Residential land use, transport and congestion in a computable general equilibrium model

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Abstract

Computable general equilibrium (CGE) models are widely used in economic analysis of many types of policies that may strongly influence urban form and mobility. However, existing CGE models either ignore relationships between urban form and mobility, incorporate relationships based on highly stylised and restrictive models, or model individual metropolitan areas in isolation from wider economies that consist of multiple metropolitan and non-metropolitan areas. This paper introduces an *ad hoc* but flexible approach to modelling aggregative relationships between key variables influenced by urban form. Our approach permits implementation of detailed model structures suitable for applied analysis. It is straight-forward to account for multiple modes of transport and types of land use, as well as for congestion and other externalities that are important in the urban context.

We illustrate our approach by extending the Victoria University Regional Model (VURM, formerly MMRF), multi-regional model of Australia, to account for the relationship between households' demands for residential land and for urban mobility, for choices between car, bus and train travel accounting for both pecuniary and time costs, and for positive and negative externalities affecting the costs of each mode. We present illustrative simulations that highlight the potentially large effects these latter factors may have on patterns of growth and on responses to policies.

Introduction

The majority of people in developed and many developing countries live in cities. Concentrations of economic activity in urban areas are even more pronounced. The proximity of firms to one another and to households can reduce transport costs, permit realisation of scale economies and facilitate human capital accumulation and knowledge spillovers, making cities more productive places to work and enriching places to live (see e.g. Fujita and Thisse 2002). However, the predominantly low density, car-dependent growth characteristic of Australian and U.S. cities is increasingly undermining these benefits. In particular, 'urban sprawl' has been associated with negative impacts on productivity (Fallah, Partridge, and Olfert 2011), health (Reid Ewing et al. 2014), the local environment (Wilson and Chakraborty 2013) and rising greenhouse gas emissions (Glaeser and Kahn 2010). Ewing and Hamidi provide a broad-ranging review of these extensive literatures (2015). The majority of global carbon dioxide emissions are produced directly or indirectly by urban activity, with urban transport and buildings being major contributors to the total (World Bank 2010; The Global Commission on the Economy and Climate 2014). Many cities also face substantial costs due to climate change impacts and adaptation (OECD 2010; IPCC 2014). The Global Commission on the Economy and Climate (2014; p8 ch2) estimates the annual cost of urban sprawl in the U.S. at over 2.6% of US GDP and concludes that 'more compact urban growth, connected infrastructure, and coordinated governance could boost long-term urban productivity and yield environmental and social benefits', as well as substantially reducing infrastructure financing requirements (*ibid.*; p3).

Despite the potential importance of urban form in many different policy contexts, computable general equilibrium (CGE) models used to analyse policies at (or above) the national scale almost invariably lack any conception of space at the city scale. While many such CGE models employ a multiregional structure, the regions usually correspond to large areas such as states or provinces of a single country, or to entire countries in multi-country models. Although land may be considered as a distinct factor of production (at least in agriculture, although rarely in other sectors) there is no concept of spatial location within a single region. Household migration is sometimes modelled, but each household lives and works in the same region. There are no commuting flows and only rarely tourism flows. The main linkages between regions are via trade flows, usually assuming regionally differentiated products, following Armington (1969). When freight transport margins are modelled, transport inputs are usually simply proportional to commodity flows. Well-known examples of such multi-regional models include the global model GTAP (Hertel 1998) and in the Australian context, MMRF-GREEN (Adams, Horridge, and Parmenter 2000) and TERM (Wittwer 2012).

One way in which explicit spatial considerations at the urban scale can be incorporated into multi-sector CGE models is to define discrete regions at this scale and to allow for complex interactions between them. An early example of this approach is Horridge's (1992) stylised multi-regional model of the city of Melbourne, Australia. A key feature of this model is that households with heterogeneous preferences make discrete choices over locations of residence and work (McFadden 1974; Anas 1982). The most prominent example is the Regional Economy, Land Use and Transportation Model (RELU-TRANS) developed for the Chicago metropolitan statistical area (Anas and Liu 2007; Anas 2013). This model has several productive sectors and discrete choices of households include the choice between several dwelling types. Transport mode choices and the network structure of the actual metropolitan transportation system are also represented. The limitation of these models though is that a single metropolitan area is studied in isolation from other metropolitan areas and from the national economy as a whole.

