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A spatial general equilibrium analysis of transport policies in Sydney, Australia

James Lennox*† and Janine Dixon†

Centre of Policy Studies (CoPS), Victoria University

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Abstract

'VU Cities–Sydney' is a spatial computable general equilibrium (SCGE) model of the Sydney–Newcastle–Wollongong region, which encompasses Australia's largest city and is home to around 5 million people. The model is intended to be used to simulate the impacts of policies, planning and public investments in the urban and transport sectors. We demonstrate its potential with an analysis of the spatial impacts of hypothetical transport policies that simultaneously reduce travel times by rail and increase private vehicle operating costs. We show how these policies increase the centralisation of employment in central Sydney and increase residential densities along train lines at the expense of outer areas that are highly car-dependent.

VU Cities–Sydney has a detailed spatial structure with 363 employment and residential zones. Households make discrete choices of their places of work, residence and industry of employment. They make continuous choices over the consumption of tradable and non-tradable goods and services. The model allows for localised spillovers of both productivity and residential amenity. It is calibrated using census and land use planning data together with travel costs derived from the New South Wales Strategic Transport Model.

Keywords: generalised travel costs; transport modes; spatial impacts; labour supply; agglomeration effects

1 Introduction

Many cities in the world are struggling with challenges of accommodating growing populations in ways that are socially, economically and environmentally sustainable. The extent to and the means by which cities provide accessibility—to people, goods and services and

information—is increasingly recognised as crucial to their success or failure(Duranton and Guerra, 2016; Rode et al., 2017). Accessibility results from the interaction of land use and transport systems, which too often are considered in quasi-isolation from one another. The consequences of ignoring these interactions have become very obvious in Australia's largest cities. Governments at all levels have failed to facilitate additional housing supply where it is most needed and have chronically under-invested in urban infrastructure, particularly public transport infrastructure. As a consequence, living costs have risen while accessibility to employment opportunities and services have declined for many Australian households (Kelly and Donegan, 2015).

Increasing residential population densities in the inner and middle suburbs together with major investments in the public transportation systems of Australia's largest cities will be crucial to improving accessibility in the face of continuing population growth and structural economic changes (Kelly and Donegan, 2015; Infrastructure Australia, 2018). These considerations are now being recognised in public documents, such as the 'Greater Sydney Regional Plan' and 'Plan Melbourne', which espouse goals such as the '30 minute city' (Sydney) or '20 minute neighbourhood' (Melbourne). However, recent analysis of liveability policies in Australian cities (Arundel et al., 2017) suggest that the ability of policy-makers to deliver on their ambitious rhetoric should be questioned.

Quantitative analysis of land use, transport and accessibility in Australia tends to focus on first specifying land use planning scenarios informed by policy objectives and subsequently undertaking detailed modelling of mobility outcomes using sophisticated transport network models. However, less capability exists to model the economic drivers of land use change and transport demands. The VU Cities modelling framework attempts to redress this imbalance. VU Cities–Sydney is a large-scale spatial computational general equilibrium (SCGE) model of the Greater Sydney–Newcastle –Wollongong region. It features production, consumption, commuting and shopping activities within and between 363 spatial zones. To illustrate the potential of the model, we present the results of a stylised counter-factual policy simulation. In this simulation we: (i) increase vehicle operating costs to reflect distance-based road user charging; and (ii) decrease rail travel times to reflect service improvements that could help increase public transport mode shares and thus serve accessibility needs more efficiently.

2   Background

Australia is a highly urbanised country. The four largest cities, Sydney, Melbourne, Brisbane and Perth now account for 58% of the total population and this share is expected to grow to 64% over the next thirty years (Infrastructure Australia, 2018, p 3). In 2015–16, Sydney accounted for 20% of Australia's population but 24% of its GDP—and 40% of GDP growth (SGS, 2016). However, not all areas within cities have fared equally. Employment growth has been strong in inner cities and weak in outer suburban areas. This has been exacerbated by declining manufacturing employment and strong growth in finance, insurance and professional services industries, which are highly concentrated in central business districts (Infrastructure Australia, 2018, p 61). There is a strong and growing mismatch between the residential and workplace locations. For example, just 8% of Sydney's population but 26% of jobs are located in Sydney City and the Inner South.[1]

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[1]These statistics are for the geographic area defined by the Australian Bureau of Statistics' Statistical Area 4 'Sydney City/Inner South'. The area which incorporates suburbs to the south and south-west of the CBD out to Marrickville and Sydney Airport.

While housing demand has grown strongly, supply has been constrained, especially in the inner and middle suburbs of Australia's largest cities. Hsieh et al. (2012) note the role of complex planning processes and negative attitudes of existing residents as key barriers to infill development. In a cross-country study, Caldera and Johansson (2013) estimate the long run price elasticity of housing supply in Australia to be 0.53. While they find that many European countries have even less elastic housing supply, it is interesting to note that Canada and Sweden have elasticities of 1.2 and 1.4 respectively. Like Australia, high proportions of the populations of these countries are concentrated in their largest cities.

Local, state and federal taxes substantially distort property markets(Abelson and Joyeux, 2007; Coates, 2017). With the notable exception of New South Wales, local rates are based on assessments of improved rather than unimproved land value, which is likely to discourage development. State governments do levy land taxes but all implement a progressive schedule of tax rates on total property holdings (excluding the land value of owner-occupied dwellings). This fails to collect very much revenue while heavily distorting the market by imposing more-or-less prohibitive tax rates on putative medium- or large-scale investors in residential property.[2] State governments do, however, raise a great deal of revenue by levying stamp duty on property sales. This tax has undesirable effects including decreasing labour mobility and reducing households' abilities to up- or down-size their dwellings over time as their needs change.[3] The federal government levies a discounted capital gains rate on investment properties and exempts owner-occupied properties from the tax. Owner-occupied properties are also exempted from the public pension assets test.

Political pressures over unaffordable housing have grown steadily in Australia. However, rather than undertaking meaningful reforms, state and federal governments have resorted to policies that are popular but unlikely to be effective (Coates, 2017). The most notable are the many past and ongoing concessional or cash grant schemes for first home buyers (Dungey, Wells, and Thompson, 2011). More recent responses include the imposition by most states of higher rates of stamp duty on foreign purchasers of residential property and vacant property taxes.

Together with historically strong cultural preferences favouring a suburban lifestyle (Burton, 2015), these factors have led Australian cities to grow outwards rather than upwards. Their urban forms are comparable to the most sprawled of American cities (e.g. Houston, Atlanta). As shown in international comparative studies such as Andrew Spencer and Schmahmann (1996), this is primarily due to very low densities *throughout* most of their suburban areas rather than insufficient densities in central areas.

Implications of urban form for the future growth of Australia's largest cities is explored in Infrastructure Australia (2018). The report presents case studies of Sydney and Melbourne featuring three alternative scenarios for growth to 2046: 'expanded low density', 'centralised high density' or 'rebalanced medium density'. Los Angeles, New York and London respectively are cited as exemplars of these forms of development. The first finding of this study is that the low density scenario (which most closely resembles a continuation of historic development trends) yields the worst infrastructure and accessibility outcomes for residents (p7). Its second finding is that an increased role for public transport is crucial to improving accessibility (p8). The report also echoes recommendations of many academic

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[2]The rate in New South Wales for large holdings is 2% of the assessed land value per annum.

[3]The Australian Capital Territory is the one jurisdiction to have begun phasing out stamp duty in favour of a land tax.

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studies that call for movement towards a system of road user pricing (p8) as a means to fund transport infrastructure more sustainably (Hensher and Bliemer, 2014), reduce congestion (Terrill and Parsonage, 2017) and reduce greenhouse gas emissions (Stanley et al., 2018).

The Infrastructure Australia studies exemplifies the relatively sophisticated understanding that exists in Australia of the implications of different urban forms for urban transportation demands and accessibility outcomes. This reflects the development and widespread use of sophisticated transport network modelling capabilities, especially in Sydney and Melbourne. However, metropolitan–scale land use modelling capabilities are much more limited. For the most part, governments rely on scenarios based on actual or proposed land use plans, aggregate demographic projections and rule-based methods for distributing projected housing demand over different areas.

A notable exception is Truong and Hensher (2012), who link a discrete choice model of residential and workplace location, dwelling type and transport mode with a multiregional CGE model. The model presented in this paper also incorporates discrete locational choices within a general equilibrium framework. However, we operate at a significantly higher level of spatial resolution. This facilitates connections with land use planning information, transport modelling and is more appropriate for modelling agglomeration effects. Finally, from a technical perspective, we directly incorporate discrete choices within the framework of an SCGE model, avoiding the complications of iteratively solving separate models of discrete locational choices and of regional general equilibrium.

3 Model structure

3.1 Overview

VU-Cities is a comparative static spatial computable general equilibrium (SCGE) model that we have developed to study issues relating to land use and transportation in Australia's major cities. It is similar in basic concept to the 'RELU' SCGE model of Chicago of Anas and Liu (2007). Anas and Liu (henceforth A&L) incorporate dynamic processes and model in some detail decisions of property developers, but model a modest number of quite large regions. They also link their model to a transport network model ('TRAN') in order to investigate effects of road traffic congestion. Our model has a simpler structure and we treat transport costs as exogenous. However, we have developed it to run at a much higher level of spatial resolution with some hundreds of small zones in urban and peri-urban areas. In addition, we consider positive spatial externalities in both productive and residential sectors, following Ahlfeldt et al. (2015). Congestion effects could, in principle, be allowed for by iteratively solution of VU-Cities and a transport network model, but this remains a subject for future research.

In our current implementation of VU-Cities for Sydney, the metropolitan areas of Sydney, Wollongong, Newcastle and surrounding peri-urban areas are divided into 363 Statistical Areas. An overview of this region is shown in figure 1. Land in each of these areas is exogenously allocated between land use planning zones, each of which permits different types and mixes of land use. Not all uses are permitted in all zones, e.g. there is no residential use of industrial-zoned land. In each area, zoned land may be endogenously reallocated between uses based on relative land rental rates in those uses. Using sectors (industries and households) consume property services, which are produced using flexible combinations of land and structures, this development density is endogenous for each use
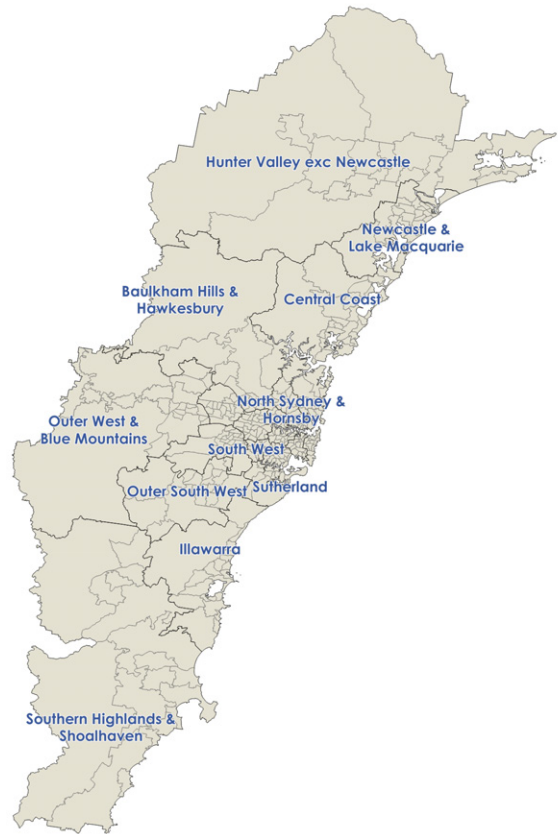
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Figure 1: Regional overview map showing Statistical Areas Level 4 (heavy boundaries) and 2 (light boundaries) of the Australian Statistical Geography Standard (ABS, 2011b)

in each planning zone.

