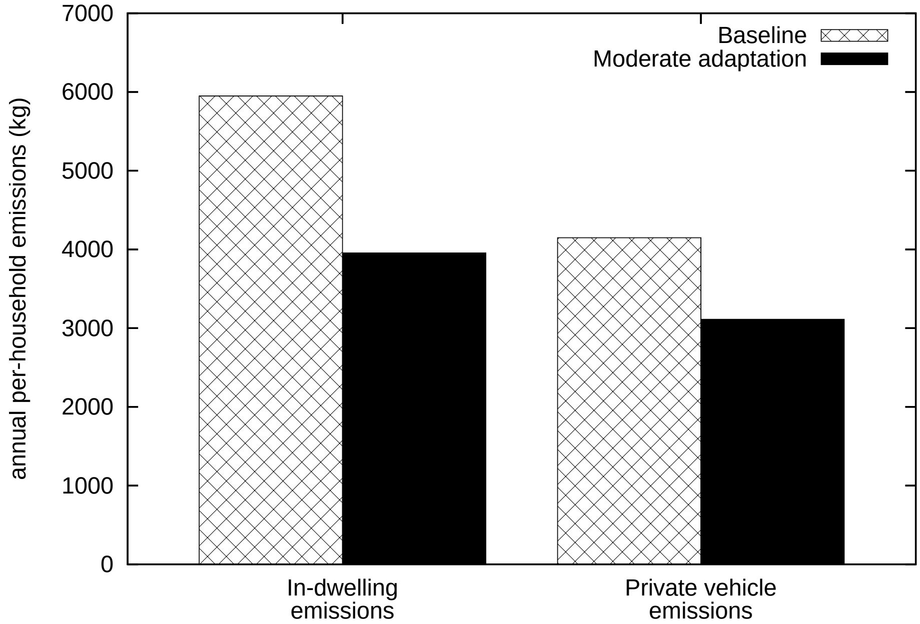


Figure 9.93: Reduction in emissions from in-dwelling and private transport energy use, assuming moderate efficiency gains.

9.4.3 Scenario 14: Multi-pronged approach, moderate response

Total reduction in greenhouse emissions achievable: 22.5%

This scenario is, like scenario 13, the same, in land-use terms, as the baseline scenario (scenario 1). Instead of a 12% increase in vehicle efficiency, however, a 25% increase is assumed (a trend of slightly over 1% increase per year), and instead of a 25% decrease in per-household emissions due to in-dwelling energy use, a 30% decrease is assumed. It is also assumes a further 5% reduction in emissions from in-dwelling energy due to the adoption of green power generation technologies (such as solar, geo-thermal, or wind).

Figure 9.93 shows the decrease in greenhouse emissions achievable through moderate efficiency gains. This represents a 22.5% reduction in total emissions compared to the baseline scenario.

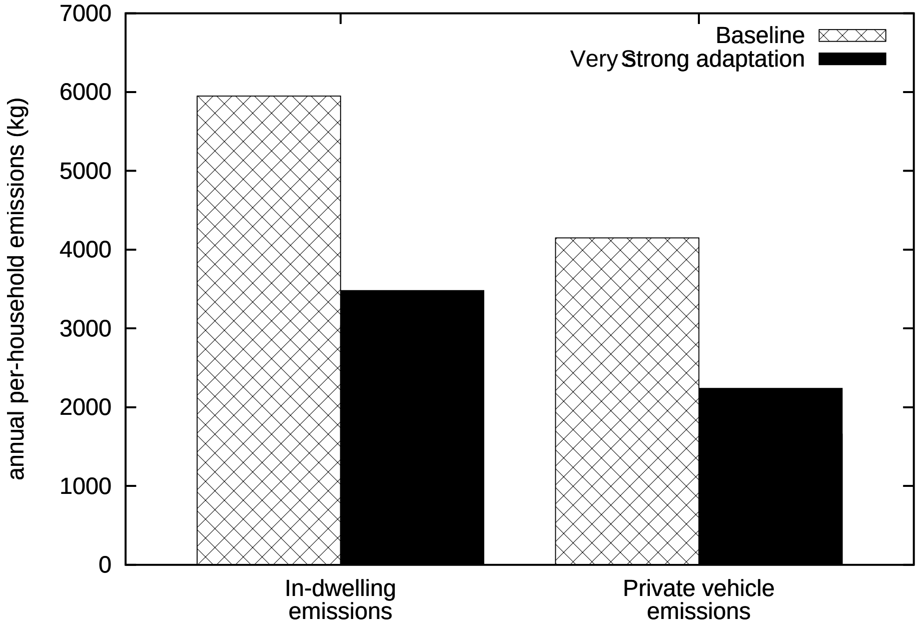


Figure 9.94: Reduction in emissions from in-dwelling and private transport energy use, assuming an immediate focus on energy efficiency.

9.4.4 Scenario 15: Multi-pronged approach, strong response

Total reduction in greenhouse emissions achievable: 30.6%

It is possible that vehicle fuel consumption per kilometre could fall by 40%, if households started to move to smaller, more efficient vehicles (including hybrid petrol-electric) in the next few years. Failing that, the fact that a vehicle fleet takes around 20 years to turn over (see discussion in Section 7.3.7) will make an improvement of this magnitude difficult to achieve. For this scenario, I assume that there is an immediate, strong trend towards the purchase of energy efficient vehicles, and this results in a 40% improvement in fuel efficiency. I also assume that some discretionary travel is either eliminated, or shifts to lower-energy transport modes (such as public-transport, or cycling), and this results in a further 10% decrease in transport energy use.

Regarding in-dwelling energy use, I assume that insulation retro-fits, widespread installation of energy efficient hot water systems, and energy efficient air-conditioning and lighting result in a 35% decrease in in-dwelling energy use (compared to the baseline scenario). Of all in-dwelling energy, 10% is assumed to be sourced from renewable energy sources.

Figure 9.94 shows the decrease in greenhouse emissions achievable from the responses just detailed. This represents a 32.5% reduction in total emissions compared to the baseline scenario.

