USING INTEGRATED URBAN MODELS TO RESPOND TO CLIMATE CHANGE IN CITIES

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Abstract

This paper presents a single, integrated urban model that focuses on the key areas of transport, domestic energy-use, and domestic water use and how these relate to urban planning and other policies. The model structure is spatial — requiring a sub-division of the urban region into disjoint sub-regions. Such a sub-division is necessary, not only because spatial information is essential to any transport model, but also because climatic and demographic factors are common to all resource models, and are spatially heterogeneous.

The model is intended for use by local, regional, and state authorities, government departments, energy, and utility service companies as a modelling and decision support tool for analysing the impact on cities of a range of energy, water, transport, and land use related policies. In particular, it seeks to understand the impact-reductions possible at household and city scales. Growing awareness of the threats from climate change has focused attention on greenhouse gas (GHG) emissions and the need to reduce them.

Using a sample analysis of Sydney, our on-going research collaboration seeks to examine the working relationships between multiple infrastructure sectors through a single analysis platform. The need to integrate policy for multiple infrastructures is critical given the multiple fronts on which the sustainability of urban systems are now jeopardised.

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I. Introduction

Currently, a lack of integration between the approaches and models that inform planning, limits the exploration of the links between population, transport, and land use in climate change impacted cities. In response to this, we have developed a single, integrated urban model that focuses on the key areas of transport and residential energy-use and residential water use (i.e. not commercial and industrial) and how these relate to urban planning and other policies.

We have evolved an integrated model structure, which is essentially independent of the urban area under investigation, or any particular resource use sub-model. As we will explain, the model structure is spatial — requiring a sub-division of the urban region into disjoint sub-regions. Such a sub-division is necessary, not only because spatial information is essential to any transport model, but also because climatic and demographic factors are common to all resource models, and are spatially heterogeneous.

We present the research in five sections. Following this introduction, we provide an overview of trends in urban modelling, paying particular attention to literature on transport / land use models and those that look the interface of urban structure, building design, and water / energy use. We argue that complex models often become so data intensive that they not used effectively, and that policy makers and researchers need models linked to decision making processes which deliver good outcomes.

In response to these limitations, we explain the development of our easy to calibrate computational model that simulates behaviour at the household level, whilst operating with a manageable amount of data. At this stage, we only model household decisions. The integration of multi-stakeholder decisions within the model is still under development.

Using data for Sydney, Australia, we then demonstrate the capacity of the model with a specific focus in this paper on energy and greenhouse outputs. We expand on this by analysing housing satisfaction and income segregation to show how the model produces outputs that stimulate a wider ranging discussion rather than mere prediction.

Our integrated urban model offers analytical capability as a decision support tool for local, regional, and state authorities, and government departments. It also enables energy and utility service companies to model the impact of changed land use configurations on consumption on the climate-constrained city in relation to other impact mitigation measures. We conclude by summarising how this research can provide policy guidance to city officials responding to climate change, its role in resilience and potential for informing adaptation priorities.

II. Trends in urban modelling

The level of sophistication in modelling urban systems has paralleled the advancement of computing capability. However, more complex models do not necessarily lead to more accurate models or better decision outcomes. What is required is a functional model embedded in effective decision making processes involving researchers, policy makers and citizens. The evolution of computational transport / land-use models (see Wegener 1994; US EPA 2000; Hunt *et al.* 2005) has been summarised by Timmermans (2003) as three ‘waves’ of development (see Table 1).

*** INSERT TABLE 1 HERE ***

Older models, such as ITLUP/DRAM/EMPAL (Putnam, 1983, 1991), investigate spatial interactions and remain in widespread use. In contrast, UrbanSim (Waddell, 1998, 2002) takes a behavioural approach to capture complex interactions, by predicting the behavioural ramifications of a particular policy scenario. At the development scale, UrbanSim models simulate decisions to build on undeveloped land in terms of the type of development and density. Though the model has already had several applications, UrbanSim remains largely a work in progress and the designers (Waddell and Borning, 2004) acknowledge that many technical challenges remain in the context of modelling complex systems in urban regions.

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. They engage inter-zonal flow information to determine location-specific demand for floor-space, rather than having any explicit representation of firms.

Currently, there is move towards models which incorporate explicit interaction with businesses and households, rather than using aggregate spatial interactions. If we take transport simulations as an example, within Timmermans (2003) ‘waves’, the first wave treated travel behaviour as a product of interacting spatial variables. In the second wave, the examination of travel is at the household level. Travel behaviour is further deconstructed at the third wave, with household level behaviour being broken down to the individual trip / activity.

The evolution of the three ‘waves’ has seen increasing complexity in line with expanded computational capacity. This complexity comes at some cost in terms of applicability, portability, and intelligibility. Such models are time consuming to develop and apply, and often difficult to interpret. The trend in transport modelling, towards behavioural accuracy and away from intelligibility, whilst not unique to this area, illustrates the general issues involved in adopting complex computational models in a policy driven environment.

The level of complexity increases when we expand models beyond transport / land-use simulations to integrate urban structure, building design and domestic water consumption. Within the context of our particular research environment (metropolitan Sydney, Australia), there are several examples of mapping the relationship between water-use and dwelling type (see Troy *et al.,* 2005; ; Troy and Randolph, 2006). These assert that per capita water use in detached dwellings is similar to per capita consumption in units, whilst detached dwellings (housing more people than units) use a greater volume of water per household. The New South Wales government regulator (IPART, 2004) also found detached households use more water than households in units. Studies in Melbourne seek to explain the water consumption to describe the water consumption down to the end-use level of showers, clothes washing garden watering etc. (Roberts, 2005).

While several studies have found a positive correlation between income and water use (Beatty *et al.*, 2006; IPART, 2004), the role of income as driver for demand merits further research to understand the changes in end uses which lead to this finding. A further point to emphasise is the need to consider the energy implications of urban water supply – particularly in the Australian context where persistent drought has necessitated the construction of desalination plants to augment supply and encouraged the significant uptake of rainwater tanks (with associated energy costs for pumping) in homes (Retamal *et al.*, 2009).

An urban Australian study by Randolph and Troy (2007) explores the extent to which dwelling type and socio-behavioural character of households influence the pattern of electricity and gas consumption. They reveal useful insights on household practices and attitudes towards energy consumption with notable difference between house dwellers and flat dwellers, and further variations between low-rise and high-rise flat dwellers. However, the researchers were unable to link actual energy consumption data with individual survey data due to data protection and privacy legislation.

Attempts to analyse interdependencies between urban structure and energy use are fraught with problems. First, data required for such a meta-analysis remains fragmented and access to linked data raises privacy problems. Second, many analyses fail to provide appropriate comparisons. Studies comparing recently built high-rise apartments and housing stock in general, often find higher levels of energy consumption in high-rise apartments (Myors, 2005).

A Canadian study by Norman *et al.* (2006) compared high and low-rise residential density to provide an empirical assessment of energy use and GHG emissions arising from transport, operational energy and materials. They found that Low-density suburban development was twice as intensive as high density development on a per capita basis. Studies have shown that smaller houses can be shown to be more energy intensive if only assessed on a unit area basis without taking into account house size, number of occupants and total energy (Thomas *et al.,* 2000).

There are three other examples of urban models relevant to our Sydney case study. The first is the Sydney Strategic Transport Model (TDC, 2005). This analysis of disaggregated transport and traffic patterns draws on the five-yearly Census of population and housing. Based on a moving sample of some 4,000 households, it includes detailed socio-demographic data, journey-to-work data and a continuous Household Travel Survey (HTS).