As in A&L, we distinguish the production of non-tradable services that must be consumed where they are produced from the production of goods or services that are tradable (either within or outside the metropolitan region). Households have preferences over non-tradables produced in all zones and in consuming these services, incur costs for travelling between their place of residence and the place of consumption/production. As a result of these travel costs, most non-tradables markets are very localised. However, large agglomerations of non-tradables production also exist (e.g. in Sydney's CBD) serving larger markets. Households also consume tradable goods and services for which there is a common price (which serves as the numeraire). In this initial version of VU Cities–Sydney, we abstract from firms' use of tradable and non-tradable intermediate goods, which A&L allow for. However, we do distinguish three different non-tradable industries and four tradable industries. We also distingiush working households by five skill levels, as well as non-working households.

Conditional on skill class and on these three discrete choices, households also make continuous choices of residential floorspace, non-tradables and tradables consumption. This structure is similar to A&L, except that in their model, households make a discrete choice between dwelling type and labour is perfectly mobile between industries, whereas in ours, households make a discrete choice between industries but treat high- and low-density floorspace as perfect substitutes. By incorporating the discrete choice between industries,

we can account for substantial wage differentials between industries that remain after controlling for skill composition. We omit the discrete choice between types of floorspace mainly because of limitations of our current datasets.[4]

Firms are subject to positive externalities of agglomeration, their productivity depending on the distance-weighted density of firms within the same sector. Reflecting the available empirical evidence, these effects are of modest strength and quite localised (Ahlfeldt et al., 2015). There are also positive externalities of agglomeration on the household side, which depend on the distance-weighted density of households. These are somewhat stronger but even more localised than the productive externalities, reflecting the estimates of Ahlfeldt et al. (2015).

3.2 Working households

Working households are measured in numbers of full-time equivalent (FTE) workers. Each FTE worker–household is treated as independent decision-making unit. Thus, we abstract from issues relating to days and hours worked or to joint residential location choices of dual-worker households. Each worker–household has a fixed skill level k and can choose an industry of employment i, a place of residence r and a place of work s. Commuting from r to s entails generalised travel costs τ_{rs}. Skill k workers in industry i at location s earn a wage W_{kis}. Households of type h living in r face a local consumer price index Q_{hr} that depends on local residential rental prices, local price indices for each type of non-tradable good $j \in \mathfrak{N}$, region-wide prices of tradable goods $j \in \mathfrak{T}$, and on consumption preferences, which differ by skill.

As is common in the literature, we assume commuting costs in units of utility to be an exponential function of generalised travel costs (GTC) in minutes $\tau_{\mathrm{W}rs}$: $D_{krs} = e^{\kappa_k \tau_{\mathrm{W}rs}}$. The parameter κ_k may differ between skill levels. A second set of GTCs applies to trips made for the purpose of consuming non-tradables. For convenience, we will refer to these as 'shopping' trips, although the actual purposes covered range from grocery shopping trips to visiting healthcare providers to attending educational institutions. We denote shopping costs $D_{jrs} = e^{\kappa_j \tau_{\mathrm{S}rs}}$ for $j \in \mathfrak{N}$, where the parameter κ_j is common to all shoppers but may differ by commodity purchased. For simplicity, we omit pecuniary costs associated with commuting or shopping travel from households' income constraints.[5]

Households of each type earn amounts of taxable and non-taxable non-wage income that we assume to be independent of location choice. Non-taxable income includes pension income (which is of most importance for non-working households, discussed below) and imputed rental income from owner-occupied dwellings. We adopt the common device of assuming that an absentee landlord owns all property in the region.[6] There is a fixed average tax rate for each household type, which is applied to the total of wage and taxable non-wage income.

Households derive utility not only from their composite consumption of goods, services and housing c_{kirs}, but also from natural and public amenities in each place of residence.

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[4]We follow A&L in employing a multinomial rather than a nested logit function in the initial version of VU Cities–Sydney for its simplicity.

[5]Explicit accounting for these costs, as in e.g. Anas (2007) is theoretically appealing, but would greatly complicate the model and increase computational costs. This is because local price indices would depend on commuting costs and thus residence–workplace pairs, squaring the number of associated equations.

[6]Without much more difficulty, we could have assumed that each household owns an identical share in the entire stock of regional property without much more difficulty. However, we are unaware of any spatial economic model that accounts for the ownership of particular property assets by particular households.

To allow calibration of the model to match initial data on places of residence, we assume an interaction between perceived amenity, skill and choice of industry, thus amenity is denoted B_{kir}.

Finally, we assume that each individual working household $o(k)$ draws an idiosyncratic shock to their utility from an independent Fréchet distribution, as in Anas and Liu (2007) and Ahlfeldt et al. (2015). We thus define utility of working household $o(k)$ to be

$$U_{o(k)irso} = \frac{z_{o(k)irs}B_{kir}c_{kirs}}{D_{krs}} \tag{1}$$

From households' first order conditions, the indirect utility function is

$$V_{o(k)irso} = \frac{z_{o(k)irs}B_{kir}M_{kis}}{D_{krs}Q_{kr}} \tag{2}$$

with

$$M_{kis} = (1 - t_k)(W_{kis} + m_{1,k}) + m_{2,k} \tag{3}$$

where effective after-tax income M_{kis} depends on gross wage income W_{kis}, taxable non-wage income $m_{1,k}$, the effective income tax rate t_k and non-taxable non-wage income $m_{2,k}$ that includes imputed rental income.

Local consumer price indices are given by the nested cost functions:

$$Q_{kr} = R_{\text{H}r}^{\beta_{\text{H}k}} \prod_j \mathbb{P}_{jr}^{\beta_{jk}} \tag{4}$$

where $\beta_{\text{H}k} + \sum_j \beta_{jk} = 1$ and

$$\mathbb{P}_{jr} = \begin{cases} \left(\sum_q (D_{jrq}T_{jq}P_{jq})^{1-\varepsilon_j}\right)^{\frac{1}{1-\varepsilon_j}}, & \text{if } j \in \mathfrak{N} \\ \sum_{g \in \mathfrak{T}} \iota_{gj}P_g + \sum_{g \in \mathfrak{N}} \iota_{gj}\mathbb{P}_{gr} + P_j, & \text{if } j \in \mathfrak{T} \end{cases} \tag{5}$$

For non-tradable goods, the equation above is a Dixit-Stiglitz-like price index reflecting residents' desire to consume varieties of non-tradable goods produced in all locations q. However, with generalised shopping travel costs reflected in the term D_{jrq} and $\varepsilon_j \gg 1$, consumption patterns are strongly biased towards varieties produced closer to home. The additional taste parameter T_{jq} is introduced in order that producer prices of non-tradables can be set to unity in the initially calibrated equilibrium.

For tradable goods, consumer prices incorporate the cost of transport and retail margins. Margin intensities per unit of consumption are given by ι_{mj}. Retail margin demand in each location should, in reality, be associated with the purchases of goods in those same locations. However, we find it impractical to make such a direct association. Firstly, we lack data on where different types of tradable goods are sold to retail purchasers. Secondly, formulating the model in this way would involve treating margin-inclusive tradable goods in the same way as we treat non-tradable goods. This would make the model more difficult to solve computationally. Instead, we associate demand for the spatially aggregated composite of retail services with aggregate consumption of each non-tradable good. This is reflected in the appearance of $\mathbb{P}_{jr}$ in the expression for consumer prices of tradable goods.

Integrating over individuals, the probability that a worker having skill k chooses to work in industry i in s while residing in r is[7]

$$\pi_{irs|k} = \frac{\Phi_{irs|k}}{\sum_{i'} \sum_{r'} \sum_{s'} \Phi_{i'r's'|k}} \tag{6}$$

where

$$\Phi_{irs|k} \equiv \left(\frac{B_{kir} M_{kis}}{D_{krs} Q_{kr}} \right)^{\epsilon_k}$$

where $\epsilon_i > 1$ is the shape parameter of the Freéchet distribution. The larger ϵ_i, the more responsive are households' location choices to changes in the spatial relativities of prices, wages, transport costs or amenity levels.

The labour supplied to each industry in each location is found by summing the above probabilities over places of residence and multiplying by the total population (in FTE workers) of each skill level:

$$L_{kis} = \mathcal{L}_k \sum_r \pi_{irs|k} \tag{7}$$

Similarly, by place of residence, the number of FTE workers is:

$$L_{kir}^{(\text{H})} = \mathcal{L}_k \sum_r \pi_{irs|k} \tag{8}$$

The average income of an FTE worker of skill k resident in r is

$$M_{kr}^{(\text{H})} = \frac{\sum_i \sum_s M_{kis} \left(\frac{M_{kis}}{D_{rs}} \right)^{\epsilon_k}}{\sum_i \sum_s \left(\frac{M_{kis}}{D_{rs}} \right)^{\epsilon_k}} \tag{9}$$

3.3 Non-working households

We define as non-working households as (i) sole person households where that person does not work; (ii) single parent households where the single parent does not work; and (iii) couple households where neither member of the couple works. To give some level of consistency with our treatment of working households, we treat the number of non-working household members over the age of fifteen as the unit of measure. In this paper, we take the location of each non-working person–household to be fixed. However, we intend in future work to allow for a discrete residential location choice of non-working households based on the relative prices of housing and non-tradables.

Every non-working person–household has identical income

$$M_{\text{N}} = (1 - t_k)m_{1,\text{N}} + m_{2,\text{N}} \tag{10}$$

3.4 Government consumption, inter-regional and international trade

We take the aggregate value of government and regional export demands for non-tradables to be exogenous.[8] We do not distinguish between goods and services that are traded inter-regionally or internationally. Government demands for non-tradables relate mainly to the direct public funding of education and healthcare services provided to households.

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[7]See Ahlfeldt et al. (2015) for a detailed mathematical exposition.

[8]In the model database, there is a small amount of investment demand for non-tradables. This is treated in the same way.