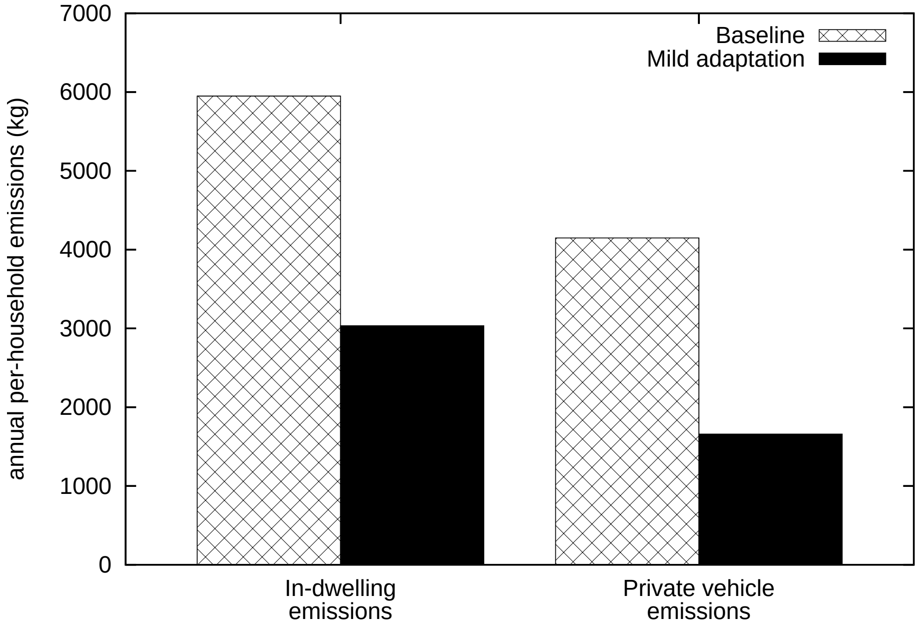


Figure 9.95: Reduction in emissions from in-dwelling and private transport energy use, assuming a strong and immediate focus on energy efficiency.

9.4.5 Scenario 16: Multi-pronged approach, very strong response

Total reduction in greenhouse emissions achievable: 40.1%

Pushing things a little, it may be possible to halve the fuel-consumption of the vehicle fleet by 2031. This would probably require, however, either swift government regulatory action, such as mandating fuel efficiency standards, or an immediate substantial, and sustained increase in petrol prices. Beyond the increase to fuel-efficiency, I also assume a further 20% reduction in emissions through reduced travel and/or mode shifting.

On the in-dwelling energy front, after the low hanging fruit is picked, further savings become more difficult, without assuming (against all trends and projections) a decrease in household appliance ownership. Large savings are possible through the installation of solar hot water systems, retro-fitting insulation, efficient air-conditioners, and energy efficient lighting. Further reductions are not so easy to obtain, but are certainly possible. With either strong regulatory measures, and/or significant increases in the cost of energy, a 40% reduction in per-household emissions from in-dwelling energy use is possible, and I assume this occurs in this scenario. I also assume that 15% of all in-dwelling energy is drawn from renewable sources. Such a significant shift in energy generation technology would require government intervention.

Figure 9.95 shows the decrease in greenhouse emissions achievable through the substantial changes just detailed. This represents a 40.1% reduction in total emissions compared to the baseline scenario.

9.5 Chapter summary

At first glance, the results presented from the detailed modelling in this chapter suggest that the effect of physical land use planning on transport-related and dwelling-related residential energy use is limited. Table 9.2 shows the changes in transport-related and dwelling-related greenhouse emissions for scenarios 2a-11a, 13, and 14, compared to the equivalent emissions in the baseline scenario (1a)[12]. The results for scenarios 1-11 (i.e. those without land-use→transport feedback are not reported, but are similar when compared with the equivalent baseline scenario (i.e. scenario 1). Also note that the numbers reported in Table 9.2 are not comparable with those shown in Sections 9.3.1-9.3.11, as the basis for comparison in those sections is the baseline scenario *without* land-use→transport feedback, whereas in Table 9.2 results are compared using the baseline scenario *with* land-use→transport feedback.

The most striking finding that can be drawn from the results in Table 9.2 is that the savings achievable through even moderate efficiency gains are greater than those achievable through even the quite radical physical planning in scenarios 9a & 10a. However, the two approaches are not mutually exclusive. There is nothing to prevent the suite of efficiency measures assumed in scenario 13 or 14 being implemented alongside the land-use planning approach described by (say) scenario 7a. The general pattern is clear – curbing fringe development and consolidating within the urban area results in lower energy use and emissions. Although the general pattern is clear, there are good reasons to believe that the numbers shown in Table 9.2 substantially underestimate the true effects achievable through physical planning policy. These reasons are:

1. I have concentrated on residential housing policy. I have not been concerned with the distribution of employment or other activities.

2. I have taken a conservative approach in assuming 'business as usual' travel behaviour. An increase in local area density is associated with a small decline in local car ownership and distance driven (all other things equal), and this effect is included in the travel model used. However, as already pointed out, the city-wide changes to congestion, parking availability, and public transport service levels are not captured, and there is reason to believe that these city-wide changes dominate over local effects (see 9.3 for more on this point).

3. As a partial solution to (2), scenarios 1a-11a include a 'correction' to account for city-wide effects, but the correction I use (a 1% decrease in vehicle travel for each unit increase in density) is at the low end of what can be reasonably justified.

4. The data on which the 'correction' in (3) is based (Newman and Kenworthy, 1999) is a cross-sectional data-set collected during a period of low oil prices. Energy use is likely to be more sensitive in a period of higher oil prices (and carbon taxes/trading), and so the Newman & Kenworthy data may itself understate the effect that urban form has on transport energy use.

5. I estimate the effect of housing location policy over a single 25 year period, but the effect will

[12] Scenario 12 is excluded as it did not include estimates of changes to energy use, and scenarios 15 and 16 are excluded because they include assumed changes to transport behaviour (i.e. reductions in discretionary travel and mode-switching) in addition to efficiency gains.

likely be greater over a longer time period, as households and transport authorities continue to adjust to changes in land use.