The second is the Melbourne Region Stocks and Flows Framework (MRSFF), which integrates a range of different models to analyse the *city metabolism* to characterise the interactions between model components like buildings and demography, within the *whatIf?* modelling environment (see www.whatiftechnologies.com). The outputs are forecasts of development over short, medium, and long-term time horizons (Baynes *et al.*, 2005). The model is distinguished by the big picture aggregated level analysis of the main development patterns it provides as output.

Finally, BASIX – the online Building Sustainability Index introduced by the New South Wales Government (http://www.basix.nsw.gov.au/information/about.jsp). The compulsory assessment tool is designed to ensure new homes are designed to use less potable water (40% reduction target) and be responsible for fewer (25% reduction) greenhouse gas (GHG) emissions. A critical component of the policy tool is the database for each application that includes information on location, house size, and building design and includes measures for energy and water efficiency. In terms of our research, the database is constrained in that it only contains information regarding buildings where development consent has been granted over the last five years.

In reviewing the above examples, it is evident that significant data is required to calibrate the more sophisticated land-use transport models, and this has been an impediment to their widespread adoption. 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 calibrating that model.

Modern models based on behaviour at the household / firm level are seen 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. However, accurate input data on travel time and cost is often many years out of date, and when combined with (differently) out of date data on land prices, employment distribution, and fuel price elasticity, the validity of the output is often undermined.

Whilst a simple model can offer some approximation of reality, the tendency to proceed to refine the model can be a distracting journey towards a hypothetically ‘true’ model. Models can only approximate reality by providing a useful mental tool, rather than a faithful representation of truth. There is a point of diminishing return, as a model grows more complex. We need to remain focussed on the broader role the model plays in informing effective decision making processes.

III. An integrated metropolitan scale model

The role of our integrated model is to understand trade-offs by different types of households (family type and size, income etc) between internal space, private open space, accessibility, housing type and price and how these are influenced by government policy.

We start by accepting that that land-use / transport models of urban areas, however sophisticated, suffer from the following limitations:

- There are limits to the precision possible;
- There is enough (stochastic) uncertainty within the system being modelled to admit a range of different possible outcomes, given an identical starting point; and
- There is enough (fundamental) uncertainty to make their use in long-range forecasting questionable.

Faced with these limitations, it is hard to avoid concluding that land-use / transport models are much better employed to explore different scenarios rather than as long-range forecasting tools. Timmermans (2003) supports this view, suggesting that there is a need to adjust our expectations and claims of models, to acknowledge that they provide a useful qualitative indication rather than a detailed quantitative assessment.

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.

Accepting the limitations inherent in the modelling process, we have chosen to develop a model this sits in a middle ground between those very complex models at the forefront of land-use / transport modelling research, and simpler econometric / statistical models. We identify a key benefit of our approach being that the model has relatively modest data requirements, and hence has the potential for application in other cities. Despite being somewhat simpler than other recently developed models, our model is sophisticated enough to generate a rich set of visual and other outputs to usefully serve in facilitating decision making processes.

To develop our model we established a transdisciplinary team of researchers that bring together expertise in sustainability, climate change, urban resource management, transport planning, property theory, design, urban economics, spatial modelling, GIS and mathematics. An internal competitive ‘Challenge Grant’, supported by the University of Technology Sydney, funded our research collaboration (see Rickwood *et al.*, 2007). We realised that no single discipline has the capacity to evolve a computational model that models behaviour at the household level, but which is easy to calibrate and apply. Our team have developed a model structure that does not require an unreasonable amount of data to use. At this stage, our model design is capable of analysing household decisions. The evolution of the model to incorporate firms, land developers and other stakeholders is still under development.

*** TAKE IN FIGURE 1 ***

The ‘heart’ of the model structure is a residential location model (see Figure 1). The core model design is easy to understand and portable, requiring only widely available data for calibration. Analysis-specific household behaviour models are attached as required, dependent on available data and intended outputs. We provided a detailed explanation of the evolution of the model and the specifics of inputs / outputs in an earlier paper (Rickwood *et al.*, 2007). This is expanded in Rickwood (2009, Chapter 5). Our focus here is to provide rich analysis, by demonstrating what the model can represent.

Our residential choice model can be calibrated using only widely available census style data. It does not require estimates of house prices / rents. Besides the census data required to calibrate the residential choice model, the only other data required is policy and demographic data, and the data required by any household behaviour modules ‘attached’ to the core model.

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For the purposes of illustration, we have analysed two modules (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. Alternatively, if policy-makers were interested in matters other than transport and in-dwelling energy use, then other modules that model the behaviour of interest can be incorporated. As a result, the amount of data required to calibrate the entire model is largely under the control of the modeller By selective simplification, we 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.

IV. Sample Analysis of Model Results and Outputs (for Sydney 2006-2031)

As a Sydney based team of researchers, we are going to use our home city to demonstrate the capacity of our model. As the then Premier of New South Wales, the Hon. Morris Iemma, stated in his vision for the NSW Metropolitan Strategy, “Sydney is Australia’s only global city. Its mix of national parks, beaches and waterways, diverse and energetic cultural life, vibrant suburban centres, varied cultures and job and business opportunities provide a diversity of choices to the regional community. Yet as the city has grown, so too has pressure on roads, on housing supply and on infrastructure and services” (NSW Department of Planning, 2005, p.3).

*** TAKE IN FIGURE 2 ***

In 2005, the Sydney region contained some 4.2 million people. Whilst the population has doubled since 1950, water consumption has tripled. Australia has the highest per capita greenhouse gas emission rate of any developed nation, with each person in Sydney currently creating 27.2 tonnes of CO_2 per annum. Single and two person households are in the majority in Sydney, with 22% being occupied by one person. This single occupancy figure is anticipated to increase to 30% by 2031, requiring an additional 300,000 single person households. Meanwhile, government forecasts suggest that there will be an increase of 140,000 households with couples and children over the same timescale (NSW Department of Planning, 2005, pp.24-29).

We start by incorporating energy and greenhouse data. We will then integrate aspects of housing satisfaction and income segregation to show how the model produces outputs that have the capacity to stimulate a wider range of options, rather than relying on a prediction of what will / might happen. Our outputs, as presented, are only for the baseline scenario.

*** TAKE IN FIGURE 3 ***

Our baseline scenario is grounded on the Sydney metropolitan planning strategy (NSW Department of Planning, 2005). :Land-use is exogenously determined to reflect policy decisions (i.e. the user provides it as an input, in this case based on Metropolitan Planning Strategy forecasts). Figure 3 shows the number, and spatial distribution, of new dwellings projected to be built in Sydney between 2006-2031 under the baseline scenario.

*** TAKE IN FIGURE 4 ***

Figure 4 shows the total dwelling-related primary energy used by households in the baseline scenario. This includes energy used within the home (for heating/cooling, lighting, etc.) as well as energy embodied in residential dwellings. The difference between per-household and per-capita patterns shows the energy savings that are associated with sharing in larger households. This is the main explanation for the fact that inner-city areas have high per-capita dwelling-related energy use.

*** TAKE IN FIGURE 5 ***

Figure 5 shows the total transport-related primary energy used by households in the baseline scenario for Sydney. This includes private passenger travel and public transportation. Unlike Figure 4, we see that the spatial pattern is much the same regardless of whether one reports results in per-capita or per-household terms. This is because the benefits of sharing are less for transport energy use (compared with in-dwelling energy), and because travel behaviour is much more sensitive to location than is dwelling-related energy use.

*** TAKE IN FIGURE 6 ***

*** TAKE IN FIGURE 7 ***

*** TAKE IN FIGURE 8 ***

Figures 6-8 show the spatial pattern of per-capita greenhouse emissions in the baseline scenario. Figure 6 shows the emissions resulting from dwelling-related energy use; Figure 7 shows the emissions from residential transport-related energy use; and Figure 8 shows the combined emissions. Importantly, Figure 8 shows that transport-related emissions dominate the overall spatial pattern of emissions.