Regional exports of non-tradables relate mainly to purchases of accommodation, restaurant meals and retail services by tourists visiting the region. Following the logic of the model, these non-tradable services must be 'shopped for', so the exogenous values are those at the places from which the demands emanate, rather than at the locations of production.

In reality, it is households that 'shop' for government funded or subsidised services. This might be explicitly represented in future VU Cities by making adjustments to the underlying database. Government purchases on behalf of households could be added to household private consumption expenditures. To offset this additional expenditure, pseudo-cash transfers to households covering these expenditures would be introduced.

As concerns regional exports, the model could potentially be extended to allow for location choices made by tourists; in particular, the place of accommodation or for day-trippers, some nominal centre of activity. Services *other* than accommodation would then be shopped for as is currently modelled.

Goods and services imported from other regions of Australia or from overseas are treated as additional members of the set of tradables goods. Thus, if n_N regionally produced goods are locally non-tradable and n_T are tradable, there are an additional $n_\mathrm{N} + n_\mathrm{T}$ imported tradables in the set $\mathfrak{T}$. These imports relate mainly to the consumption of regional residents as tourists to other regions and countries.

3.5 Final demands for goods, services and housing

From equations 4, 5, 8, 9 and 10 we can derive the aggregate demands for housing of non-working households, plus the aggregate demands of all groups of working households (i.e. distinguished by skill and accounting for choice of industry):

$$C_{\mathrm{H}r} = \frac{\beta_{\mathrm{HN}}(1 - s_\mathrm{N})M_\mathrm{N}L_{\mathrm{N}r}}{\mathcal{R}_r} + \sum_k \frac{\beta_{\mathrm{H}k}(1 - s_k)M_{kr}^{(\mathrm{H})} \sum_i L_{kir}^{(\mathrm{H})}}{\mathcal{R}_r} \tag{11}$$

Similarly, aggregate non-margin demands for goods and services by place of residence are:

$$C_{jr} = \frac{\beta_{j\mathrm{N}}(1 - s_\mathrm{N})M_\mathrm{N}L_{\mathrm{N}r}}{\mathbb{P}_{jr}} + \sum_k \frac{\beta_{jk}(1 - s_k)M_{kr}^{(\mathrm{H})} \sum_i L_{kir}^{(\mathrm{H})}}{\mathbb{P}_{jr}} \tag{12}$$

Combined government and export non-margin demands for good or service j in place r are:

$$E_{jr} = V_{jr}/\mathbb{P}_{jr} \tag{13}$$

where V_r are the corresponding exogenously specified values.

Aggregate margin demands by place of residence are derived from aggregate non-margin demands by place of residence (see equation 5). The combined non-margin and margin demands by place of residence are therefore:

$$X_{jr} = C_{jr} + E_{jr} \sum_{g \in \mathfrak{T}} \iota_{jg} \left(C_{gr} + E_{gr} \right) \tag{14}$$

Using equations 5 and 14, the total demand for non-tradable products by place of purchase q—which, since the services are locally non-tradable, must also be the place of production—are:

$$Y_{jq} = \frac{1}{P_{jq}} \left(\frac{T_{jq}}{P_{jq}} \right)^{\varepsilon_j - 1} \sum_r \left(\frac{\mathbb{P}_{jr}}{D_{jrq}} \right)^{\varepsilon_j - 1} \mathbb{P}_{jr} X_{jr} \tag{15}$$

3.6 Firms

Individual firms operate with constant returns to scale in perfectly competitive input and output markets. Technologies of production are specified by the nested production function

$$Y_{is} = F_{is}^{\alpha_{\mathrm{F}i}} \left\{ \theta_{\mathrm{L}js} \prod_{k \in \mathfrak{L}} (A_{ks} L_{ks})^{\alpha_{ki}\rho_L} \cdots \right.$$

$$\left. + (1 - \theta_{\mathrm{L}js}) \left[\theta_{\mathrm{H}js} \prod_{k \in \mathfrak{H}} (A_{ks} L_{ks})^{\alpha_{ki}\rho_H} + (1 - \theta_{\mathrm{H}js}) K_{is}^{\rho_H} \right]^{\frac{\rho_L}{\rho_H}} \right\}^{\frac{\alpha_{\mathrm{F}i}}{\rho_L}} \quad (16)$$

At the lowest level, high-skill levels of labour are combined in a Cobb-Douglas sub-nest. This composite is then combined with capital/intermediate inputs K_{is} in a constant elasticity of substitution (CES) nest with an elasticity of substitution $\sigma_H \equiv 1/(1 - \rho_H) = 0.6$.

This composite is in turn combined with a Cobb-Douglas sub-nest of low-skill levels of labour in another CES nest with an elasticity of substitution $\sigma_L \equiv 1/(1 - \rho_L) = 1.5$. Finally, this composite is combined Cobb-Douglas with commercial/industrial property F_{is}. This complementarity between high-skilled labour and capital, in turn being substitutable with low-skilled labour and the CES elasticity values adopted here are based on (Krusell et al., 2000, p1034 and tb 1).

Denoting the rental price of developed property by $\mathbb{R}_{is}$ firms' unit costs functions are

$$P_{is} = \left(\frac{\mathbb{R}_{is}}{\alpha_{\mathrm{F}i}} \right)^{\alpha_{\mathrm{F}i}} \left(\frac{C_{\mathrm{L}is}}{1 - \alpha_{\mathrm{F}i}} \right)^{1 - \alpha_{\mathrm{F}i}} \quad (17)$$

where, for convenience, we define unit cost indices for upper and lower CES sub-nests as

$$C_{\mathrm{L}is} = \left[\theta_{\mathrm{L}js}^{\sigma_{\mathrm{L}}} \prod_{k \in \mathfrak{L}} \left(\frac{W_{kis}}{\alpha_{ki} A_{ks}} \right)^{\alpha_{ki}(1-\sigma_{\mathrm{L}})} + (1 - \theta_{\mathrm{L}js})^{\sigma_{\mathrm{L}}} C_{\mathrm{H}is}^{\frac{1-\sigma_{\mathrm{L}}}{1-\sigma_{\mathrm{H}}}} \right]^{\frac{1}{1-\sigma_{\mathrm{L}}}} \quad (18)$$

$$C_{\mathrm{H}is} = \left[\theta_{\mathrm{H}js}^{\sigma_{\mathrm{H}}} \prod_{k \in \mathfrak{H}} \left(\frac{W_{kis}}{\alpha_{ki} A_{ks}} \right)^{\alpha_{ki}(1-\sigma_{\mathrm{H}})} + (1 - \theta_{\mathrm{H}js})^{\sigma_{\mathrm{H}}} p_{\mathrm{E}i}^{1-\sigma_{\mathrm{H}}} \right]^{\frac{1}{1-\sigma_{\mathrm{H}}}} \quad (19)$$

Producer prices P_{is} in tradables sectors are set exogenously while producer prices in non-tradable sectors are determined endogenously by local market clearing conditions. Prices of capital/intermediates $p_{\mathrm{E}i}$ are also exogenous.

Firms' demands for commercial/industrial property, low- and high-skilled labour are respectively:

$$F_{is} = \alpha_{\mathrm{F}i} P_{is} Y_{is} / \mathbb{R}_{is} \quad (20)$$

For low skilled labour

$$L_{kis} = \alpha_{ki} (1 - \alpha_{\mathrm{F}i}) \frac{P_{is} Y_{is} \theta_{\mathrm{L}js}^{\sigma_{\mathrm{L}}} C_{\mathrm{L}is}^{\sigma_{\mathrm{L}}-1}}{W_{kis}} \left(\prod_{k \in \mathfrak{L}} \left(\frac{W_{kis}}{\alpha_{ki}} \right) \right)^{1-\sigma_{\mathrm{L}}} \quad (21)$$

For high skilled labour

$$L_{kis} = \alpha_{ki} (1 - \alpha_{\mathrm{F}i}) \frac{P_{is} Y_{is} (1 - \theta_{\mathrm{L}js})^{\sigma_{\mathrm{L}}} C_{\mathrm{L}is}^{\sigma_{\mathrm{L}}-1}}{\theta_{\mathrm{H}js}^{\sigma_{\mathrm{H}}} C_{\mathrm{H}is}^{\sigma_{\mathrm{H}}-1} W_{kis}} \left(\prod_{k \in \mathfrak{H}} \left(\frac{W_{kis}}{\alpha_{ki}} \right) \right)^{1-\sigma_{\mathrm{H}}} \quad (22)$$

3.7 Land allocation and development

3.7.1 Development

Land in each planning zone may be combined with structures in sector-specific technologies. There is one technology for each industry sector and another for residential development. The technologies are common to all planning zones within an SA2, but may potentially differ between SA2s as necessary to account for the different characteristics of production classified to the same industry in different locations. For example, the activities of primary and manufacturing firms in the CBD clearly relate to management, marketing or other such activities.[9]

In the residential sector only, we allow for differences in the density of development by planning zone due to regulatory constraints. Their effects are mimicked by the imposition of shadow taxes and offsetting subsidies on structures and land inputs respectively (Horridge, 1994). This is done in a relative, rather than an absolute sense. Thus, the highest residential densities within an SA2 are taken to reflect the minimum acceptable regulatory constraints while lower densities are assumed to be explained by more stringent constraints.

We assume that users of developed land within a given sector are indifferent between planning zones within an SA2. However, planning rules together with other (e.g. geographic, geological) factors cause the bare land in each planning zone of an SA2 to be imperfectly transformable between uses. Thus, bare land rents differ by *both* planning zone and use within each SA2.

The production functions for each industry or residential sector j are:

$$F_{zjs} = S_{zjs}^{\mu_j} N_{zjs}^{1-\mu_j} \tag{23}$$

For residential property, the first order conditions for structures and land are

$$S_{z\text{H}s} = \mu_{\text{H}s} \frac{\mathbb{R}_{\text{H}s} F_{zjs}}{(1 + \varsigma_{zs}) r_{\text{H}s}} \tag{24}$$

and

$$N_{z\text{H}s} = (1 - \mu_{\text{H}s}) \frac{\mathbb{R}_{\text{H}s} F_{z\text{H}s}}{(1 - \zeta_{zs}) R_{z\text{H}s}} \tag{25}$$

respectively, where $r_{\text{H}s}$ are the (exogenous) rental prices of structures, ς_{zs} and ζ_{zs} are the pseudo-tax rates on structures and pseudo-subsidy rates for residential land respectively, and $R_{z\text{H}j}$ are rental rates for bare land allocated to residential use. The pseudo-taxes and subsidies are revenue-neutral for all land users, so satisfy

$$\varsigma_{zs} r_{\text{H}s} S_{z\text{H}s} = \zeta_{zs} R_{z\text{H}s} N_{z\text{H}s} \tag{26}$$

For the property used in each industry, the first order conditions are simply:

$$S_{zis} = \mu_{is} \frac{\mathbb{R}_{is} F_{zis}}{r_{is}} \tag{27}$$

and

$$N_{zis} = (1 - \mu_{is}) \frac{\mathbb{R}_{is} F_{zis}}{R_{zis}} \tag{28}$$

where variables are defined analogously to those for housing.