% change in greenhouse emissions			
Scenario	Transport	Dwelling	Total
Land-use planning focus			
1a	+0%	+0%	+0%
2a	-3.0%	-0.7%	-1.6%
3a	-2.8%	-0.8%	-1.6%
4a+	NA	NA	≈ 0%
5a	+4.0%	+0.9%	+2.2%
6a	+4.2%	+1.0%	+2.3%
7a	-3.0%	-1.9%	-2.4%
8a	-3.9%	-0.0%	-1.6%
9a	-6.1%	-3.5%	-4.6%
10a	-7.8%	+0.1%	-3.1%
11a	+14.0%	+3.9%	+8.1%
Efficiency focus			
13	-8.9%	-18.8%	-14.7%
14	-18.6%	-25.2%	-22.5%

Table 9.2: Percentage change in transport-related, dwelling-related, and total greenhouse emissions for scenarios 1a-11a, and scenarios 13-14. Percentage changes are expressed relative to the emissions from the same end-use in baseline scenario 1a. + Scenario not evaluated, because results are so similar to baseline results.

Although there are only relatively small changes in total residential greenhouse emissions from the different physical planning scenarios evaluated (from -4.6% to +8.1%), it would be a mistake to conclude that physical planning policy is ineffective in influencing residential greenhouse emissions. What the results in this chapter suggest is that focusing on housing location policy alone is likely to result in only small changes to emissions & energy use. Although land-use→transport feedback is generally accepted, the results suggest that it may be better to focus first on improving transport infrastructure and services, with land-use planning decisions linked to specific transport-planning projects/improvements. Paul Mees has been making this argument for some time (Mees, 2000). The same argument for land use planning policy to be developed along-side targeted transport-planning decisions is also made in Hensher (2003):

> Growing patronage requires identifying and servicing specific corridors where one can focus on a high quality service in terms of frequency, reliability, travel time, visibility, and security.

Hensher (2003, page 5)

It is particularly disappointing, in this context, that the Metropolitan Strategy for Sydney has been reduced to a land-use only policy through the abandonment of the major transport infrastructure projects contained within it – the North-West and South-West rail extensions, and CBD rail capacity expansion.

The common characteristic separating those scenarios that have lower emissions than the baseline scenario from those that don't is the amount of fringe development. Thus, those scenarios with more fringe development than the baseline all have worse emissions outcomes, with the 'Urban sprawl' scenario (11 & 11a) being the most notable example – causing a 14% increase in transport emissions, and an 8.1% increase in overall emissions. Conversely, those scenarios with less fringe development (and hence more redevelopment of existing areas) all have better emissions outcomes, with the 'Parisian' model (scenarios 9 & 9a) of inner-suburban medium-density consolidation resulting in a 4.6% decrease in total emissions.

One of the stated aims of the integrated analysis undertaken in this chapter was to evaluate the effect of physical land-use planning policy on *combined* dwelling-related and transport-related energy use. The results indicate, unsurprisingly, that transport-related energy use & emissions are more sensitive than dwelling-related energy use & emissions. The effect on dwelling-related emissions is, however, far from negligible. For example, scenario 10/10a ('Hong-kong' style inner city development) results in the largest decrease in transport-related emissions (-7.8% for 10a), but overall emissions are higher than for the a comparable scenario where development is focused on inner-suburban areas (i.e. scenario 9/9a). The fact that dwelling-related energy use is less sensitive to planning policy than transport-related energy use suggests that it may be better to consider planning policy as primarily (though not exclusively) a tool for influencing transport-related energy use. Although I have evaluated only housing location planning scenarios, transport-related energy use & emissions will clearly be more sensitive to any physical planning policy with an employment location or transport focus, and so the same conclusion applies.

Although the focus of the analysis in this chapter has been on energy use and associated emissions, the figures shown in Section 9.2.1 give an indication of the rich variety of outputs available from the model. I have demonstrated that such rich outputs are possible even with a comparatively simple model structure, provided that the model is carefully constructed. The benefits of such visualizations are threefold:

1. They help to engage a wide range of policy-makers and major stakeholders in the debate.
2. They help to engage the wider urban citizenry in the debate.
3. They encourage a broad consideration of a fuller range of policy scenarios, rather than a narrow technocratic estimate of the 'best' policy.

Given that many policy debates are essentially *values* debates, rather than *facts* debates, these three points are especially important. It is important in this context that a mathematical model provide not just answers to questions of fact ("Which of scenarios X and Y is likely to result in lower greenhouse emissions?"), but also information that encourages and facilitates the value debate ("What do we value in a city? What degree of segregation (by income, race, or age) is acceptable? How should this be weighed against environmental concerns?").

9.5.1 Implications for planning policy in Sydney

As discussed briefly in the preceding discussion, an important conclusion that can be drawn from the results presented in this chapter is that land-use centric planning alone is not likely to be effective in reducing greenhouse emissions, and that it may be better to make land-use planning decisions that are supported by existing and planned transport infrastructure. While one can argue that the Sydney metro-strategy's focus on 'centres and corridors' does just this, I do not find this argument convincing, for the simple reason that many of the centres and corridors identified in the metro-strategy are poorly serviced by public transport. If one instead focuses on the key centres and corridors that are currently well serviced by public transport, or could be well serviced with feasible extensions to public transport network coverage and capacity, then development should take place in a smaller number of key centres and corridors. This means development close to the CBD (supported by light-rail where necessary) and a few other key centres (e.g. Parramatta, Chatswood, Strathfield/Burwood, Epping, Sydenham, Bondi-Junction). The key transport corridors linking these nodes are also obvious places for additional development. Because of Sydney's particular geography, its CBD is off-centre, in the sense that it lies to the east of its centre of population and employment, and this makes it difficult to overstate the importance of Parramatta as Sydney's second CBD. In this light, the Epping-Parramatta rail link is essential to better integrate Parramatta into the city's transport network, especially given the newly opened Epping-Chatswood link servicing Macquarie Park[13].

The simulation results for housing satisfaction suggest that there is likely to be suppressed demand for detached dwellings, and that any strategy which reduces the number of detached dwellings is likely to result in lower levels of housing satisfaction. This requires careful planning. The government may be able to facilitate the construction of more detached dwellings within the existing urban area by reducing government charges and relaxing regulatory/planning hurdles. Some blocks in existing areas are quite large (sometimes over 1,000m^2), and could be sub-divided and still allow for two (or more) separate detached dwellings with accompanying yards. Government charges and associated regulatory/planning hurdles limit this sub-division, but a change to these would allow for a smaller number of dwellings to be released on the city fringe while at the same time catering to the preference of many households for detached dwellings. This would be beneficial in reducing greenhouse emissions, while at the same time catering to those households with a preference for detached suburban living. It is also important for us to find out if higher-density living can be made more palatable through better urban and dwelling design. It may be that families with children are unwilling to live in small apartments without *any* communal green-space, but would be willing to live in larger apartments with access to shared outdoor green-space. It may also be that for many households, dwelling type itself is unimportant, but the neighbourhood characteristics correlated with dwelling type are important. For example, it may be that living in a relatively quiet, leafy neighbourhood with little local traffic is important for many households, but in such neighbourhoods detached housing is often the only dwelling type available. If people are happy to live in medium-density areas provided fears about noise, lack of privacy, and lack of neighbourhood green space can be allayed, the importance of good urban design becomes clear. These are all important issues for researchers to investigate.