*** TAKE IN FIGURE 9 ***

*** TAKE IN FIGURE 10 ***

*** TAKE IN FIGURE 11 ***

Spatial variation in per-household and per-capita income is shown in Figures 9 and 10. Figure 11 shows the distribution and concentration of households with children in 2031 for the baseline scenario, and the currently observed distribution. Though beyond the scope of our current research, it would be both possible and interesting to conduct detailed analysis of the segregation resulting from different housing scenarios.

*** TAKE IN FIGURE 12 ***

Figure 12 shows the projected number of people per household in the baseline scenario in 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.

*** TAKE IN FIGURE 13 ***

Figure 13 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).

V. Concluding discussion

This paper has outlined the structure and function of an integrated model for understanding how land use planning policy affects water, energy, and transport. The development of such a model addresses a key deficiency with respect to planning for efficient, resilient cities – namely, the lack of an integrated platform for water, energy, and transport data.

In demonstrating the application of the model to analysis of Sydney, the following conclusions are drawn:

- personal transport energy is lower, per person *and* per household, in the city and along public transport corridors, than in the outer suburbs where car-based travel dominates trips; and
- dwelling related energy is higher per person in the city than in the lower density outer suburbs, however the pattern for total household energy use is the reverse with the suburbs being higher.

This result is explained, in part, by the higher proportion of lone person households in the inner city. The underlying drivers and policy responses require careful consideration. If appropriate housing were available could that facilitate lone person households sharing and hence reducing per capita energy consumption. If people choose to live by themselves (and in fact for all householders), what impact reductions can be achieved with better housing design, improved appliances and changed behaviours at the household level? Moreover, if one supposes a fixed number of lone households at any one time, is it not better that they are located near the city where transport-related energy is much lower. The complexity of the drivers and policy responses suggests the need for a much broader analysis incorporating sociological and cultural factors.

As part of a broader research analysis, the integrated model serves two important functions. Firstly, it acts to provide a spatial representation of climate change and related impacts across the city, which can be tracked through time to monitor progress. Secondly, and more importantly, its ability to be configured for interactive and policy relevant scenarios, lends itself to being used as part of a deliberative process for improving the management and governance of cities.

Such processes must involve government agencies, industry, and citizens in decision-making processes. By providing a single platform for water, energy, and transport data, it is possible to overcome barriers of incompatible data formats between government holders of data.

This research provides policy guidance to city officials in responding to climate change in the carbon-constrained city. Through a straightforward approach to data management, our model offers increased understanding through clear visual representation (WB Cluster 1). In the context of Infrastructure, Built Environment, and Energy Supply our model offers integrated answers to part of the question of resilience in the face of climate change (WB Cluster 2). It supports policy led approaches to efficient / effective planning, increasing the resilience and energy efficiency of carbon-constrained cities. The research also highlights the shortcoming of institutional and governance frameworks to the mitigation and adaptation priorities (WB Cluster 3). Our model has the potential to support the role of Institutions, Governance, and Urban Planning in improving management, coordination, and planning of cities to meet climate change challenges.

For our part, the model developed in this paper will be useful for exploring several policy initiatives currently under consideration in Sydney. The City of Sydney has a 2030 Vision for a Sustainable Sydney. Our model will help explore the role that planning policy can play in achieving future targets, together with other initiatives being proposed, such as introducing Green Transformers or smart meters. Green Transformers are cogeneration plants converting waste to energy, as well as producing low-carbon energy and recycled water (City of Sydney, 2009). The introduction of smart meters for water and energy will reduce household consumption.

The role of our model is in understanding city-wide impacts of reductions at the household level using household level data. This cross-scale analysis is unique and of vital importance in assessing how cities will respond to the climate change imperative. Other initiatives to be considered would be the introduction of plug-in hybrid electric vehicles and their role in intelligent energy grids (see www.igrid.net.au). The nature of the water-energy interaction is also changing with the widespread adoption of rain-tanks across Sydney by householders and the construction of a desalination plant to add to the city’s rain-fed water supplies from dams.

Future work will proceed in two directions: extending the data used to underpin the model to consider the embodied energy in water and indirect emissions; and, applying the model within a deliberative decision making process as input to policy development.

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Tables

Table 1: The three waves of transport/land-use models. Adapted from Timmermans (2003).

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

Figures

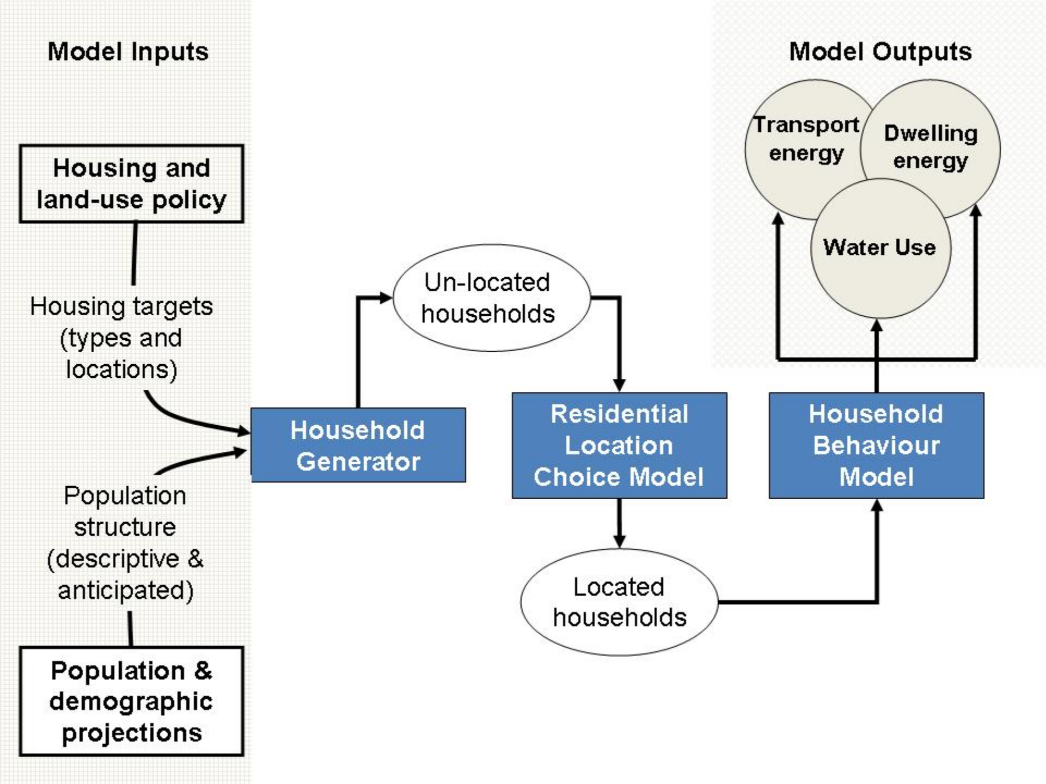


Figure 1: Integrated Model Concept (adapted from Rickwood *et al.*, 2007)