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[9]These difficulties would ideally be resolved by developing supply and use tables using an activity-based rather than an industry-based classification of establishment-level production. However, this would be very challenging in the Australian context given the limitations of publicly accessible statistics.

3.7.2 Land allocation

Zoned land allocation to sectoral uses is modelled in a two level nested logit specification. Total zoned land (Z_{zs}) is allocated between residential (variables subscripted with H)and non-residential (variables subscripted with N). The elasticities of transformation between these uses are low.

$$N_{z\text{H}s} = \frac{(\phi_{z\text{H}s}R_{z\text{H}s})^{\nu_{\text{H}}}}{(\phi_{z\text{H}s}R_{z\text{H}s})^{\nu_{\text{H}}} + ((1 - \phi_{z\text{H}s})R_{z\text{N}s})^{\nu_{\text{H}}}} Z_{zs} \tag{29}$$

Total non-residential land is allocated to use in specific industries with a higher elasticity of transformation between uses.

$$N_{zis} = \frac{(\phi_{zis}R_{zis})^{\nu_{\text{I}}}}{\sum_i (\phi_{zis}R_{zis})^{\nu_{\text{I}}}} (Z_{zs} - N_{z\text{H}s}) \tag{30}$$

The variable $R_{z\text{N}s}$ that appears in equation 29 is the weighted average rental rate for non-residential land:

$$R_{z\text{N}s} \equiv \frac{\sum_i R_{zis}N_{zis}}{Z_{zs} - N_{z\text{H}s}} \tag{31}$$

3.8 Spatial externalities

Agglomeration effects on productivity and on amenity are specified following Ahlfeldt et al. (2015) as

$$A_{is} = a_{is} \sum_r \left(e^{-\delta\tau_{\text{W}sr}} \frac{\sum_{k \in \mathfrak{H}}\sum_j L_{kjr}}{\sum_z (Z_{zr} - N_{z\text{H}r})} \right)^{\lambda_j} \tag{32}$$

We assume that the relevant densities for productivity spillovers are of skilled workers in all sectors per hectare of developed non-residential land.[10] There is a common rate of spillover decay with travel time δ but we allow for a different elasticity of productivity to effective density (λ_j) in each industry.

To model positive externalities of effective residential density, we use the density of residents per developed hectare and common decay and elasticity parameter ϱ and η.

$$B_{kir} = b_{kir} \sum_s \left(e^{-\varrho\tau_{\text{S}rs}} \frac{\sum_{ki} L_{kis}^{(\text{H})}}{\sum_z Z_{zr}} \right)^{\eta} \tag{33}$$

Rates of spatial decay of effective density are high for firms and even higher for households. This poses a practical problem because the unmodelled internal distribution of density and trips within any SA2 may, in reality, be important. That is clearest in the case of peri-urban or rural SA2s that have high intra-SA2 GTCs and one or more inter-SA2 GTCs of similar magnitudes. The absolute size of spillover effects in such an SA2 will be very small, which is a plausible result. However, the elasticities of spillover effects to changes in intra-SA2 GTCs or to density changes in neigbouring SA2s can become implausibly large.[11]

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[10]The most appropriate ways to define density for the purposes of these equations require further investigation.

[11]This is because in computing changes in spillover effects, the travel cost discounting factors weight different changes only relative to one another and implausibly small weights are given to changes within the SA2 itself if the intra-SA2 GTC is relatively high.

As a partial if imperfect solution to this problem, we use constant intra-SA2 GCTs of $min(\tau_{Wss}, 10)$ and $min(\tau_{Srr}, 10)$ in the equations above. Using estimates of average business-to-business travel times from the STM in equation 32 rather than work commuting times might also improve the results.

4 Data and solution method

4.1 Datasets

VU Cities–Sydney is calibrated to match the following data sets:

- FTE workers by place of work, skill and industry

- FTE workers by place of residence, skill and industry

- Persons over 15 years of age residing in non-working households by place of residence

- Land area by planning zone in each SA2

- Initial allocations of zoned land to using sectors in each SA2

- Shares of residential population by planning zone within each SA2

- Travel times, distances and costs between locations by mode, time of day and purpose (work commuting or shopping)

- Regional average wage rates by skill and industry

- Regional non-wage income per household, average propensity to consume and expenditure shares by skill and for non-working households.

- Aggregate investment, government and regional export demands

- A production cost structure common to each industry and land development sector

- Rates of transport and retail margins associated with purchases of each regional or imported commodity by household and by other users.

The basic geographical units with which we work are delineated by the Statistical Areas Level 2 (SA2) of the Australian Statistical Geography Standard (ABS, 2011b).[12]

The first three datasets are compiled using the 2011 Australian Census of Population and Housing ABS (2011a).[13] The full cross-tabulations as described above cannot are not feasible because of limits on table size and the presence of random errors in small counts to preserve confidentiality. We therefore retrieve spatial cross-tabulations using full- and part-time labour force status in lieu of hours worked. We estimate the average hours of full- and of part-time workers by skill level and industry from a second cross-tabulation that omits the spatial dimension.

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[12]Most urban SA2s are geographically small areas that house 10,000–30,000 people. In rural areas, most SA2s are geographically large and house 3,000–10,000 people. A few urban SA2s are predominantly (or entirely) commercial or industrial. A few others correspond to large parks, reservoirs, etc. with few (or no) residents or workers.

[13]These data are accessed using the ABS' 'TableBuilder' query interface. TableBuilder permits construction of cross-tabulations by place of residence, work and/or enumeration, and by responses to various census questions or derived indicators. Query results are in the form of counts.

We aggregate to the five skill levels and seven industries of VU Cities–Sydney from skills by 3-digit ANZSCO occupation[14] and from 3-digit ANZSIC industries[15]. Examples of occupations associated with the five ANZSCO skill levels used in VU Cities–Sydney are:

SK1: executives, engineers, scientists, teachers

SK1: science technicians, office managers, paramedics, chefs

SK1: real estate agents, electricians, secretaries, cooks

SK1: machine operators, truck drivers, child carers

SK1: factory process workers, cleaners, fast food cooks

The seven VU Cities–Sydney industries are (with their abbreviated labels used in tables below):

Prim: primary production

Mfg: Manufacturing

CUWT: Construction, utilities, wholesaling and storage

BusAdmin: Business services and government administration

Retail: Retail services

AccRes: Accommodation, restaurants and hospitality

PrsPubSrv: personal services, healthcare, education and other public services

Data on non-working households are compiled from two sets of cross-tabulations. The first includes the labour force status of sole person households. The second includes the labour force status of parents in other households and the number of household members over fifteen years of age. As the model does not currently incorporate an individual labour supply choice, we also include households in which all members are unemployed.

Cadastral and planning layers provided by the NSW government were used to estimate the zoned area in each SA2 covered by property parcels, omitting the areas covered by road casements and the like, which not available for productive or residential uses. Land zoned explicitly for non-productive purposes (e.g. nature reserves) was also excluded. We then overlaid a layer delineating Census meshblocks in order to associate a count of total residential population with each land use zone within each SA2. Counts of meshblocks overlapping two or more zones were allocated in a second stage using proporland use tions reflecting the average residential densities of those zones estimated in the first stage. Ideally, similar procedures would be carried out for the business premises of each sector. However, as we lacked access to administrative datasets from which such information could be derived, our initial land allocations by sector were based on the stated purposes of each zoning.

Weighted average generalised travel costs (GTCs) between SA2 pairs were derived from the New South Wales Strategic Transport Model (STM).[16] The STM identifies

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[14]The Australia and New Zealand Standard Classification of Occupations (ANZSCO) associates one of five skill levels with each 4-digit occupation. However, it is possible to make an adequate concordance at the 3-digit level.

[15]Australia and New Zealand Standard Industry Classification. A detailed concordance is available from the authors on request.

[16]See https://www.transport.nsw.gov.au/performance-and-analytics/forecasts-and-projections/travel

nine travel modes and seven travel purposes. For VU Cities–Sydney the travel modes are aggregated to three: car, bus or rail.[17] Only two of the seven purposes were considered: work and shopping. The former corresponds to commuting trips while the latter was taken to represent all travel for consumption purposes. Trip matrices were provided for each mode and purpose together with times, distances, tolls and fares (as relevant). These values were derived by spatially aggregating up to SA2 level from the more detailed STM model resolution, therefore travel costs *within* each SA2 could also be obtained.

Key behavioural parameters used in simulations are shown in Table 1.

Table 1: Key parameter values

Parameter	Symbol	Value
Elasticity of substitution between HS and equipment	σ_{extscH}	0.67
Elasticity of substitution between LS and HS nest	σ_{extscL}	1.67
Residential structures share	μ_{H}	0.6
Non-residential structures share	μ_j	$0.5-0.78$
Commuting time semi-elasticity	$\kappa_k \epsilon_k$	0.045
Multinomial logit parameter	ε_k	9
Elasticity of substitution between local goods	ϵ_i	9
Elasticity of productivity w.r.t. employment density	λ	$0.02-0.12$
Decay rate of productivity spillovers	δ	0.76
Elasticity of amenity w.r.t. residence density	η	0.1
Decay rate of amenity spillovers	ϱ	0.36

4.2 Solution method

Initial equilibrium wages, local non-tradables prices and land and property rental rates are determined by recursively solving model equations for these variables. The model itself is programmed in the TABLO language and solved in percentage change form using the GEMPACK software (Harrison et al., 2014; Harrison and Pearson, 1996).

We note that an unusually large number of solution steps (several hundred) are required to solve the model. We believe this difficulty is due primarily to the high elasticities used to model location choice and to spatially distribute demand for non-tradables.

5 A simulation of transport policies

5.1 Hypothetical road and rail transport policies

To illustrate the capability of the VU Cities model, we simulate the impacts of imposing two hypothetical transport policies simultaneously. The first policy increases vehicle operating cost per kilometre by 10%. This could reflect, for example, the introduction of a scheme of distance-based road user charging. The second policy results in a decrease of in-vehicle travel times for rail journeys by 10%. This could reflect, for example, the effects of investments made throughout the rail network to permit increased speeds and reduced boarding times. This combination of policies and their specific details are chosen arbitrarily and do not reflect any actual policy proposals of the New South Wales government. However, they have the virtue of being relatively simple and easily understood by readers

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[17]Rail journeys include any multi-modal journey that have one or more rail segments.

who may be unfamiliar with the geography of Sydney and on the other hand, whilst still generating results that exhibit rich spatial variability.