9.5.2 Conclusions

The analysis in this chapter is largely designed to address the third thesis question: "How does housing location policy influence aggregate dwelling-related and transport-related household energy use?". The short answer to this question is that the influence is small, but significant. More importantly, the research confirms that housing policies which limit the amount of new fringe

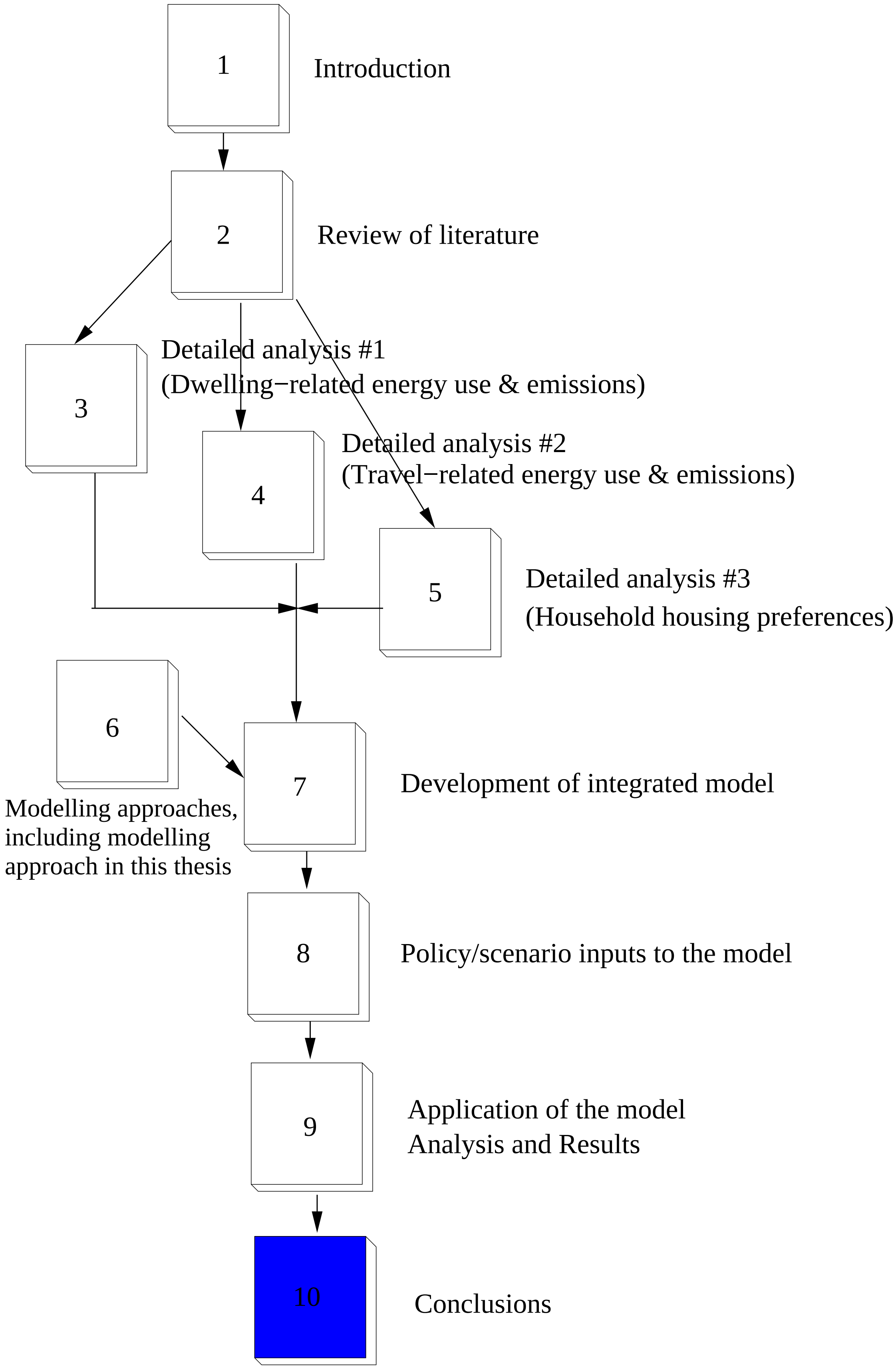
[13] The Chatswood-Epping link was originally part of an intended Chatswood-Epping-Parramatta link, but the Epping-Parramatta stage was cancelled.

growth result in lower transport-related and aggregate energy use than those that do not. The model developed for scenario evaluation does not fully take into account the range of policy levers available. In particular, it does not include any explicit modelling of transport-planning decisions. Importantly, the research indicates that, contrary to the suggestions of some, it will *not* be the case that the transport-energy savings of urban consolidation policies will be offset by losses due to increased in-dwelling and embodied energy use in higher-density dwellings. Since this chapter demonstrates that this is the case even for land-use centric physical planning policy, it is a very strong argument against such claims.

The research in this chapter suggests that it is important not to focus solely on physical planning policy measures, as large energy savings can result from other policies such as vehicle, dwelling, and appliance efficiency standards. Although not evaluated here, economic measures such as congestion pricing or a carbon tax may also have substantial benefits. In concert with these other policy measures, housing location policy appears to have a small independent effect on household primary energy use, with the effect on transport energy use being the most pronounced. This suggests that transport-focused planning policy, in tandem with non-planning dwelling and transport measures, is likely to be the most effective policy mix for reducing overall energy use.

Chapter 10

Conclusions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10.1 Summary of key findings relating to thesis questions

In this concluding chapter, I will first return to the three specific questions posed at the beginning of this thesis, before identifying areas for future research and engaging in some more general discussion.