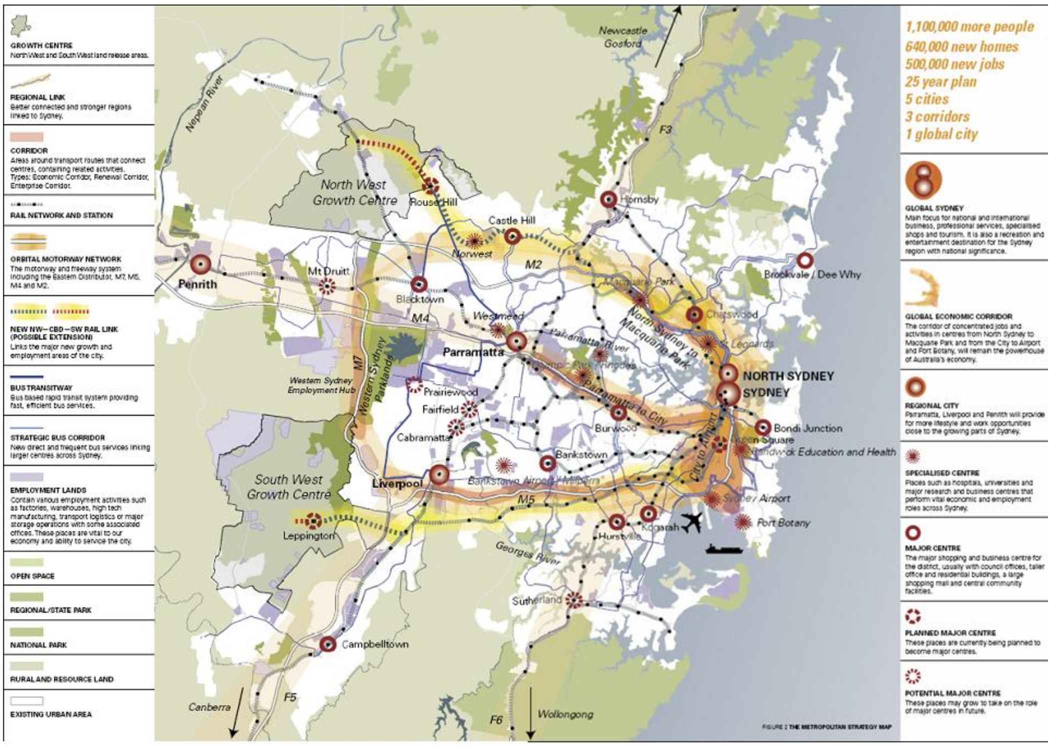


Figure 2: Sydney in the context of the Metropolitan Strategy (source NSW Department of Planning, 2005, pp.10-11)

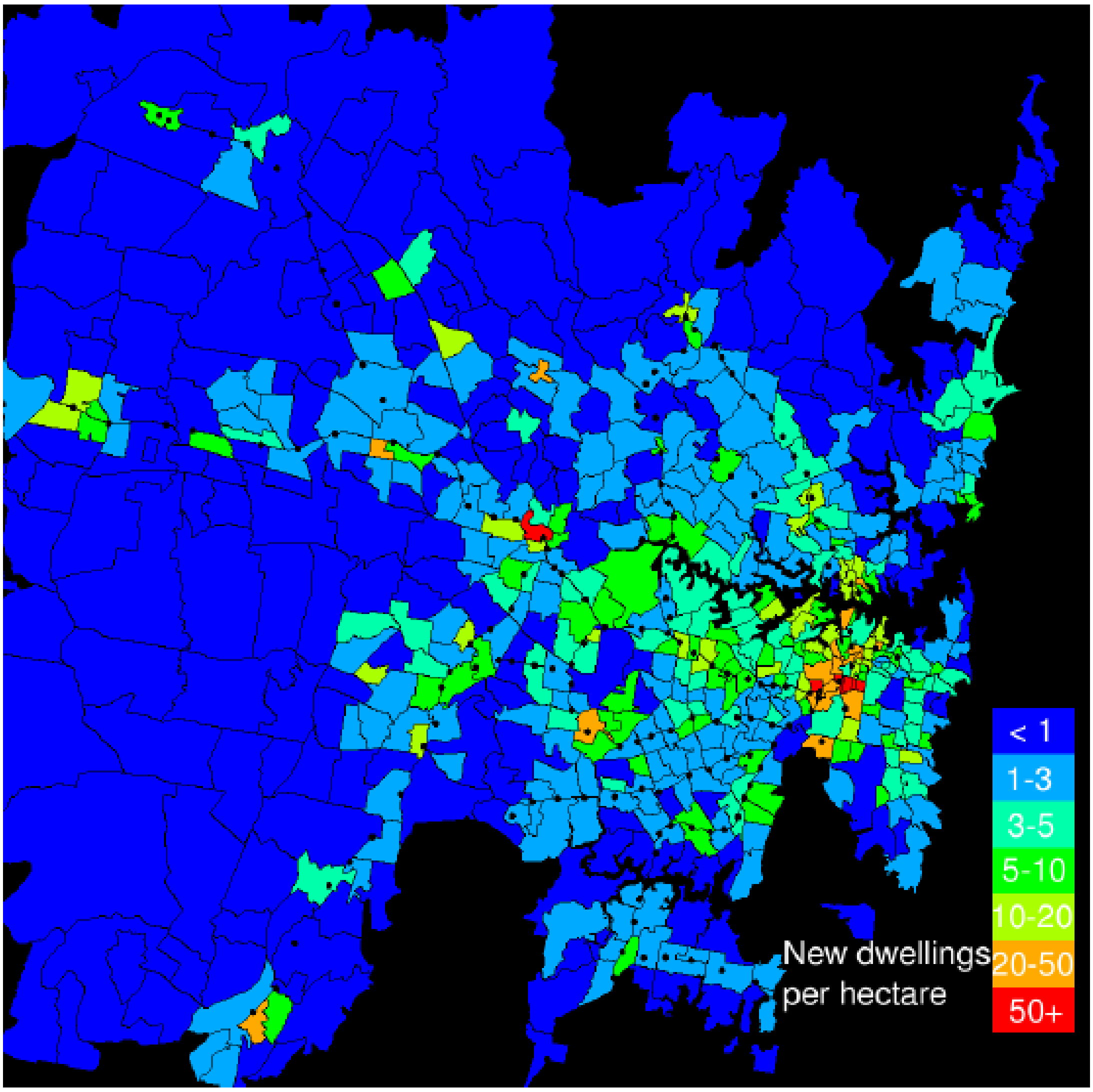
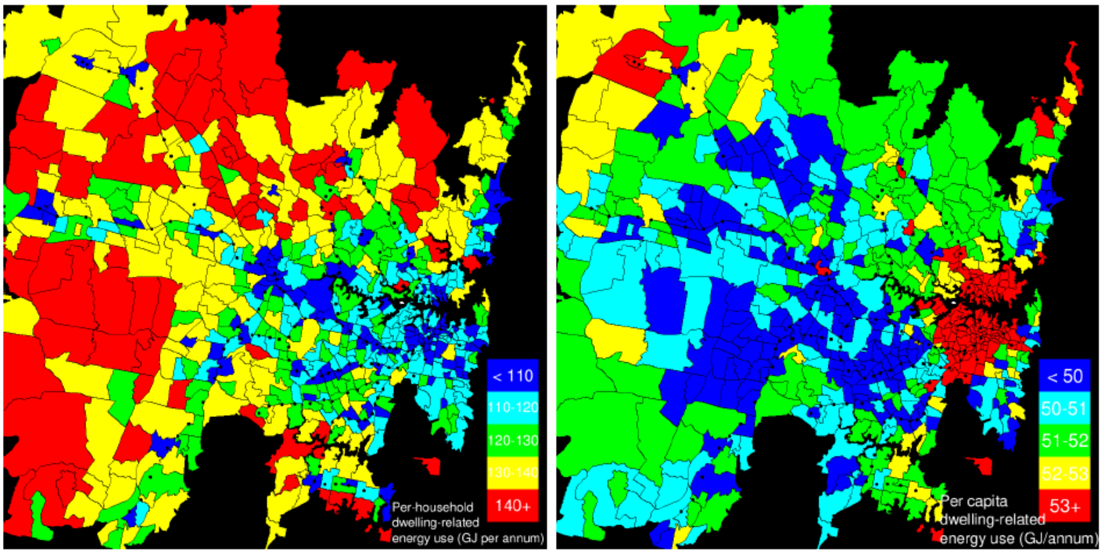
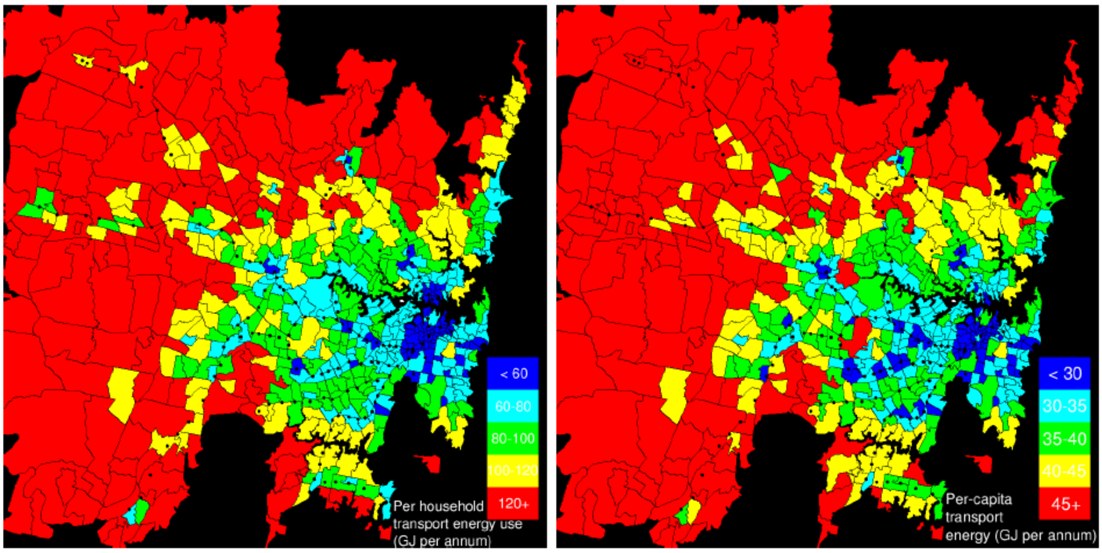