A different approach is taken by Dixon et al. (2005), who treat space within each large model region (an Australian state or territory) as a continuous variable. Assuming a simple 'circular city' configuration with commuting to the CBD, the effects of congestion are investigated. More recently, Grazi and Waisman (2009) take a similar approach in the multiregional global model IMACLIM-R to account for both positive spillovers between firms and commuting costs. Provided that closed form expressions can be found for the aggregative relationships implied by the spatial equations, such models represent space in an extremely succinct way. For example, Dixon et al. (2005) derives explicit relationships between population, aggregate travel time and aggregate land rents. However, such aggregative relationships can only be derived from very simple spatially explicit micro-foundations, obliging the modeller to sacrifice detail and realism to maintain analytic tractability. A further practical difficulty with these models is that most 'spatial' economic data are actually reported for discrete regions of arbitrary geometries and consequently.

In this paper, we propose an alternative 'top-down' approach in which we allow for *ad hoc* aggregative relationships between variables that determine and are determined by urban form. Forgoing explicit micro-foundations allows us to formulate complex and flexibly parameterised model structures. For example, alternative urban land uses and multiple modes of transport can be easily accommodated. So can externalities such as congestion, which are pervasive in the urban context. This level of detail is likely to be important in many applied modelling studies.

We are applying our proposed approach to extend the Victoria University Regional Model (VURM, formerly MMRF) to account for urban form. VURM is a recursive dynamic, multi-regional model of Australia in which the eight regions correspond to the eight Australian States and Territories. Each region is modelled with a representative household, region-specific industries and prices, and inter-state/territory and international trade. The federal and state/territory levels of government are also represented explicitly. Full technical details of the standard VURM model can be found in Adams et al. (2015). Here we describe the first steps in development of this extended model, which we name 'VURM-Cities'. We focus initially on residential land use and urban mobility demands of households. We abstract at this stage from the competing demands for urban land of manufacturing and service industries, from non-commercial urban land uses (e.g. public parks, roads) and from competition between agricultural and non-agricultural uses at the urban fringe.

Household transport demands have been modelled in detail in a number of CGE models. For example, Mayeres (2000) considers modal choices for peak and off-peak travel by non-motorized modes, public transport and car, with the latter mode subject to congestion externalities. Households are endowed with a fixed time budget that may be used for leisure or travel. Berg (2007) models the allocation of time across labour supply, travel and leisure. Travel is distinguished by work and non-work purposes, with different modal choices in each case. Our approach in VURM-Cities is closer to that of Mayeres (*ibid.*), but we simplify by considering only motorised modes and ignoring the peak/off-peak distinction. However, unlike Mayeres, we consider not only the negative externality of road congestion, but also positive demand density externalities affecting public transport. These externalities arise because a higher density of demand for public transport reduces the cost of providing services at higher frequencies and with better connectivity (Mohring 1972). To our knowledge, this so-called 'Mohring effect' has not previously been considered in a CGE model.

The structure of this paper is as follows. We first provide a mathematical description of the utility function of VURM-Cities, in which land and transport services appear in a multi-level nested constant elasticity of substitution (CES) structure. To demonstrate the potential of our modelling approach, we present illustrative simulations of two scenarios. In the first scenario, suburban growth is unrestricted. In the second, the urban area is fixed at its initial level – an extreme case of what are commonly referred to by planners as 'urban growth boundaries' (UBGs). We show how the rates of growth of residential land use and transport differ in the two scenarios, both with and without accounting for the effects of time costs and externalities. We also show how these features affect the macroeconomic costs of imposing UBGs. We conclude the paper with a brief discussion of pros and cons of our approach and an outline of ongoing developments of the VURM-Cities model.

Model

Urban form

In the classical circular city model of urban economics, transport costs (or more specifically, commuting costs) increase with the square root of area. On the other hand, the growth of transport costs will be limited by the relocation of firms and households throughout the city (Levinson and Kumar 1994). Our first aim is to capture the idea of a relationship between the aggregate demand for urban area and the aggregate demand for urban mobility, whilst also allowing for some influence of relative prices of land and mobility. We do this by making mobility complementary in consumption to a measure of 'effective' area that is 'produced' from the actual area with decreasing returns to scale. The elasticity of substitution between mobility and effective area and the scale coefficient will determine the strength of relative price effects as well as the elasticity of urban mobility with respect to urban area.

We replace the utility function of the representative household in each of the VURM regions with the structure illustrated in Figure 1.[1] All nests are Cobb-Douglas except for that in which 'Urban Mobility' and 'Metropolitan Land' are combined in a constant elasticity of substitution (CES) sub-utility function to yield 'Accessible Metropolitan Land'. We use a fixed factor 'CBD' to generate decreasing returns (given by the value share of CBD in the nest) in the conversion of the actual area of 'Suburban Land' to the effective area of 'Metropolitan Land'. Households' production of mobility with private cars and coproduction of mobility using bus and train services is dealt with in the next section.