10.1.1 Question 1: "How does dwelling type affect residential dwelling-related energy use?"

Pleasingly, there are some clear answers to the first, and most specific, thesis question. The findings relating to this question are:

For low-rise buildings, dwelling type has *no* independent effect on embodied energy

The independent effect of dwelling type on *embodied* energy (per square metre floor area) seems small to non-existent, at least for buildings of up to 3 storeys, and possibly for buildings up to seven storeys. Far more important factors are dwelling size and choice of construction materials. Since higher density dwelling types (such as apartments) are generally smaller than detached dwellings with the same number of bedrooms, the per-dwelling embodied energy will be lower for such dwellings.

Embodied energy is greater for high-rise apartments

High-rise apartments have higher embodied energy per square metre than any other dwelling type. Even after allowing for the fact that high-rise apartments are smaller than, say, a detached dwelling with the same number of bedrooms, they still have higher embodied energy on a per-dwelling basis. The best available estimate (based on analysis in Treloar et al. (2001a)) is that embodied energy per unit inhabitable floor area is 50% higher for 15-storey buildings, and nearly double for 40+ storey buildings (see Rickwood et al. (2008, page 61) for a fuller discussion).

In-dwelling energy use is lowest in medium-density dwelling types (i.e. low-rise apartments & townhouses)

In-dwelling *delivered* energy use (for heating/cooling, appliance use, etc) is higher in detached dwellings than in low-rise apartments and townhouse/semi-detached/terrace dwellings, after one controls for other factors. That is, the independent effect of moving the same household from a detached dwelling to an apartment or townhouse is a reduction in in-dwelling energy use by that household. This finding is supported by three separate empirical analyses on separate data sets of actual household consumption (described in Section 3.3). The finding is also supported by thermal simulation studies that show that attached dwellings require less heating & cooling energy (Newton et al., 2000; Miller and Ambrose, 2005). In fact, the empirically estimated effect of dwelling type on in-dwelling energy consumption ($\approx$ 15% lower in low-rise apartments and $\approx$ 10% lower in townhouses/terraces/semi-detached) can be explained largely on heating/cooling grounds. The main unresolved question is whether reduction in floor area is the important factor, or dwelling-type itself.

Probably the most important unresolved issue is whether in-dwelling energy use is higher in high-rise apartments than in low-rise apartments. There are a number of descriptive Australian studies suggesting that in-dwelling energy use in high-rise dwellings is higher (Myors et al., 2005; Perkins et al., 2007), but nothing amounting to a conclusive controlled analysis. If energy use is higher, is this because high-rise apartments have tended to be poorly designed (see Pears (2005)), or is the increase related to properties of the building form? It seems quite plausible that lifts, car-park-ventilation, common-area lighting and air-conditioning, and difficulties in allowing natural lighting and ventilation will, together, result in higher energy use in high-rise dwellings, but we are still lacking research that establishes this conclusively.

10.1.2 Question 2: "How does transport and land-use policy influence household travel behaviour (and resulting energy use)?"

This question is of course much broader than the first thesis question, and so we can not expect conclusions anywhere near as definitive.

The analysis in Sections 4.2 and 4.3 both suggest that characteristics of the trip (i.e. travel time/cost) *and* characteristics of trip end-points both affect travel behaviour. This finding is more easily understandable if one accepts that variables relating to trip end-points are serving at least in part as proxy variables for more relevant, but difficult to measure variables relating to transit stop safety & amenity, parking costs, and congestion. The importance of such difficult-to-measure features of the transport network are highlighted particularly by the disaggregate study in Section 4.3, which finds that variables describing the built environment at trip end points have effects of comparable magnitude to variables describing trip travel time (see Table 4.7, Section 4.3.3), and add weight to Cervero's claim that models of travel behaviour that exclude variables describing the built environment are under-specified (Cervero, 2002, page 266). The analyses in Sections 4.2 and 4.3 also suggest that in cases where trip travel time information is unavailable, variables relating to urban form can serve as useful proxies. Local area density and distance from the CBD, in particular, were found to be good joint predictors of travel behaviour.

The analyses in Chapter 4, taken together with both the analysis of disaggregate travel in Section 7.3 and the integrated modelling results in Chapter 9, also suggest that *access provided by* public transport is more important than *access to* a local transit stop in reducing transport-related emissions. In Sydney, as in most cities, the access provided by transit is best for the inner suburbs and a few key sub-regional centres.

The analyses in Sections 4.2 & 4.3 focused on public/private transport mode choice. The mathematical analysis in Section 4.4, on the other hand, considered the effect that a city's size and pattern of intra-urban density had on trip length, considering only a single mode of transport (car). The study found that increased urban density can be expected to reduce average trip length even in the absence of congestion or parking difficulties. There are two mechanisms through which this occurs. Firstly, increased density implies increased centralization of activities (population/jobs). Secondly, increased density implies a physically smaller city, and this also acts to reduce mean trip lengths. The fact that trip length decreases even without considering congestion, parking costs, or the availability of *any* public transport, lends support to the claim that urban structure can have an important effect on travel behaviour.

Importantly, the results from each of the five separate transport analyses contained in this thesis[1] are all consistent with one another: areas that have properties associated with compact planning policies, such as employment and population density, are associated with travel behaviours that result in lower transport-related energy use than low-density outer-suburban areas.

10.1.3 Question 3: "How does housing location policy influence aggregate dwelling-related and transport-related household energy use?"

This thesis question was addressed most directly through the scenario analysis in Chapter 9. The results in that chapter indicate that housing location policy does have an effect on aggregate household energy use, but that the effect is small: in the order of a few percent for most scenarios, and still less than +/- 10% for extreme land-use planning scenarios.

In answering the third question, I have demonstrated that it is possible to obtain plausible estimates of the effect of land-use policy on combined transport/in-dwelling energy use at the metropolitan scale. This is something that, to my knowledge, has not been achieved before, despite a great deal of recent interest in the area (e.g. Brown et al. (2008); Glaeser and Kahn (2008)).

The results of the integrated modelling indicate that the amount of new fringe growth is the single most important factor in determining the energy-use outcome of a particular land use scenario. Scenarios that include substantial new development on the urban fringe are consistently associated with higher household energy use. The results of the integrated modelling also suggest that concentrating development close to the CBD is more effective in reducing transport energy use than a general strategy of distributed centralization, but such intra-urban distribution effects are minor compared to the effect of new fringe development.