Figure 3: Exogenous housing inputs: new dwellings per hectare 2006-2031 in Sydney.



(a) Per household (b) Per person

Figure 4: Annual dwelling-related energy use (including embodied) in 2031, by zone.



(a) Per household

(b) Per person

Figure 5: Annual personal transport related energy use (including energy embodied in cars) in 2031, by zone.

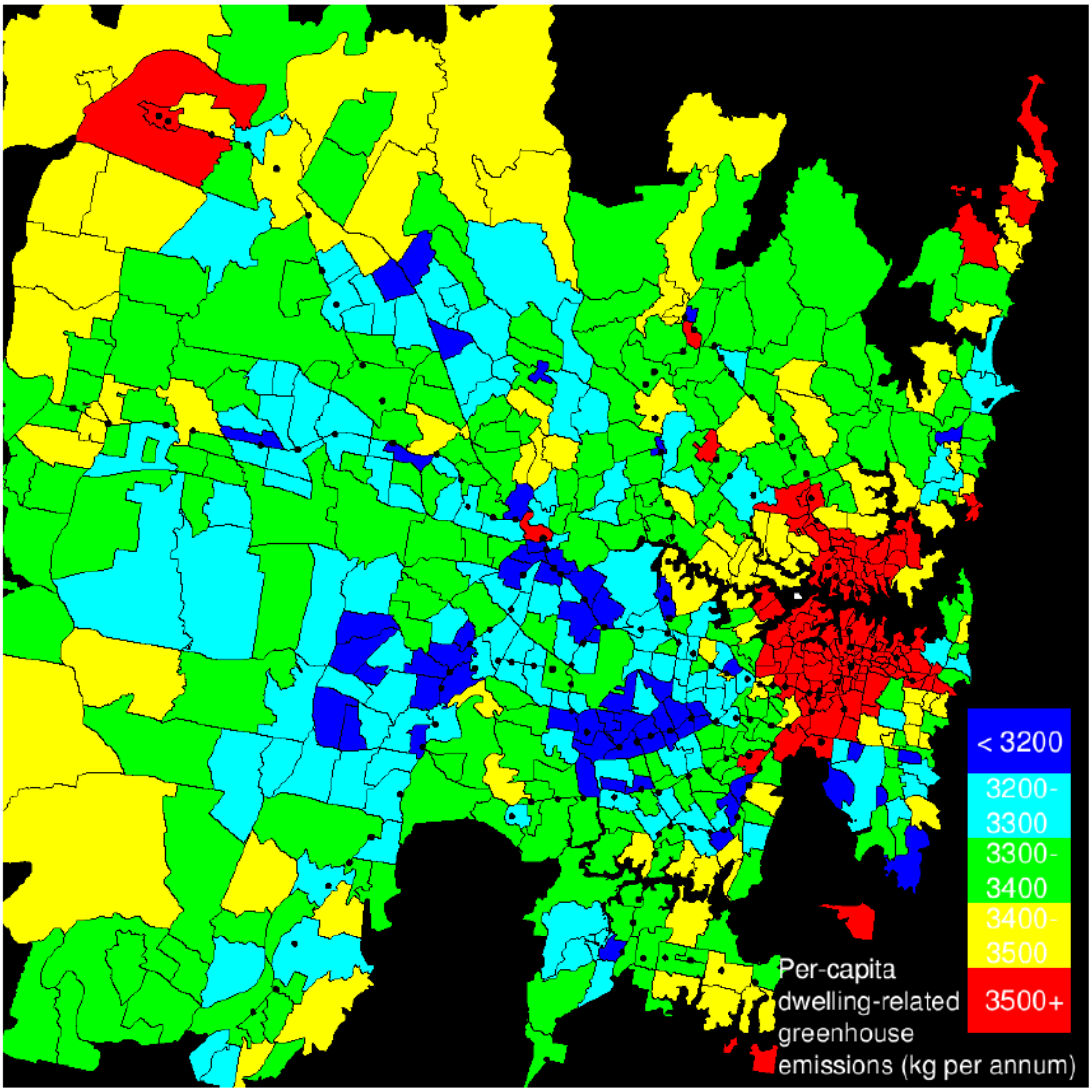


Figure 6: Annual dwelling-related emissions per-person (including embodied) in 2031, by zone.