Again for simplicity, these policies are simulated against the baseline data to which the VU Cities–has been calibrated. For policy applications, it would generally be more appropriate to first project the baseline forward to a future period of interest and then to impose policies against this future baseline. The reader may interpret the results presented here as reflecting the modelled impacts on the city that might have occurred had the modelled policies been implemented in the past. For reasons of space, we focus on results for the Greater Sydney area, which is shown in more detail in figure 2.[18]

Generalised travel costs (GTCs) by mode were recalculated with these changed cost components. New weighted average generalised travel costs for all modes combined were then calculated allowing for changes in mode shares. These latter were estimated using a set of multinomial logit models as we did not have access to the STM for that purpose. The effect of these changes on GTCs by mode can vary significantly between SA2 pairs. For car trips, vehicle operating costs are relatively most important for SA2 pairs with high average driving speeds and low/no toll charges. For train trips, in-vehicle time savings tend to be most important for long trips with no changes of vehicle. Changes in mode shares generally make small contributions to the changes in weighted average GTCs because we model the three modes as being poor substitutes.
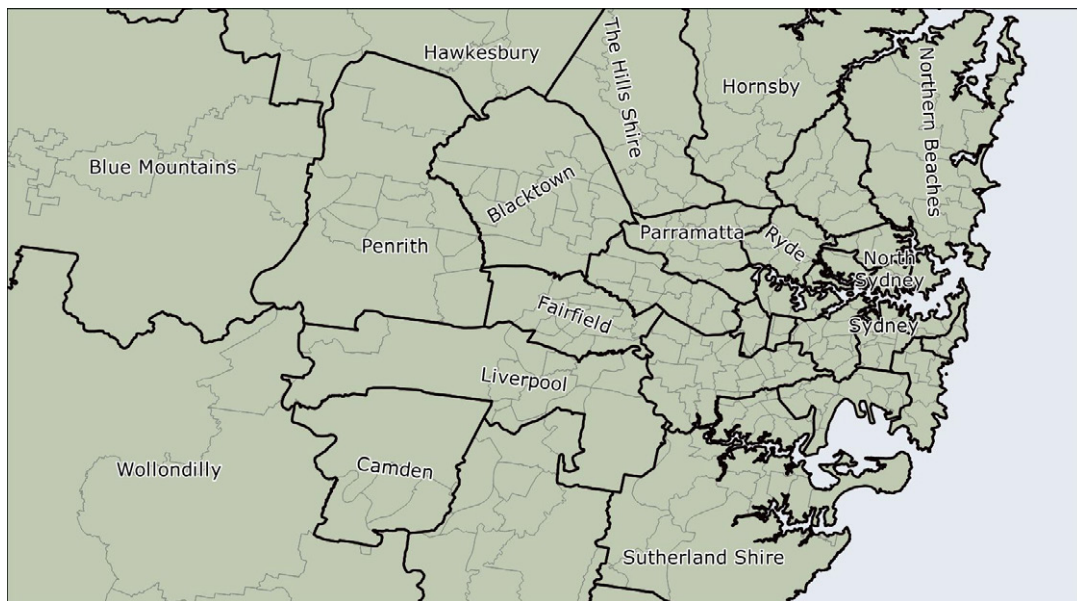

Figure 2: Overview map of the Greater Sydney sub-region showing Local Government Areas (heavy boundaries) and SA2s (light boundaries)

Figure 3 shows the percentage changes in GTC of resident workers, weighted by their original commuting propensities. Reductions in GTC tend to be seen along rail corridors with larger reductions being seen further out from the CBD. Figure 4 shows the equivalent result for places of employment, averaging over all SA2s of workers' residence. These results are even starker. Average travel times decrease only in the CBD, SA2s immediately adjoining the CBD (which include North Sydney) and Bondi, to the east.

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[18]Note that, as defined by the Australian Bureau of Statistics, Greater Sydney extends slightly further than shown in this and subsequent maps.
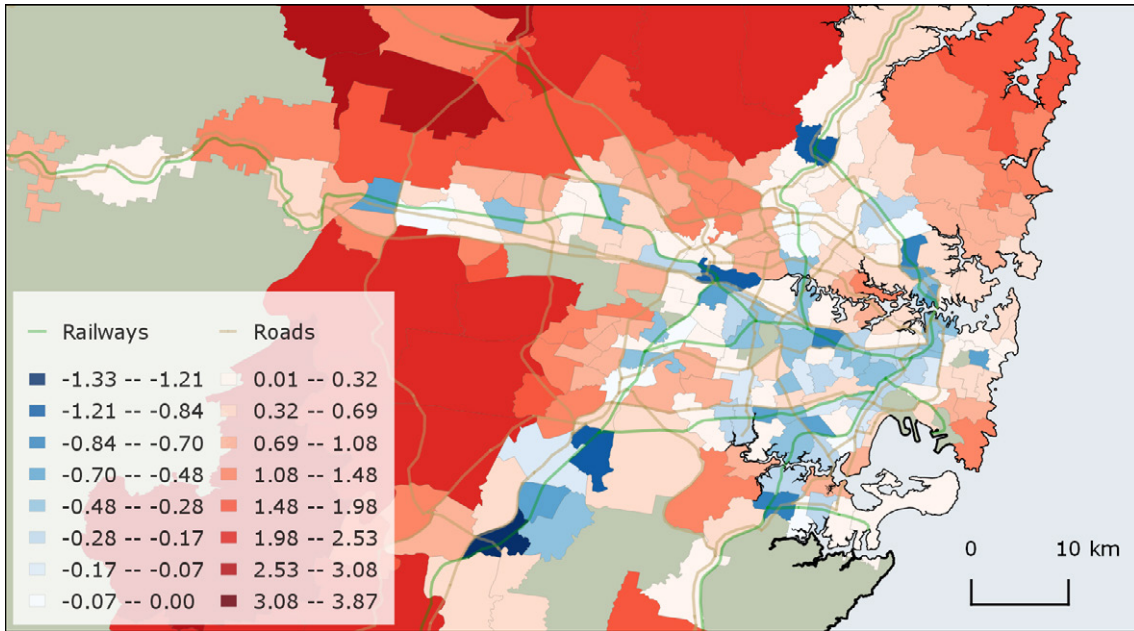
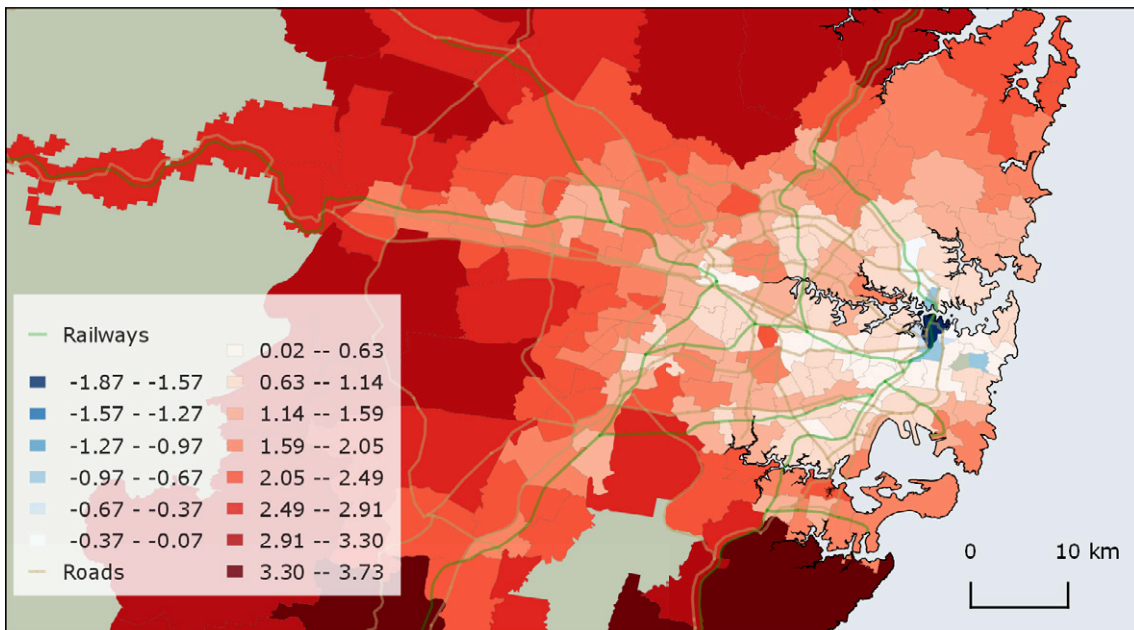Figure 3: Percent change in generalised commuting costs for residents

Figure 4: Percent change in generalised commuting costs for workers

5.2 Spatial impacts

5.2.1 Summary

Qualitatively, we can identify five different types of areas in the Sydney region according to the way they are impacted by the modelled policies, which reflects their distance from the CBD and whether or not they provide a high degree of accessibility to employment by rail:

- CTR: central areas including the Central Business District, the SA2s immediately adjacent to it and North Sydney

- IM/HR: inner and middle suburban areas (within approximately 20km of the CBD) with high rail accessibility

- IM/LR: inner and middle suburban areas (within approximately 20km of the CBD) with low rail accessibility

- OP/HR: outer suburban and peri-urban areas with high rail accessibility

- OP/LR: outer suburban and peri-urban areas with low rail accessibility

We summarise the impacts that the policies typically have in each of these different areas in tables 2 and 3.

Table 2: Overview of effects in different places of residence

Area	Weighted avg GTC	Resident workers	Amenity effect	Rental prices
CTR	$-$	$\sim$	$+$	$+$
IMHR	$-$	$+$	$\sim$	$+$
IMLR	$+$	$-$	$-$	$-$
OPHR	$--$	$++$	$++$	$++$
OPLR	$++$	$--$	$--$	$--$

Table 3: Overview of effects in different places of employment

Area	Weighted avg GTC	Employment	Productivity effect	Wage rates
CTR	$--$	$++$	$+$	$-$
IMHR	$+$	$+$	$\sim$	$-$
IMLR	$+$	$\sim$	$-$	$\sim$
OPHR	$+$	$\sim$	$-$	$\sim$
OPLR	$++$	$--$	$--$	$+$