In agreement with other existing research on the topic, I find that transport-related energy use is similar in magnitude to dwelling-related energy use, but that transport-related energy use is more sensitive to changes in land-use policy (Perkins, 2002; Fuller and Treloar, 2004; Norman et al., 2006). However, unlike these studies, which are development or site-specific analyses, I detect a much smaller effect, for two reasons:

1. I control for factors that are difficult to control for at the site or development scale. In particular, the residential location preference model developed in this thesis demonstrates that smaller households tend to select smaller dwellings in areas with better transport. Unless one accounts for such self-selection effects, one is likely to overstate the independent impact of land-use policy on energy use.

2. My analysis is metropolitan scale, and so takes into account the large 'inertia' of a city, rather than focusing solely on the savings possible in new developments.

Although the dominant effect of land-use policy is on transport energy, the analysis in Chapter 9 shows that considering combined transport and dwelling-related energy use can still be important.

[1] Section 4.2 has two analyses of aggregate data; Section 4.3 contains an analysis of disaggregate data; Section 4.4 contains a theoretical/mathematical analysis; and Section 7.3 develops a disaggregate travel model through the analysis of travel survey data.

The clearest demonstration of this is the fact that the scenario with the lowest transport energy use (scenario 10/10a: 'Hong-Kong style re-development') is not the scenario with the lowest overall energy use. The lowest overall energy use in any land-use policy scenario was instead scenario 9/9a ('Parisian re-development'), which had both low transport energy use and low in-dwelling energy use. Despite such cases, the dominance of transport-energy effects suggest that the best approach for researchers and planners is to maintain their existing focus on transport effects, but to avoid making 'big' mistakes on the dwelling-related energy front. The scenario analysis in Chapter 9 suggests that excessive high-rise development may be a 'big' mistake, *especially* if a significant proportion of this development takes place outside the CBD. This thesis shows that a combined (transport/dwelling) analysis is useful, but that it does make sense to focus on transport energy use, where the relative difference between scenarios (in terms of total transport energy use) can be over 20%.

10.2 General discussion

It is interesting to compare the results obtained from the simulation modelling in this thesis with estimates obtained through simpler methods by other authors. Because other authors have concentrated on transport energy use, and because this thesis has confirmed that it is transport energy use that is most sensitive to planning policy, I will only compare estimates for the effect of planning policy on operational transport energy use[2]. Table 10.1 compares some different estimates.

The estimates shown in Table 10.1 are, strictly, not comparable, as the inter-city studies are comparing transport energy use between cities that may be very different (i.e. Boston and Atlanta), whereas the estimates in this thesis are for different 25-year scenarios for Sydney (2006-2031). Nevertheless, by considering these estimates together, we can see a consistent pattern. If we accept that the the 'extreme' scenarios for Sydney will result in two fundamentally different cities ('Compact Sydney' & 'Sprawl Sydney'), we see that the 25% difference in estimated energy use matches closes with estimates from inter-city studies (Ewing et al., 2002; Bento et al., 2003; Glaeser and Kahn, 2008). There are, however, good reasons to believe that the 25% estimate obtained in this thesis is actually an underestimate of the likely effect. I have concentrated on estimating changes to behaviour resulting directly from changes to housing location policy, assuming business-as-usual in all other matters. That is, I assume no city-wide shifts in car-ownership, no improvements in vehicle efficiency, no change in employment locations, and no significant transport-specific initiatives.

Restricting attention to Sydney, and considering a more realistic range of policy scenarios, the difference in transport energy consumption of the 'best' and 'worst' scenarios is 8%. This number is around half the value one gets by assuming city-wide density is the *only* factor determining transport energy use. Fitting an exponential line through density/transport-energy data in Newman and Kenworthy (1999) (as is done in Figure 9.2) implies a 1.9% decrease (increase) for each unit increase (decrease) in density. Sydney's population density can change by at most

[2] I exclude embodied, as most other authors do not included it in their estimates.

[3] I'd like to avoid using pejorative terms, but the alternatives are all far too clunky (e.g. 'energy efficient land-use policy'). I would ask that the reader interpret 'good' not as a value-label, but rather as shorthand for 'effective at reducing transport energy'. The same arguments apply to 'bad'.

Author	Reduction achievable with 'good[3]' land-use policy compared to 'bad' policy	Method
Rickwood (this thesis)	25%	Empirically calibrated mathematical model. Difference between most extreme scenarios for Sydney.
Rickwood (this thesis)	8%	Empirically calibrated mathematical model. Difference between more realistic scenarios for Sydney.
Bento et al. (Bento et al., 2003)	25%	Regression analysis of inter-city data in the U.S.
Ewing et al. (Ewing et al., 2002)	25%	Regression analysis of inter-city data in the U.S.
Glaeser and Kahn (Glaeser and Kahn, 2008)	17.5%	Regression analysis of inter-city data in the U.S.
Breheny (Breheny, 1995)	10-15%	Simple estimate obtained by observation of energy use in various regions of U.K.

Table 10.1: Different estimates of the effect of land use on transport energy use. For the results relating to this thesis, I have compared results from the scenarios *with* land-use/transport feedback.

around 4 people per hectare in either direction over 25 years, which implies a range of $\approx$ 15% (+/- 7.5%). Accepting that the 8% estimate obtained in this thesis is a lower-bound for the difference that housing policy alone can make on transport energy use, and that further reductions can be achieved through integrated land-use/transport policy, and other policy measures, then the following rules of thumb seem appropriate for policy makers:

1. Undertake programs encouraging/forcing energy efficiency and behaviour modification first, as savings are substantial, and are usually cost negative (see Figure 10.1). Programs as diverse as mandatory efficiency standards, distributed power generation, and community-based transport initiatives all fall into this category.

2. Avoid land-use policy that is likely to result in a significant increase in dwelling-related energy use. The research in this thesis suggests that planning policy that allows/encourages high-rise dwellings in areas *not* very well linked with the transport network is *not* good policy, if the aim is to reduce energy use.

3. Concentrate on land-use policy that supports specific transport-planning policies or projects. Failing to do this is likely to result in only modest reductions in energy use, at least for the range of planning policies that are politically achievable.