[1] VURM uses a Stone-Geary utility function that yields a Linear Expenditure System. However, for simplicity we assume here that all subsistence quantities are zero.

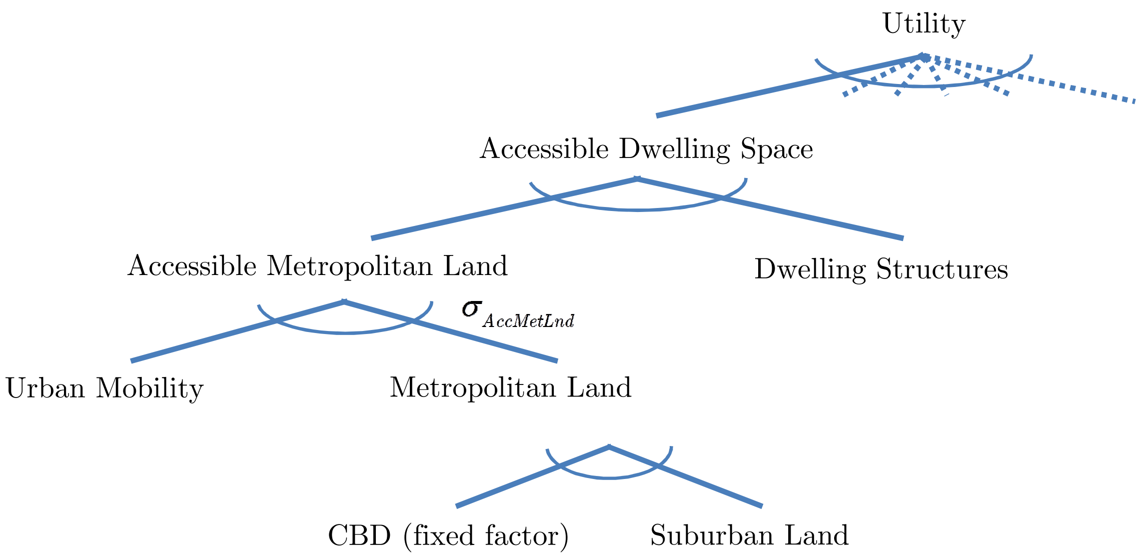

Figure 1 – sub-utility function combining structures, land and (composite) urban transport

Accessible metropolitan land and dwelling structures are combined with a unitary elasticity of substitution to form the composite good 'accessible dwelling space' (AccDwellSpc). This composite appears in the top-level of the utility function, replacing its individual constituents that enter directly in the original version of VURM. Metropolitan land and a composite good 'urban mobility' (UrbMob) are then combined with a constant elasticity of substitution (CES) of (much) less than one to form 'accessible metropolitan land' (AccMetLnd).

The demand and price equations in percentage change form (dropping regional subscripts on all variables and parameters for clarity) are

$$x_{DwellStruct} = x_{AccDwellSpc} - \left(p_{DwellStruct} - p_{AccDwellSpc}\right), \quad (1)$$

$$x_{AccMetLnd} = x_{AccDwellSpc} - \left(p_{AccMetLnd} - p_{AccDwellSpc}\right), \text{ and} \quad (2)$$

$$p_{AccDwellSpc} = S_{DwellStruct} p_{DwellStruct} + S_{AccMetLnd} p_{AccMetLnd}\,. \quad (3)$$

$$x_{UrbMob} = x_{AccMetLnd} - \sigma_{AccMetLnd}\left(p_{UrbMob} - p_{AccMetLnd}\right), \quad (4)$$

$$x_{MetLnd} = x_{AccMetLnd} - \sigma_{AccMetLnd}\left(p_{MetLnd} - p_{AccMetLnd}\right), \text{ and} \quad (5)$$

$$p_{AccMetLnd} = S_{MetLnd} p_{MetLnd} + S_{UrbMob} p_{UrbMob}\,, \quad (6)$$

where here and below S_z denotes the cost share of an input z in the relevant sub-nest.