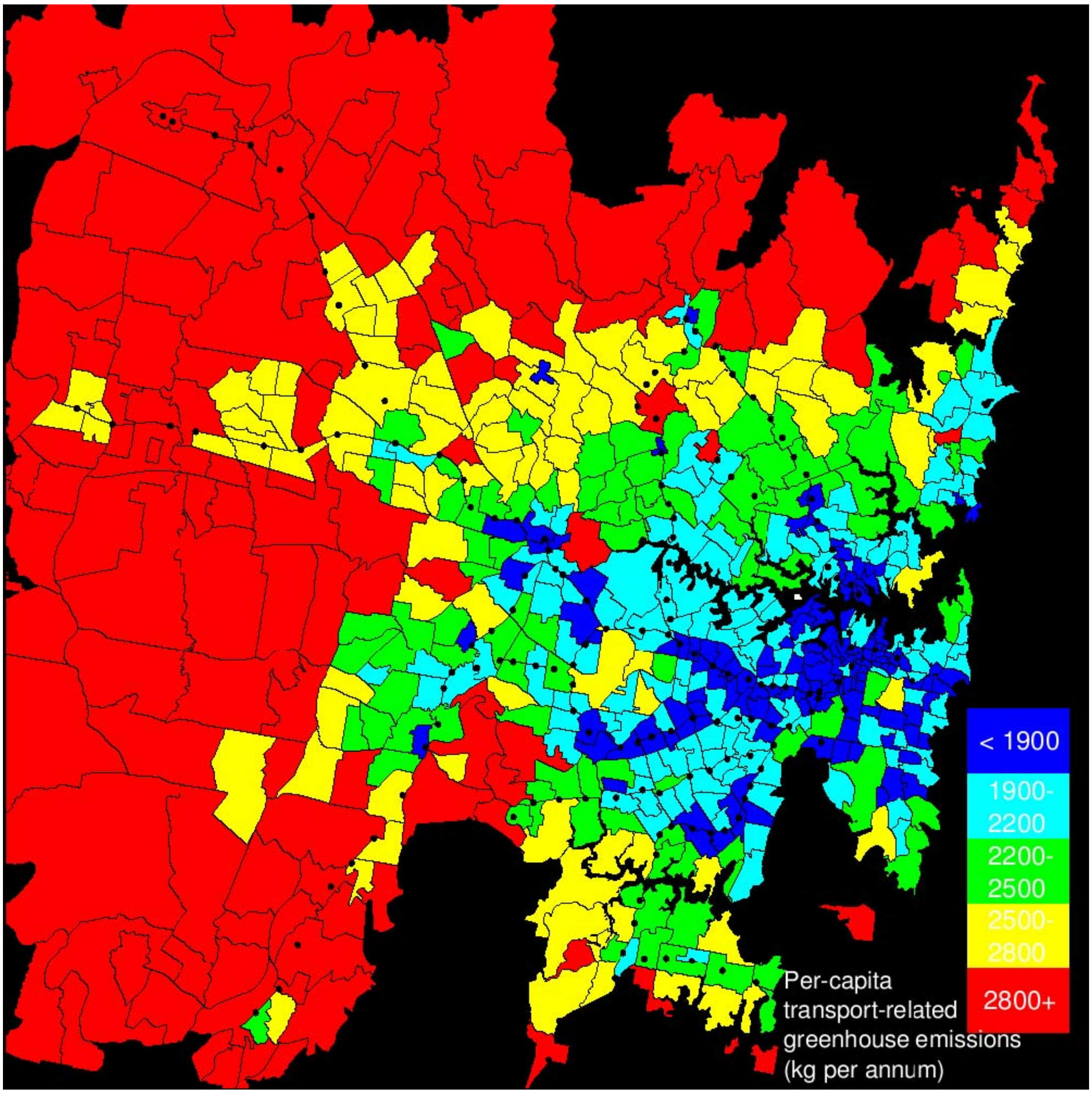


Figure 7: Annual personal transport related emissions per person (including emissions embodied in cars) in 2031, by zone.

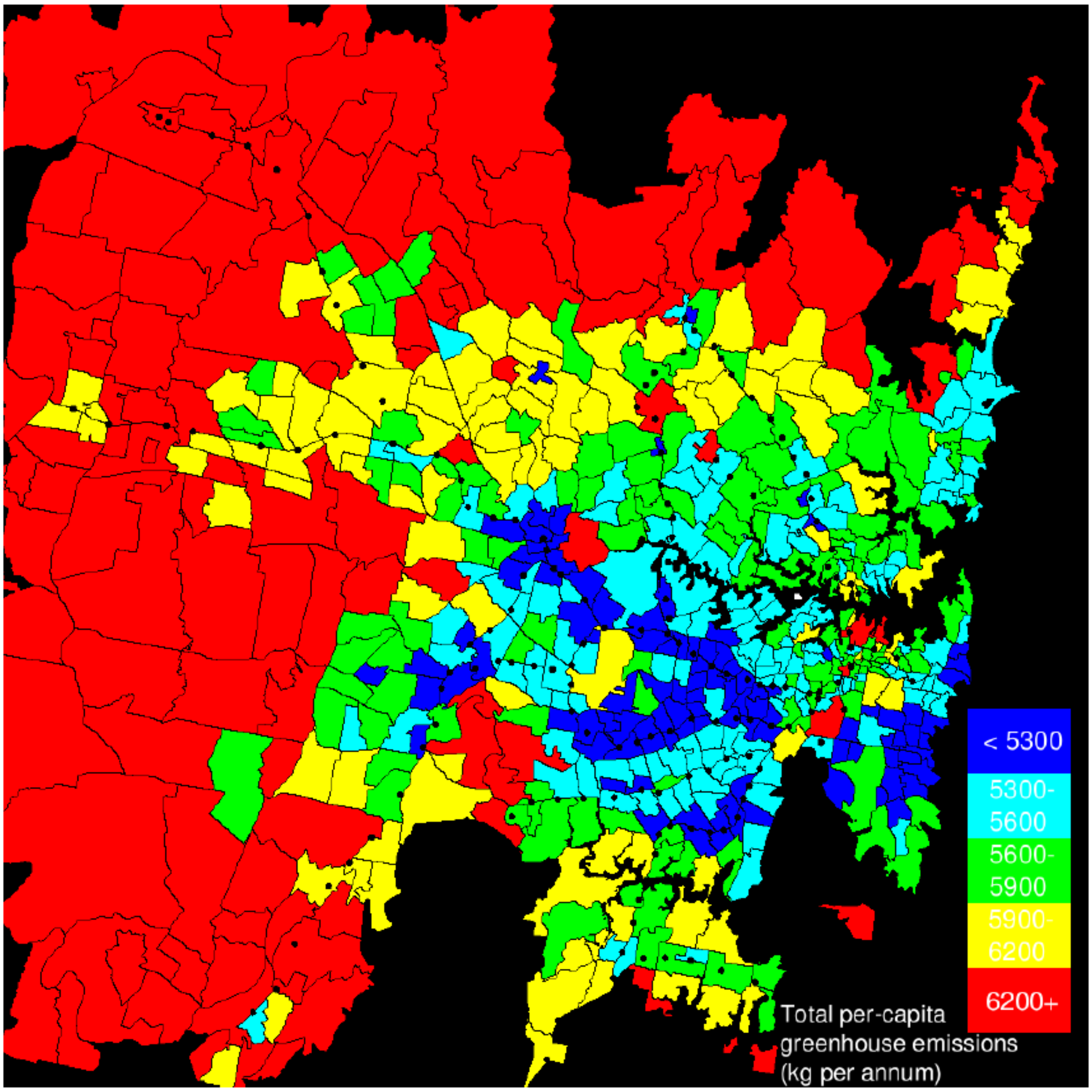
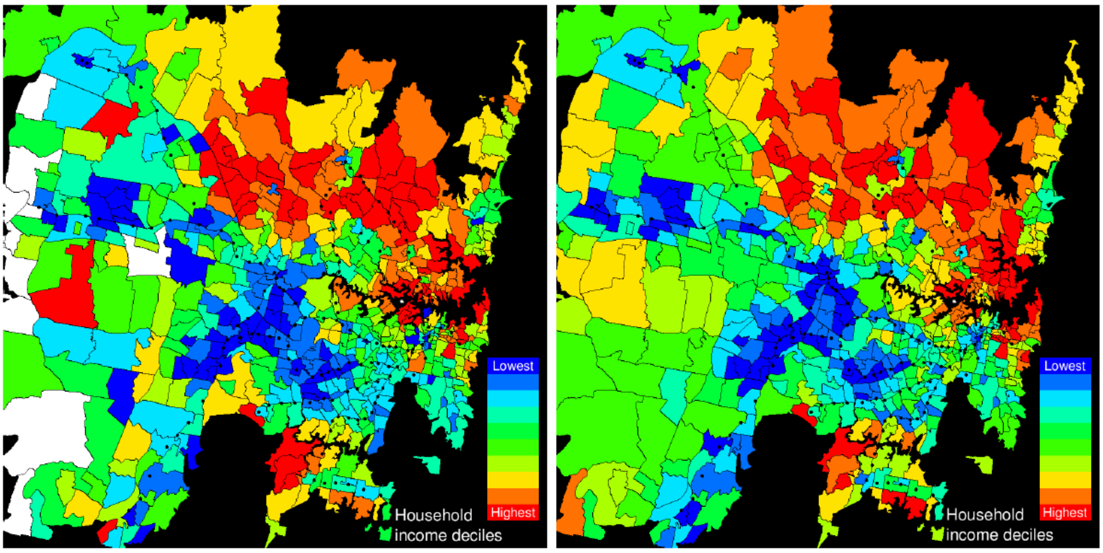