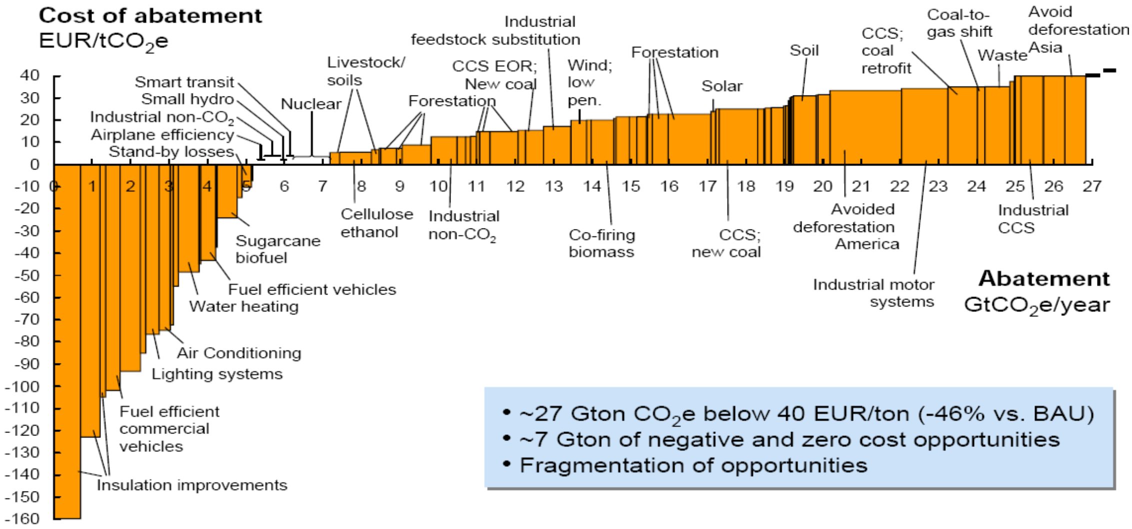

Figure 10.1: Global cost curve of Greenhouse Gas abatement opportunities beyond business as usual. Source: Vattenfall AB (2007).

10.3 Future research

Some areas for future research have already been identified in Section 10.1. This section discusses some directions for future research not mentioned earlier in that section.

10.3.1 Building life

The embodied energy calculations in this thesis, and in other published work, assumes dwelling life is independent of dwelling type, but this is an assumption of convenience, rather than one that seems reasonable. The simple fact is that we know very little about the expected life of a building, because there is so little research on the topic. It seems plausible that more expensive structures will stand longer, but there is no compelling empirical case. We are badly in need of some empirical work in this area.

10.3.2 The land-use→transport feedback, and the nature of urban feedback systems in general

Urban feedback mechanisms in general, and land-use→transport feedback in particular, are important areas of future research. Though there is already much research in this area (e.g. Pushkarev and Zupan (1977); Wegener (1995); Newman and Kenworthy (1996)), our understanding is still limited.

Turning first to consider land-use→transport feedback, I have argued at some length in Chapters 6 and 9 of this thesis that our understanding of the effect that transport has on land use is more advanced than our understanding of the effect of the land-use on transport. My basic argument is that the land-use decisions of large numbers of firms and individuals fit neatly into a disaggregate modelling framework, while the decisions of monopolistic publicly-owned transport bodies do not. Few cities have anything approaching a market-driven public transportation sector with many competing firms, and the nature and scale of transport infrastructure in general make such a situation unlikely. Given that transport infrastructure and service provision are generally publicly provided and publicly controlled, it becomes important to develop methods that allow us to better understand the process by which infrastructure and service decisions are made. Some may consider this a fruitless line of research, given the sometimes capricious nature of government decision making, but it is hard to believe that decisions are made completely by whim. Indeed, the clearly established empirical relationship between land-use measures and transport outcomes suggests that in cities with even somewhat responsive governments and transport agencies, the economies of scale enjoyed by public transportation dictate better transit service provision with dense, clustered land use. There needs to be more research in this area: governments and their transport agencies are too important to be ignored in urban modelling, or have their role simplified for modelling convenience to tax-imposition and land-use regulation.

The land-use↔transport feedback process is but one of a number of processes at work in urban systems. But the dynamics of these systems is still poorly understood, partly because dynamic systems are by nature harder to understand, and partly because the study of feedback processes is a relatively new area for urban modellers, especially those hailing from an economic tradition:

> The idea that there may be a circular process, in which individual producers choose locations with good access to markets and suppliers, but in which the decision of each individual producer to choose a location improves the market and/or supply access of other producers in that location, is hardly a new one. Indeed, it was the central theme of well-known (among geographers) studies by Harris (1954) and Pred (1966). Why, then, did this idea not become widely known in economics until the 1990s?
>
> Krugman (1998, page 10)

Bearing this in mind, it is worthwhile remembering that the nature and strength of the land-use↔transport feedback process is the essential point of disagreement between writers such as Newman and Kenworthy (who emphasise the strength and importance of land-use↔transport feedback), and the (mainly North American) economists and transport researchers who deny a strong role for land-use policy. More research is required into the nature of urban processes, and what assumptions are most useful for modelling them.

10.3.3 The proper role of government and markets in planning

There seems to have been something of a crisis amongst planners in the last few decades, as the emphasis on individual choice (enabled by efficient market forces) has seen the relevance of central-planning questioned. Over the last few decades, markets have come to be viewed as efficient allocators of resources, and this view leads naturally to the position that the 'right' way to plan is not to plan at all, but instead to price things properly, and let markets work. Recent economic developments offer stark evidence that a naïve faith in market solutions is misplaced, and that it may just be possible to argue, once again, that long-term planning led by government (not markets) is worthwhile:

> Once the [efficient markets hypothesis] is abandoned, it seems likely that markets will do better than governments in planning investments in some cases (those where a good judgement of consumer demand is important, for example) and worse in others (those requiring long-term planning, for example). The logical implication is that a mixed economy will outperform both central planning and laissez faire, as was indeed the experience of the 20th century.

Quiggin (2008)

Since physical planning decisions (especially land-use) have long-term implications, and limit the particular choices that will be available (e.g. sprawling suburbs which are difficult to retro-fit with efficient public transport), there is a strong case to be made for some form of central planning. Planners, and planning researchers, need to better articulate this. They can not do this simply by criticising economists, or seeking to deny the basic validity of classical economics. More constructively, they need to identify market failures, and establish, empirically, those situations where central planning is appropriate, and those where markets work well.