The percentage change in the quantity of the fixed factor CBD is zero by definition. Using that fact, the following relationships can be derived between the percentage changes in quantities and prices of Suburban Land and Metropolitan Land:

$$p_{MetLnd} = \frac{1-\beta_{CBD}}{\beta_{CBD}} x_{MetLnd} + p_{SubLnd} \text{ and} \tag{7}$$

$$\beta_{CBD} x_{SubLnd} = x_{MetLnd}. \tag{8}$$

Using (4), (5), (7), and (8) we can relate urban mobility demand directly to suburban land demand:

$$x_{UrbTpt} = \left[\beta_{CBD} + \left(1-\beta_{CBD}\right)\sigma_{AccMetLnd}\right] x_{SubLnd} - \sigma_{AccMetLnd}\left(p_{UrbTpt} - p_{SubLnd}\right) \tag{1.9}$$

The square bracketed term gives the elasticity of urban transport services with respect to urban area. The value of this elasticity must lie between $\sigma_{AccMetLnd}$ and unity. For our illustrative simulations, we choose $\beta_{CBD} = 0.25$ and $\sigma_{AccMetLnd} = 0.2$, which gives an elasticity of 0.4.

On the production side, the original VURM industry Ownership of Dwellings is disaggregated into a new 'Dwelling Structures' industry and the original capital rents in this sector are disaggregated into actual capital rents and rents accruing to the CBD factor and to suburban land. We assume that structures account for 60% of the rents (Kulisch, Richards, and Gillitzer 2011) and that the remaining 40% are allocated 75% to CBD and 25% to suburban land, consistent with the value of β_{CBD} above.

Urban mobility

Urban mobility is modelled in VURM-Cities as a composite of public bus and rail transport services and households' own production of private transport services using motor vehicles and motor fuels (Figure 2).[2] Use of each mode of transport also requires inputs of users' time. Transport economists have long recognised the importance of time costs; indeed, justifications for major transport infrastructure investments often rely heavily on time savings (Prest and Turvey 1965, 712). We therefore extend households' utility functions in VURM-Cities to allow for a 'travel time-leisure choice' as in Mayeres (2000). The relative importance of time costs in urban transport differs significantly by mode, with buses usually cheap but slow and cars fast but expensive. The model has

[2] The sector 'bus' also includes light rail systems that mainly share roadways, such as Melbourne's extensive tram system. There is a sector 'water transport' that includes ferries. Ferries play some role in urban transport, particularly in the cities of Sydney and Brisbane, but for the time being, we ignore this mode.

calibrated using statistics on the ratio of time to cash costs for metropolitan Sydney (Table 1) and valuing travel time costs at A$15/hr.

Table 1 – Travel times

Mode	Average distance[3] (km)	Average cost[4] ($A/km)	Average time[3] (minutes/km)	Ratio (min/$)
Car trips	9.9	$0.65	20	0.78
Bus trips	6.7	$0.22	22	3.8
Rail trips	16.7	$0.15	27	2.7

As an indication of the relative importance of different passenger transport modes in Australia and of transport relative to housing, national average budget shares for the relevant goods are shown in Table 2. These shares include only cash costs.

Table 2 – Value shares in household consumption

Original VURM commodity	Percentage of household demand (%)[5]
Housing	18.89
Total urban transport[6], of which	7.13
Petrol	2.66
Motor Vehicles	3.73
Bus	0.55
Train	0.19

Our two-level CES nesting structure is similar to that of Bruvoll and Larsen (2004), from whom we also take the elasticities of substitution. This structure is also broadly consistent with more detailed transport models, of which Proost and van Dender (1999 p. 56) is a prominent example. At the top

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[3] Figs 3.7.2 and 3.8.1 in 2010/11 Household Travel Survey, Summary Report 2012 Release, NSW Bureau of Transport Statistics.

[4] From calculations made by Shakibaei drawing on various public statistics and reports in https://transportsydney.wordpress.com/2014/01/10/the-cost-of-transport-and-fare-setting/

[5] These values are calculated from the VURM database, which is constructed using input-output, national accounts and other datasets published by the Australian Bureau of Statistics.

[6] For the purposes of this paper, we are simply assuming that all car, road passenger and rail passenger transport are urban transport while all air passenger or water passenger transport are rural, inter-urban or international. These assumptions are somewhat extreme but could easily be relaxed.

level, households choose between use of private motor vehicles ('Car') and use of public transport ('PTrans') with an elasticity of 1.2 (cf. Proost and van Dender's 0.95 for peak and 1.85 for off-peak in Brussels). At the second level, public transport users choose between 'Bus' and 'Train' modes of public transport with an elasticity of 1.2, as in (cf. Proost and van Dender's 1.1 for peak and 1.65 for off-peak). Private car use requires inputs of petrol, diesel or liquefied natural gas (Fuel) and of motor vehicles, parts and repairs (MotVeh), which have a low elasticity of substitution of 0.2.[7]