5.2.2 Detailed results

The changes in transport costs increase overall employment accessibility for workers living along rail lines, increasing the attractiveness of these areas as places of residence. Consequently, the numbers of workers who choose to reside in these areas rises (figure 5), as do
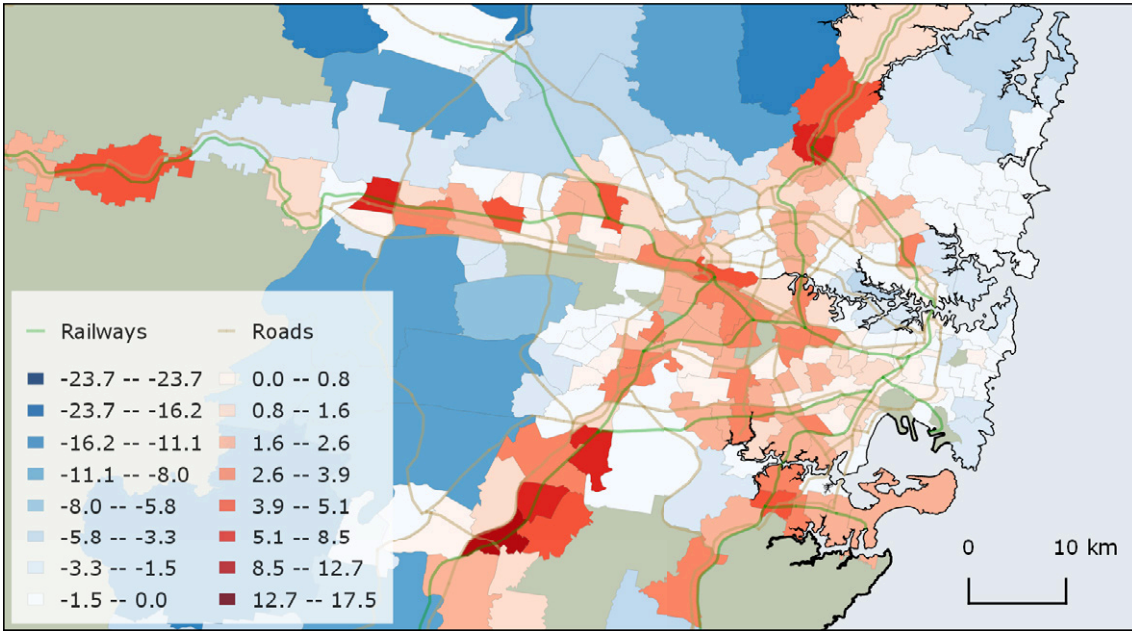
Figure 5: Percent change in FTE resident workers, shaded blue (losses) and red (gains)
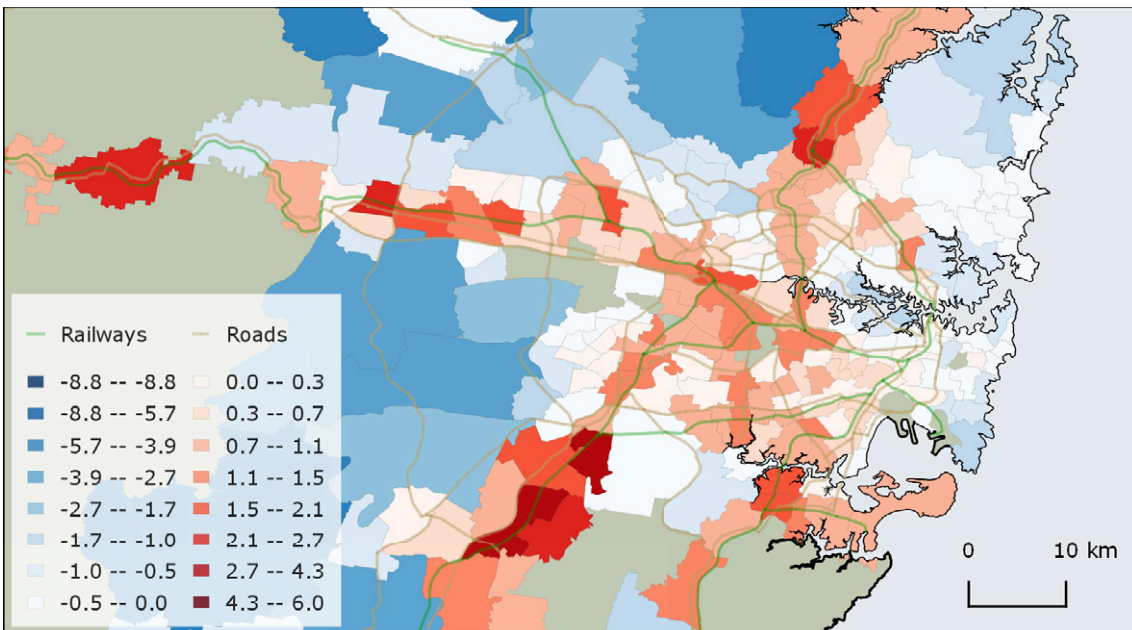

Figure 6: Percent change in residential rental prices, shaded blue (losses) and red (gains)

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residential rental prices (figure 6). These changes are reinforced by spillovers of residential density on amenity (7). While households respond elastically to relative changes in utility in different locations, their responses are not perfectly elastic. Thus, the average utility of residents in these areas that are now more attractive rises (8). To be precise, these are the gains experienced by those residents who would *not* choose the same residence with or without the transport policies.

Employment accessibility decreases most strongly in outer suburban and peri-urban areas that are highly car dependent. The number of resident workers in these areas declines and the utility of remaining resident workers decreases, on average. Density spillovers on amenity again reinforce the process, with amenity declining.

For residents of inner city areas, there is a modest reduction in the average cost of commuting. However, these areas tend to become slightly less attractive to live in on average, because resident workers tend also to work in the area and face increased competition for jobs from in-commuters. The net result is that the number of resident workers in inner city areas is essentially unchanged.

From the perspective of firms, these changes correspond to increases in labour supply for places of employment with good rail access. This is especially true of the CBD, where labour supply increases to such an extent that wage rates there decline slightly (figure 9) despite rising employment (figure 10). Negative pressures of increased labour supply are, in many areas, partly offset by increased demand for non-tradables and thus for labour in these sectors. Moreover, around the CBD (and in a few other isolated cases) there are increases in effective employment density due to the spatial concentration of increased jobs. In those areas, labour productivity increases because of agglomeration effects (figure 11), further mitigating the downward pressures on wages.

In areas where the accessibility of jobs is most negatively affected, wage rates tend to rise. In non-tradables sectors, labour demands are negatively affected in these areas by declining resident worker populations, but do not fall as much as they might because other sources of demand are assumed to be fixed. Demands for tradables are assumed to be perfectly elastic, so are unaffected by changes in the regional economy. Thus, labour supply tends to fall more than labour demand and wage rates rise so that firms may still attract sufficient workers. This partly compensates those workers who remain for their increased commuting costs.

Figure 12 shows the weighted average changes in deterministic utility of workers by place of work. This can be seen as the average change in utility experienced by workers who would choose the same workplace with or without the transport policies (see footnote 18). Increases are highly concentrated in and around Sydney CBD. The largest decreases are seen in outer areas, especially outside of rail corridors.

Finally, figure 13 shows changes in average wage rates, but by place of residence rather than by place of work (as was shown above in 9). These results reveal the importance of spatial compositional effects. Given the changes in transport costs, an increasing fraction of the workers resident along rail corridors travel to the central city. Initially, wages for a given skill in any given industry are generally significantly higher in the central city than elsewhere. This differential is narrowed as a result of the policies. However, most additional in-commuters will be receiving significantly higher wage rates than they would

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[18]Locational choices are influenced by individual idiosyncratic preferences (see equation 1). Consequently, if a policy induces a particular individual to make a *different* discrete choice, we know this new choice will be maximise her utility under the policy, but we do not know whether her utility is higher or lower than it would have been in the absence of the policy.
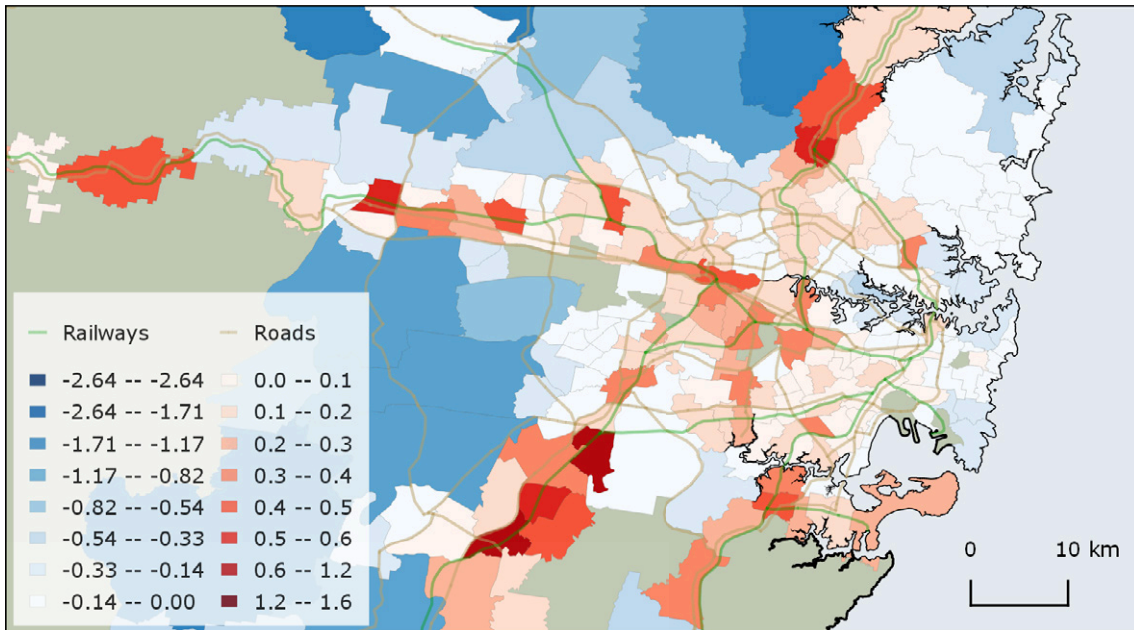
Figure 7: Percent change in residential amenity due to agglomeration effects, shaded blue (losses) and red (gains)
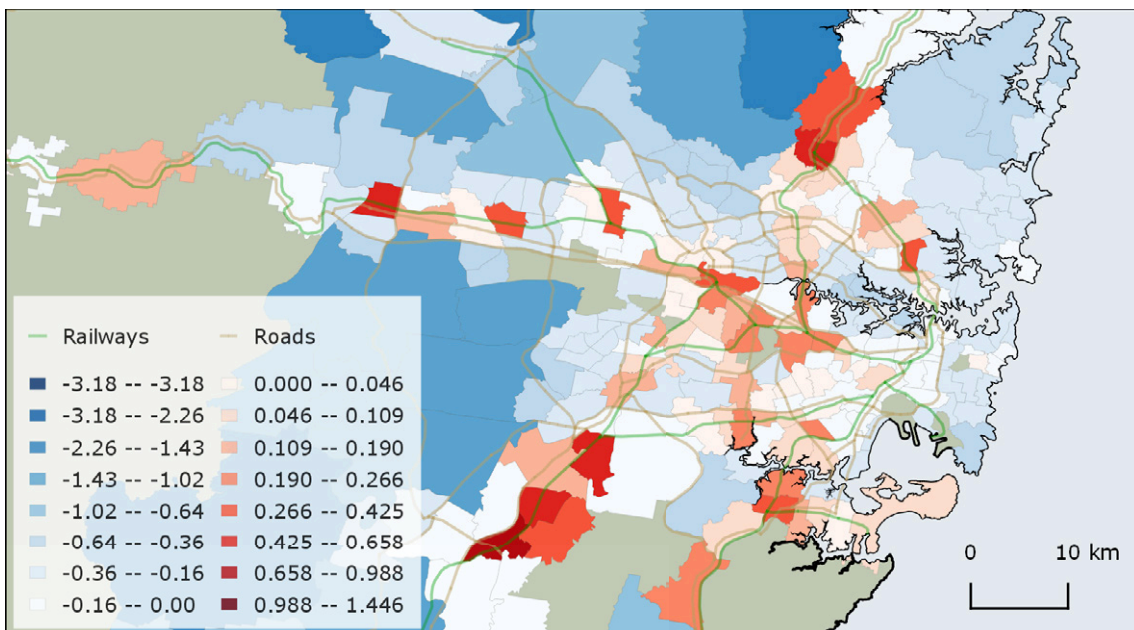