Figure 8: Annual emissions per person (including emissions embodied in cars) in 2031, by zone.



(a) 2001 (b) 2031

Figure 9: Household income deciles in 2001 (from ABS data) and 2031 (projected for baseline scenario).

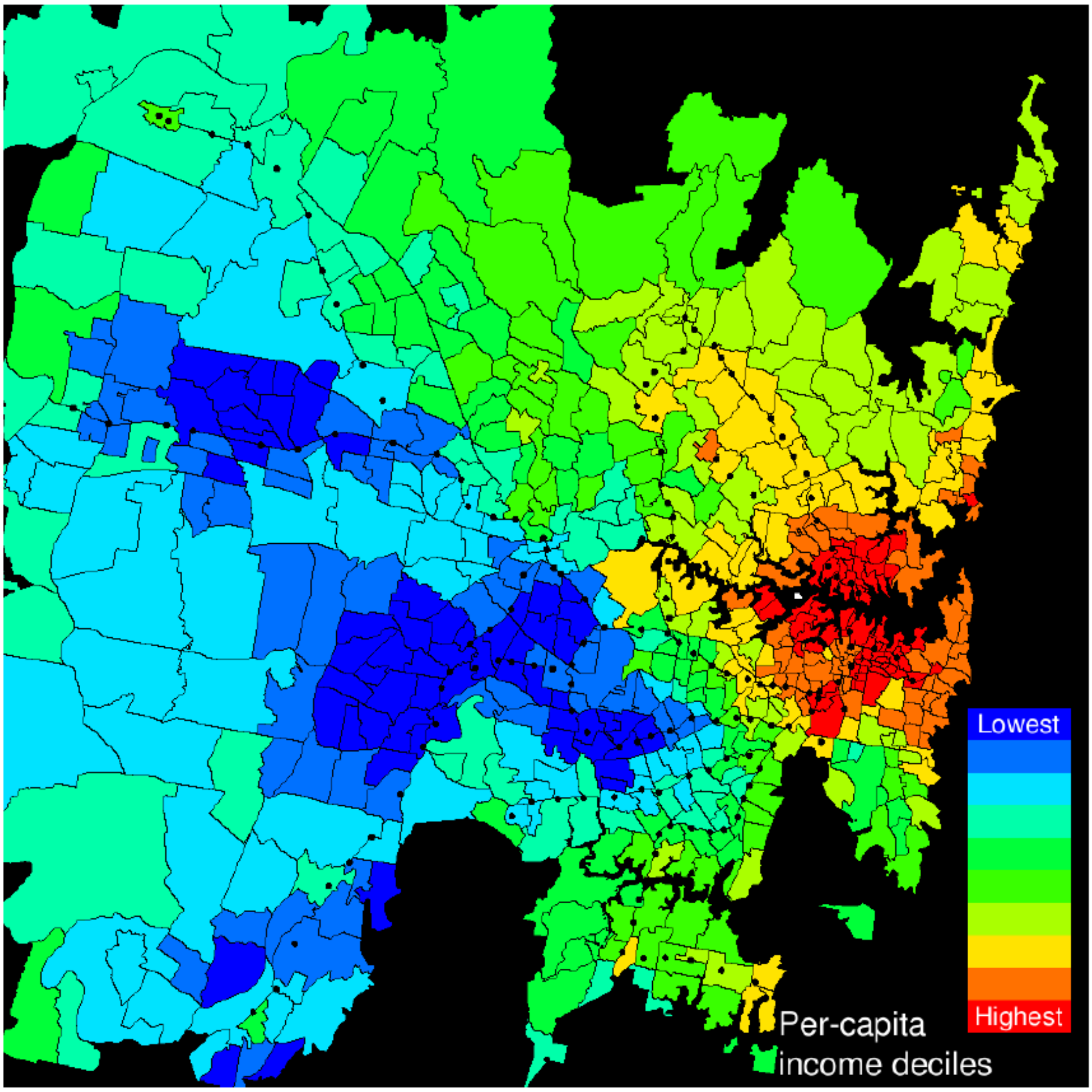
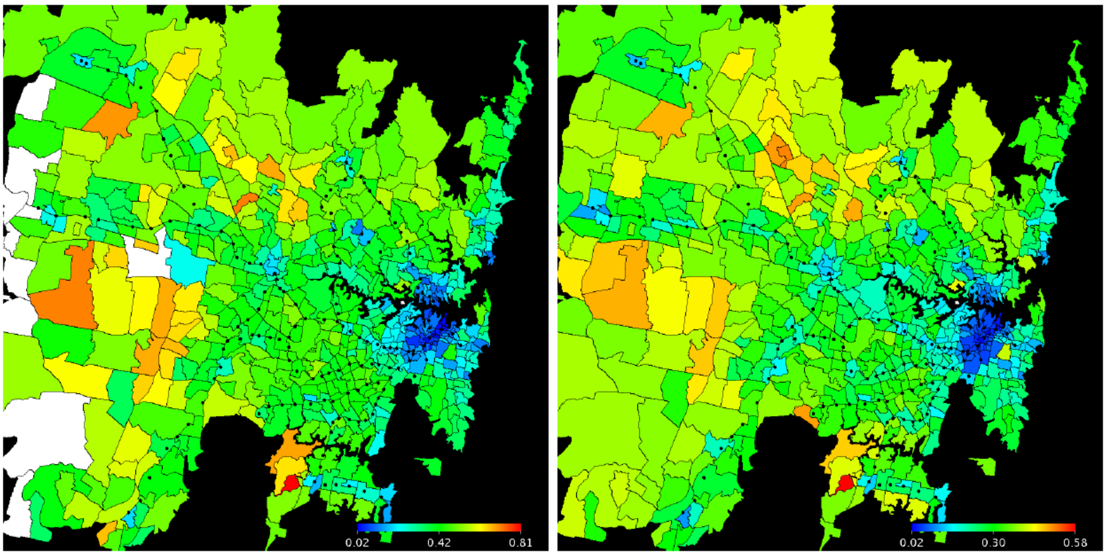


Figure 10: Per-capita income deciles in 2031 (projected for baseline scenario).



(a) 2001 (b) 2031

Figure 11: Proportion of households that are couples with children (all ages), by zone, for 2001 and 2031.