10.4 Concluding remarks

The contributions to knowledge contained in this thesis are almost wholly in the form of fairly tightly defined empirical analyses. Each analysis supports the conclusion that denser cities, and denser neighbourhoods, result in lower energy use than more sparsely inhabited cities, although the size of the estimated effect will probably disappoint some. Having established that there is a measurable effect even if one takes a very conservative approach, it is up to future research to demonstrate that greater effects can be achieved through integrated land-use/transport planning policy, or better modelling of land-use↔transport feedback.

Analysis of dwelling-related energy use also supports those arguing for urban consolidation: energy use really does tend to be lower (all other things equal) in dwelling-types typical of higher-density areas (i.e. apartments & townhouses), with high-rise apartments a likely exception to this rule. The weight of evidence both in this thesis, and in other empirical work, is now such that it seems hard to deny, on the facts, that traditional detached suburban living results in higher energy use. I suspect, however, that the real debate between supporters and opponents of consolidation is not really a debate about facts, but about values. Having spent the bulk of this thesis engaged in empirical fact-based analyses, I think it is appropriate to take a step back and conclude with some remarks regarding the value debate in planning, and the role of planning itself.

Buxton (2000) rightly says:

> The debate [on urban form] is partly about facts and their interpretation but, ultimately, it is about values, about what cities ought to look like, what their shape should be, how they should function and develop, and what they ought to become.

Buxton (2000, page 55)

We are fooling ourselves if we think that we can ‘optimize’ our cities and produce the best cities by looking at facts alone, for what constitutes ‘best’ is partly a value judgement. Some may envisage a Parisian metropolis, with others valuing the unhurried, leafy suburban life that many Australians have grown up in. Either position is in part a value judgement. It is not even simply a question of what we, as a society, value, as such judgements take place in the context of wider moral issues:

> Can it be defended ethically to aim at . . . a residential consumption level that we, for the sake of the planet's ecological carrying capacity, must hope will never be realized in the world's poor countries?
>
> Næss (2001, page 512)

Trying to incorporate values into a mechanical analysis, by, for example, introducing prices for social and environmental goods ('green space', 'social cohesion') is to avoid addressing the issue of values. This does not mean that matters of fact become unimportant – it *is* possible to analyse cities and debate the facts on particular issues, whether they be economic, social, or environmental. One can, for example, mount a convincing 'facts-based' argument that cities of a particular type result in less transport energy use than other cities, as I have done in this thesis. However, it must be acknowledged that moving towards a denser city comes with a reduction in private outdoor space, and probably reductions in personal mobility. Whether this is regarded as acceptable, when weighed against the reduction in energy use, is a value judgement – how much do we value personal mobility and traditional suburban sub-divisions? If we value them greatly, then perhaps we are better off looking to save energy and reduce pollution in ways other than drastically changing our city structures. Those wishing to argue along such lines need to demonstrate how a sustainable urban society is possible with land-use patterns that assume near universal car ownership and cheap petrol. The empirical evidence to date suggests that this will be a difficult task, because in *any* sustainable future requiring per-capita resource consumption within the planet's carrying capacity, it seems unlikely that the dominant mode of transport will be the motor car. If one accepts this, the choice is to either adopt a mix of private and public transport (e.g. walking/cycles/scooters & mass transit), or else move to an urbanized form of pre-industrial village living where travel outside the local area occurs only infrequently. The first choice requires changes to our patterns of land use. The second choice carries with it substantial economic challenges, for cities exist precisely *because of* economies of scale, and a return to local-area living would seem to eliminate these.

It is becoming increasingly common to attempt to shoehorn values into technical analysis by, effectively, giving them a price. For example, analysis of the costs of a new motorway may include dollar-value costs for transport-related deaths, pollution, and fragmentation of the urban landscape. Can we really be so glib about these things? Are our societal values about health, death, and aesthetics so easily reduced to a dollar value? Few would argue in the affirmative. Pointing this out is not the same thing as saying that there is no way to weigh costs against benefits. Such a defeatist position implies policy paralysis. The decisions we make routinely require us to weigh up outcomes that are not easily comparable, but we make those decisions nonetheless (see White et al. (2006) for an example of multi-criteria decision-making). The decision to reduce values to a form where they can become part of complex cost/benefit models is one solution to the problem, but it is an inherently undemocratic one, as value-based decisions are made, in effect, by a small number of experts/consultants tasked with determining the 'best' policy outcome. In such a setting, debate is reduced to mathematical technicalities, or to arguments about whether costs are properly estimated. Analysis of measurable outcomes *is* important. We need to have some idea, after all, of the consequences of our decisions. But this is where mathematical/economic analysis should stop. Predicting (likely) outcomes is a reasonable enough brief for technical analysis. Deciding which of those outcomes is preferable is not. The standard defence – that the general public are not sufficiently educated or knowledgeable to be engaged in a complex debate about the costs and benefits of detailed planning policies – is a clear move away from democracy towards a kind of technocratic/democratic hybrid. The alternative is a move towards educating and engaging the urban citizenry, through measures such as participatory planning (Carson et al., 2002).

> I know of no safe depository of the ultimate powers of the society but the people themselves; and if we think them not enlightened enough to exercise their control with a wholesome discretion, the remedy is not to take it from them but to inform their discretion.

Thomas Jefferson

Appendix A

Thesis Related Software

A CD attached to this thesis contains the software developed for this thesis (i.e. the microsimulation described in Chapter 7, results for which are presented in Chapter 9).

I include the source code because it acts as the ultimate specification of the model. Note that software cannot be used straight off the CD. The software requires other software and programs to run correctly. For example, the software requires at least a python interpreter and a Java Runtime Environment (version 1.4 or later) to be installed. The purpose of including the software source code is that it acts as the ultimate specification for the modelling performed in this thesis. Any sufficiently complicated mathematical model can only be completely specified by the computer code that implements that model. Indeed, that is the very purpose of computing languages – to provide the means of completely specifying a particular algorithm. Although mathematical descriptions can often provide the core details, they do not constitute a full specification.

Those familiar with the Java and Python programming languages can look at the modelling code directly (if they have a masochistic streak). Alternatively, I am happy to provide instructions for installing the necessary supporting software and getting the modelling software running, if the reader wishes to do this. Just contact me.

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