Figure 8: Percent change in average deterministic utility of residents, shaded blue (losses) and red (gains)
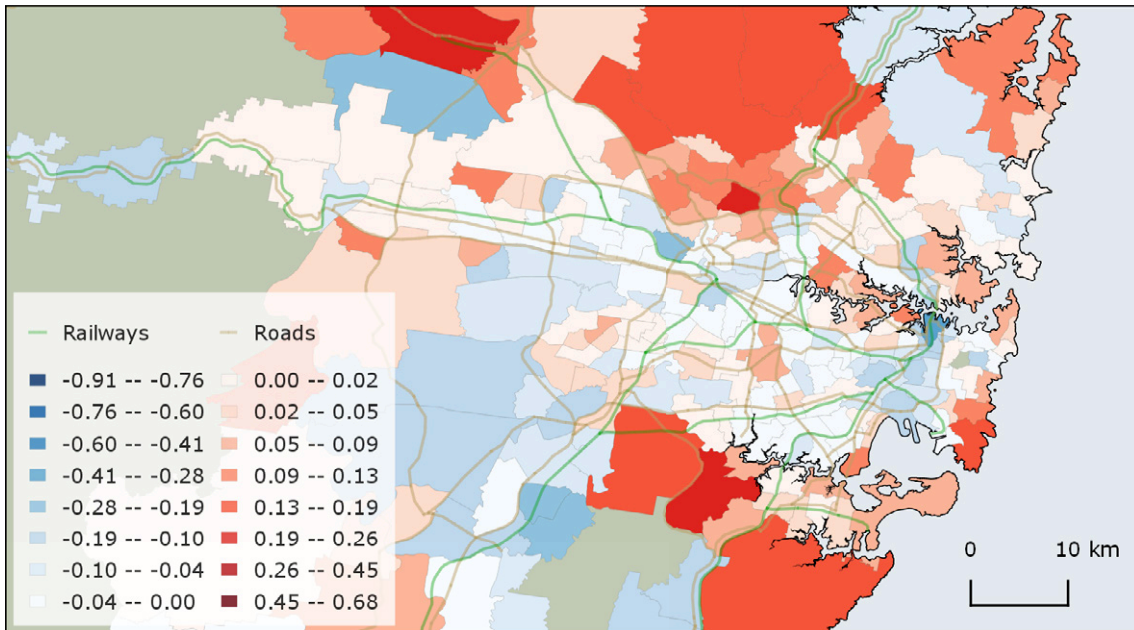
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Figure 9: Percent change in average FTE wage by place of work, shaded blue (losses) and red (gains)
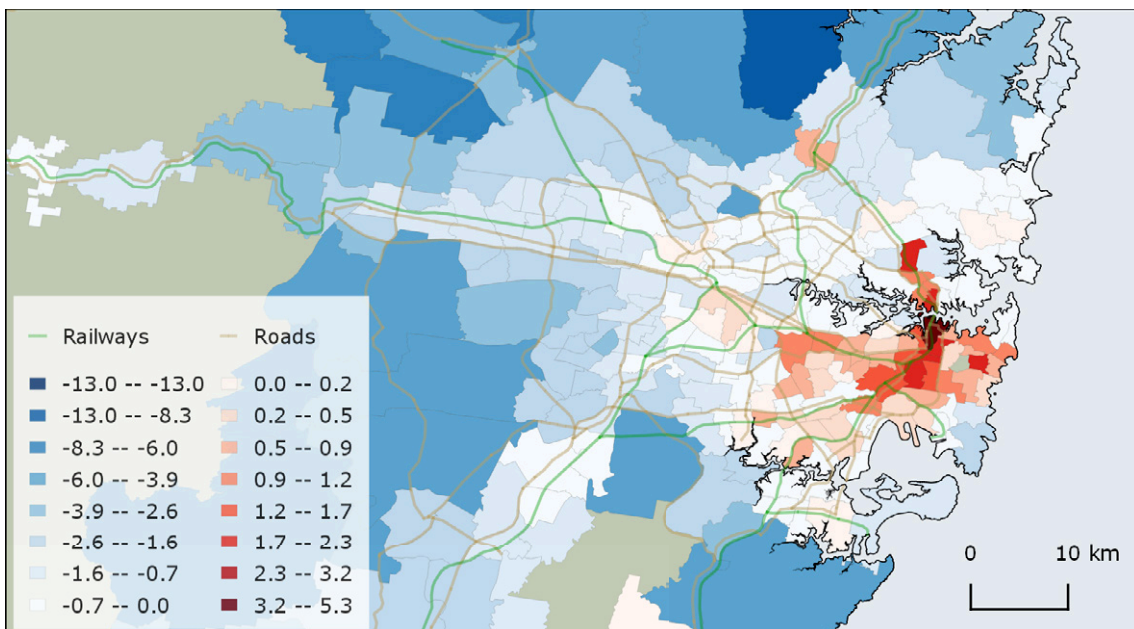

Figure 10: Percent change in FTE jobs, shaded blue (losses) and red (gains)
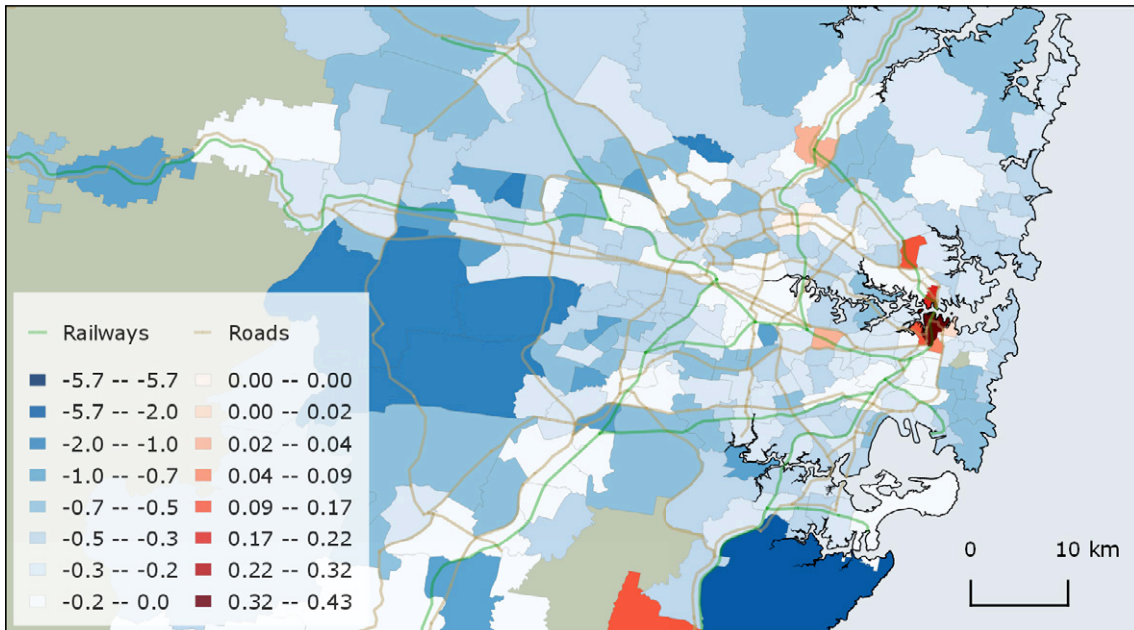
Figure 11: Percent change in productivity due to agglomeration effects, shaded blue (losses) and red (gains)
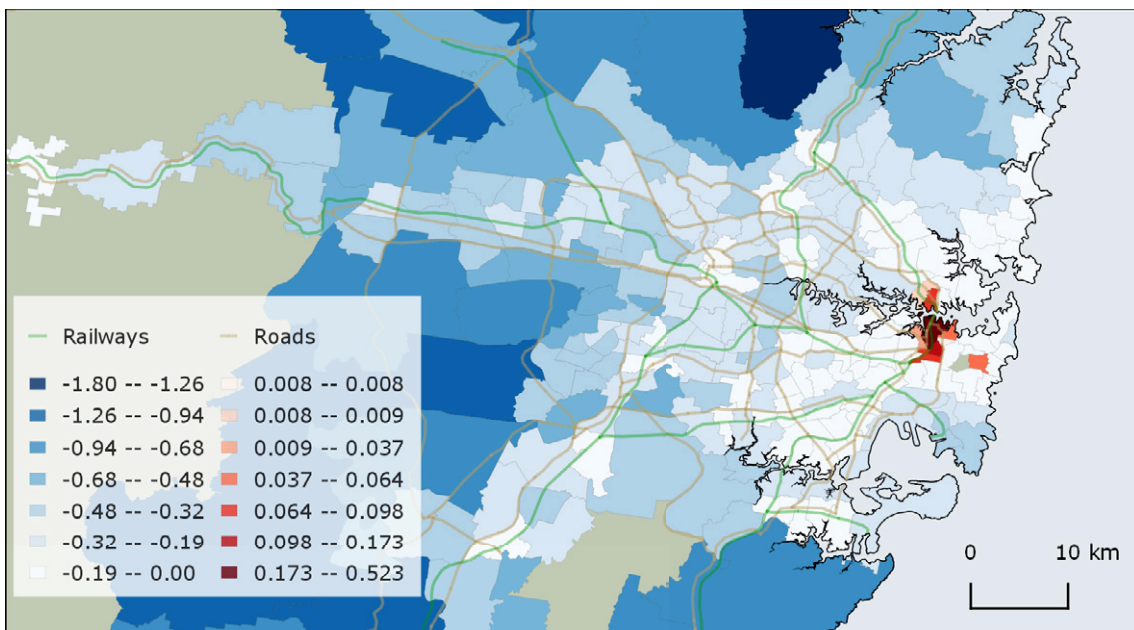