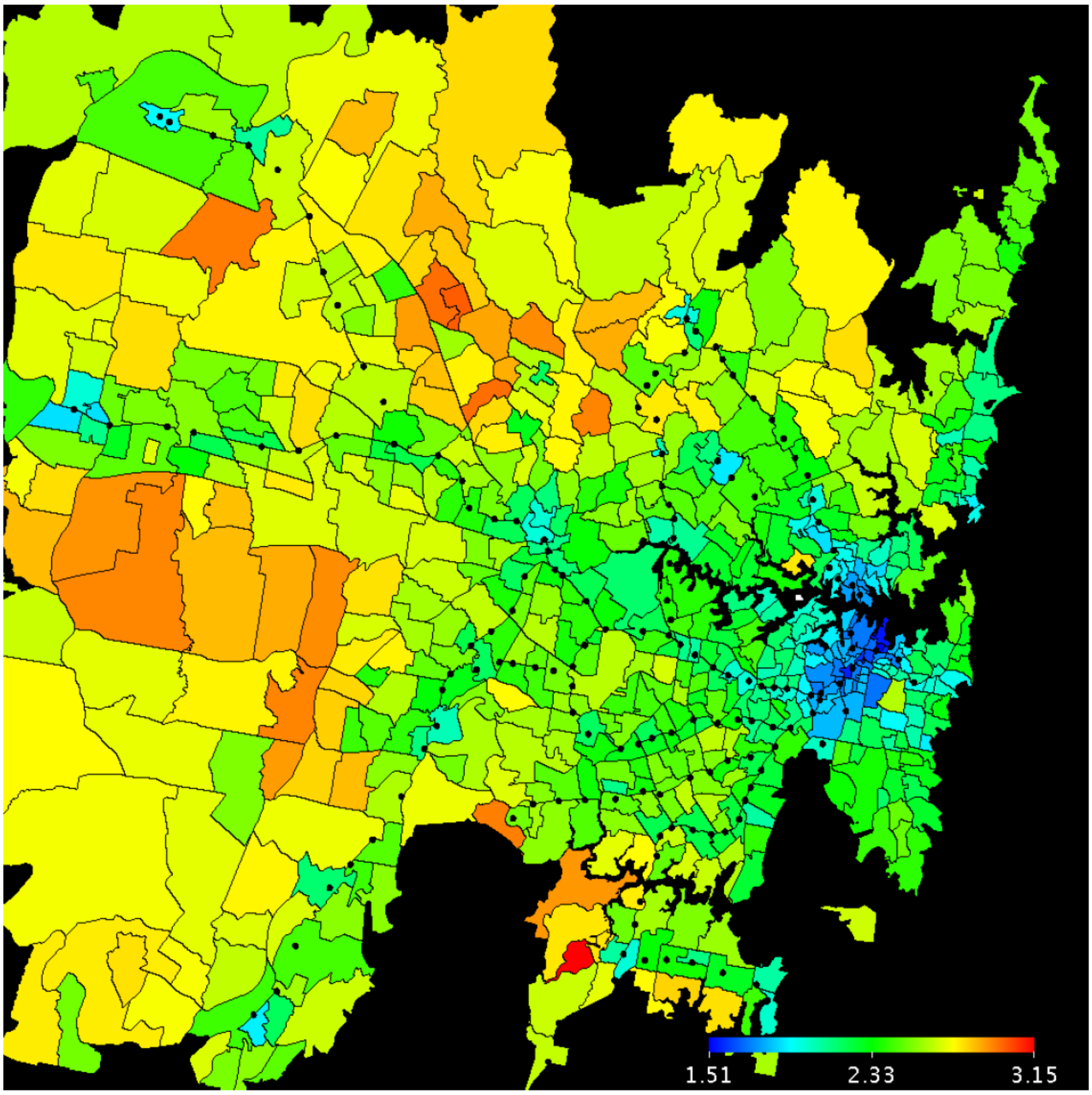


Figure 12: Persons per household in 2031, by zone.

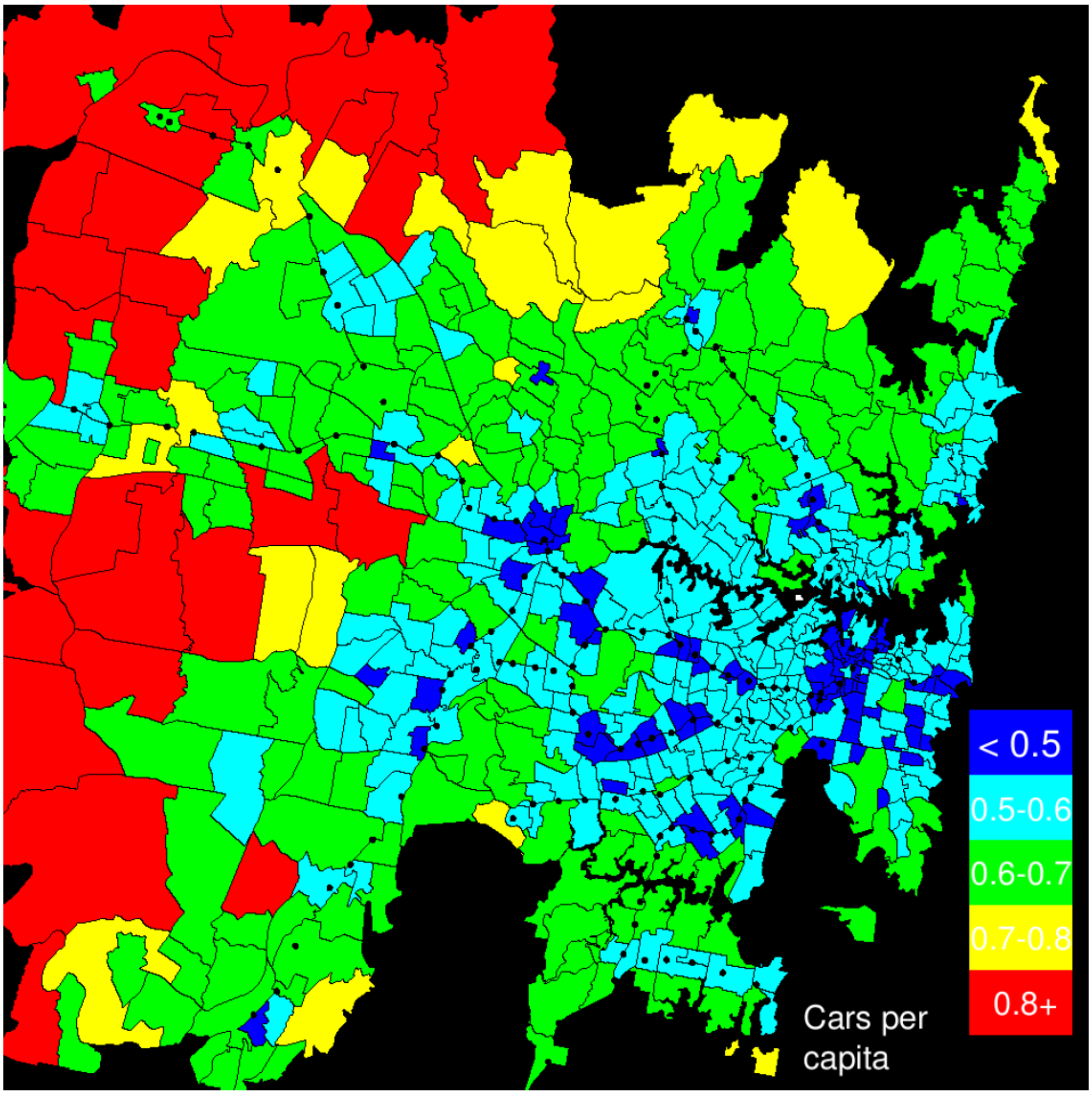


Figure 13: Cars per person in 2031, by zone.