Figure 12: Percent change in average deterministic utility of workers, shaded blue (losses) and red (gains)
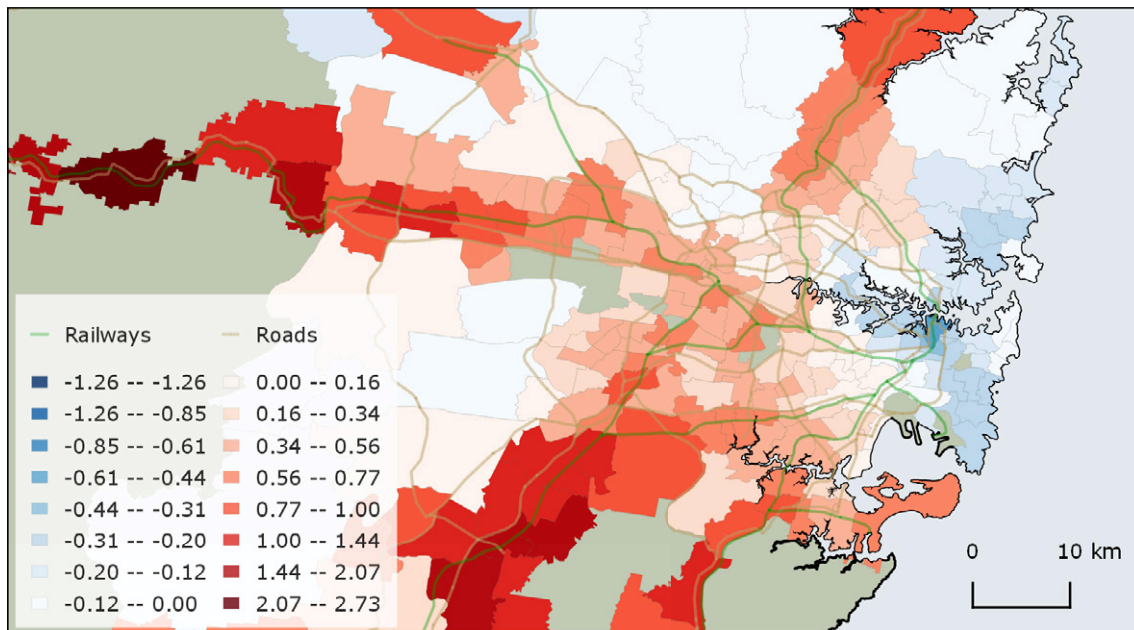
have done working in other locations.

Figure 13: Percent change in residents' average wage rates, shaded blue (losses) and red (gains)

While difficult to summarise graphically, we can gain further insight by identifying particular residence–workplace pairs that have (i) significant commuting volumes and (ii) large increases or decreases in utility. Within the Greater Sydney region, those pairs with large increases in utility are dominated by long-distance commutes along rail corridors to Sydney CBD. For instance, CBD commuters living in the Blue Mountains. Residents who would choose these commutes either with or without the modelled policies are clearly winners. Conversely, within the Greater Sydney region, the worst outcomes tend to be for long-distance inter-suburban commutes, e.g. Picton to Penrith in the outer western suburbs. Workers who would choose these commutes either with or without the modelled transport policies are clearly losers.

To this point, we have not considered any impacts on household housing (or more generally, property) wealth. For practical reasons, the model abstracts from ownership of particular assets. Households' actual and imputed property rental income is taken to be exogenous and to be unaffected by the transport policies. In reality, a majority of households in the Sydney region are owner-occupiers. Those owner-occupying households not incentivised to change their place of residence as a result of the transport policies have a natural hedge: if the capital value of their property decreases (or increases), their imputed housing rents decrease (or increase) accordingly. However, owner-occupiers who choose to relocate—the majority of whom would be moving from areas with falling property values to areas with rising property values—would suffer negative wealth impacts. Such effects could, in reality, reduce housing mobility. Finally, property investors in areas where property rents fall (rise) would experience losses (gains) in wealth.

5.3 Aggregate impacts

In this section we step back from the spatial analysis of impacts to consider how the hypothetical policies affect the economic structure of the region as a whole. Firstly, consider impacts on land use, table 4 shows that there is a small shift in the allocation of land from residential to non-residential uses. There is also a reduction in average development density for both residential and non-residential uses. Within the residential sector, there is a shift away from property in low density areas where development densities slightly decline and towards property in medium and high density areas, where development densities slightly increase. Within the non-residential sector, the land area allocated to tradables increases slightly while the land area allocated to non-tradables decreases. In both cases, development densities decline.

Changes in residential land use and development are consistent with slightly lower average incomes as the average wage rate falls and with the relocation of working households from highly car-dependent peripheral suburbs and towards suburbs along train lines. The former suburbs are zoned almost exclusively for low density residential development, whereas the latter suburbs have significant amounts of land zoned for medium or (in a few places) high density residential development. Most of the tradables industries complete mainly with low density residential development in suburban and peri-urban areas (business services and administration is an exception). The non-tradables industries tend to compete with medium and high density residential uses in the CBD and in accessible suburban locations. The latter see strong increases in residential demand. These factors along with various input substitution effects explain the differences seen within the non-residential development sector.

Table 4: Aggregate land use and development

	Residential			Non-residential		
	All	Low density	Mid/high density	All	Tradables uses	Non-tradables uses
Developed property	-0.06	-0.23	0.18	-0.51	-0.14	-2.30
Land	-0.02	-0.02	0.07	0.02	0.84	-1.81
Property rents	0.15	0.15	0.15	0.17	0.19	0.08
Land rents	0.14	0.13	0.21	0.16	0.17	0.07

Table 5 shows average impacts for each of the four tradable and three non-tradable industries. The first row shows the average changes in workers' commuting costs for each industry. The largest negative impacts are in primary industries (*Prim*), and accommodation, restaurants and hospitality (*AccRes*). In manufacturing (*Mfg*) and retail, there are actually slightly positive impacts.

Aggregate output of the primary industry is unchanged, while aggregate outputs of all other tradable industries increase. Average primary industry wages are slightly higher as low-skilled workers must be compensated for their increased commuting costs. However, property rents are lower due to reduced residential demands for land. In the other three tradable industries, average wages decline slightly, but property prices rise, with employment rising slightly in the *CUWT* and *BusAdmin* industries.

Of the three non-tradable sectors, aggregate retail output declines, whereas aggregate output of the *AccRes* and *PrsPubSrv* sectors rises. The retail sector is relatively disadvantaged in competing the most strongly with medium and high density residential uses,

facing higher property rents and substituting away from this input. There are also substantial reductions in retail employment, even as retail wages fall. The reduction is twice as large for high skill workers as for low skill workers, reflecting the possibility of substituting high skilled workers and equipment for low skilled workers (i.e. automation). Finally, notice that the average shopped price for retail falls more than the average producer price, indicating that consumers reduce their travel costs by shifting shopping patterns to favour closer destinations and/or destinations that become cheaper to reach along rail corridors.

Table 5: Regional results by industry

	Tradables				Non-tradables		
	Prim	Mfg	CUWT	BusAdmin	Retail	AccRes.	PrsPubSrv
Commuting costs	1.31	-0.03	0.93	0.99	-0.03	1.24	1.08
Spillovers[1]	-0.09	-0.09	-0.17	-0.18	-0.21	-0.05	-0.15
Output	-0.00	0.21	0.87	0.90	-0.36	0.39	0.28
Property	1.15	-0.64	0.01	-0.24	-5.37	-0.74	-1.72
- Land	3.76	0.35	0.52	0.84	-4.71	-0.07	-1.68
Employment	-0.23	-0.36	0.52	0.44	-2.62	0.02	-0.30
- low skill	-0.51	-0.36	0.56	0.22	-2.39	0.03	-0.06
- high skill	0.35	-0.32	-0.11	0.86	-4.18	0.01	-0.44
Producer price	0.00	0.00	-0.00	0.00	-0.13	-0.10	-0.13
Shopped price	-0.16	-0.09	0.00	0.00	-0.86	-0.16	-0.38
Property rents	-0.11	0.24	0.14	0.22	0.18	0.03	0.04
Wages	0.08	-0.05	-0.03	-0.06	-0.38	-0.28	-0.22
- low skill	0.20	-0.03	-0.01	0.04	-0.31	-0.02	-0.02
- high skill	-0.23	-0.23	-0.20	-0.20	-0.95	-0.56	-0.32

[1] Percentage point change in labour productivity due to change in employment density

Table 6 summarises the average impacts on worker-households by occupational skill level. On average, the largest negative impacts are felt by the highest skill group (SK1). The average increase in commuting costs and average decrease in wages are over two times those for any other group. This is consistent firstly with the fact that jobs for this skill level are most heavily concentrated in the CBD and other centres, where increased labour supply depresses wage rates. Secondly, members of this group disproportionately reside in Sydney's harbourside and other prestigious suburbs, relatively few of which are served by train lines (instead relying on bus services, public ferries and private cars). The average impacts on residential amenities are also negative.

Table 6: Aggregate differences by skill level

	SK1	SK2	SK3	SK4	SK5
Utility	-1.19	-0.36	0.35	-0.10	-0.23
- Commuting costs	2.50	1.13	-0.13	1.12	1.17
- Wage	-0.67	-0.24	0.15	-0.01	-0.16
- Amenity	-0.20	-0.03	-0.02	-0.01	-0.01

There are smaller negative average impacts on the SK2, SK4 and SK5 skill groups while there are small positive average impacts for the SK3 group. The SK3 group is unique in that its average transport costs are reduced. This reflects not only a spatial

distribution of jobs and residences in this group favouring rail use, but also the potential to substitute workplace and especially residential locations in response to the changed travel costs. By contrast, the lowest skill group sees relatively large increases in average travel costs and lower average wages. With low incomes, residences in this group are disproportionately in car-dependent peripheral suburbs. In addition, employment for this group is relatively decentralised (including factory work, suburban fast food outlets, etc.) and for jobs they can access in centralised locations (e.g. cleaners in the CBD), demand is negatively impacted by substitution effects.

6 Conclusions and future work

Our simulations demonstrate how the VU Cities framework may be used to analyse spatial economics impacts of transport policies within a general equilibrium framework. The model captures relationships between GTCs, wages land uses and housing. Complex and often counter-acting effects are seen in our illustrative analysis of hypothetical transport policies that increase private vehicle operating costs and reduce rail travel times. The overall impact of these policies would be to make living along rail corridors and working in the central city more attractive relative to other commuting patterns and especially those involving long car commutes.

The framework is equally suited to analysing changes in land use policies such as zoning changes. To take full advantage of the framework's potential though, land use–transport interactions should be accounted for by using VU Cities in conjunction with a transport network model. This would allow both for a more sophisticated treatment of mode choice and account for impacts of transport demand changes on congestion, consequently bilateral GTCs.

Another issue that is important to consider is the way in which land uses and development densities are assumed to respond to economic forces. In this study we effectively held constant relative differences in regulatory constraints on residential development density but allowed both lower and higher densities to increase or decrease in response to relative prices changes. Our rationale is that while land use plans and associated decision-making processes tend to operate by imposing constraints, these plans and themselves adjust over time, partly in response to economic imperatives. It is, however, possible to model more prescriptive behaviour within the VU Cities framework.

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