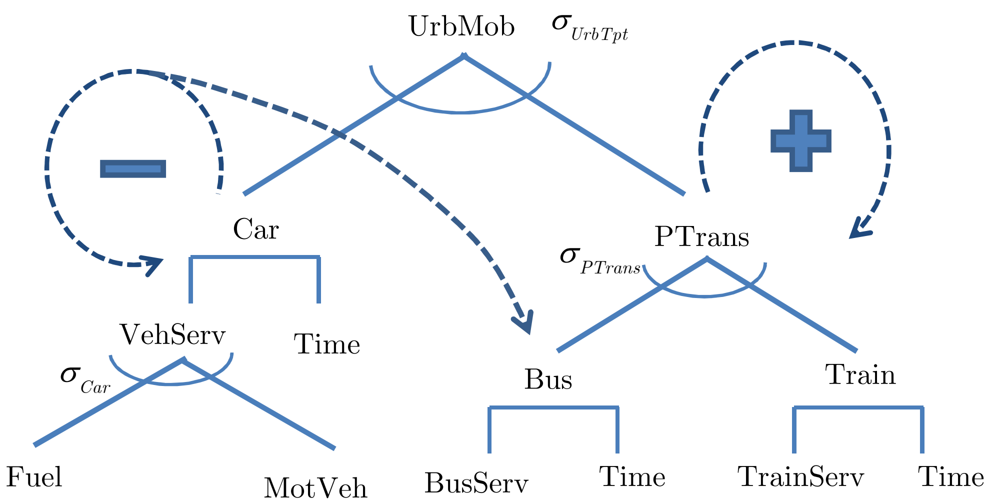

Figure 2 – Household urban transport demands, dotted lines indicating externalities

Car and bus modes are subject to congestion while public transport is subject to positive demand density externalities, as indicated by the '+' and '–' symbols and dotted lines in Figure 2. Congestion costs involve time and vehicle operating costs increasing with the density of road use. Such costs cannot be avoided altogether, but in the absence of optimally set congestion charges or other policies having comparable effects, congestion costs will be higher than is socially optimal. The reason for this is that the marginal costs of congestion are higher than the average costs. Public transport is also subject to several forms of congestion. Passengers can cause congestion of buses and rail carriages, as well as associated infrastructure such as platforms. Buses and trains can in turn congest road (and specific bus) infrastructure and rail infrastructure respectively. On the other hand, buses and especially trains are also subject to positive demand density externalities, as described in the introduction. It should be noted that in our initial development of VURM-Cities, we emphasise the roles of private actors and the operation of market forces. However, it must be

[7] Note that we do not explicitly model household's stocks of motor vehicles.

acknowledged that public transport provision and pricing is heavily regulated and is subject to various political as well as market failures in Australia (see e.g. Owens 2004) as in most countries.

Positive and negative externalities are modelled in VURM-Cities using a specification similar to that developed in the context of a macroeconomic growth model by Eichner and Turnovsky (2000). Modelling of congestion is simplified by assuming that while both car and bus passengers are affected by congestion, only cars contribute to congestion.[8] This is justifiable given that the modal share for cars is much higher than that for buses and also by the lower marginal cost per bus passenger kilometre relative to a car passenger kilometre. We have not yet extended the model to account for congestion of or by freight and business travel, although these are important. Finally, we assume that rail use does not affect road use and vice versa, although some interactions between these modes do occur (e.g. where tracks cross roads at grade). Positive demand density externalities in public transport are modelled to reflect the ideas that (i) these are substantially stronger for rail than for bus and (ii) that, to some extent, rail and bus services operate as an integrated system to facilitate multi-modal journeys. Conceptually, we model the net effect of these externalities after accounting for congestion caused by passengers. Congestion of rail infrastructure by rolling stock should be less problematic, because the costs are readily internalised by the one or several operators involved. While we intend to extent VURM-Cities to explicitly model the supply of road and rail infrastructure, for the purposes of this paper we proxy these stocks by the quantity of metropolitan land, since this quantity is closely related to the demand for urban transport.

The decisions problems of individual transport users are constrained by the following three production functions that link transport inputs to transport mobility output:

$$\tilde{X}_{Car,i} = \xi_{Car} X_{Car,i} \left(X_{MetLnd} X_{Car}^{-\eta_{Car}} \right)^{\gamma_{Car}} , \tag{1.10}$$

$$\tilde{X}_{Bus,i} = \xi_{Bus} X_{Bus,i} \left(X_{MetLnd} X_{Car}^{-\eta_{Bus}} \right)^{\gamma_{Bus}} , \tag{1.11}$$

$$\tilde{X}_{Train,i} = \xi_{Train} X_{Train,i} \left(X_{MetLnd} X_{Train}^{-\eta_{Train}} \right)^{\gamma_{Train}} \quad \text{and} \tag{1.12}$$

[8] For convenience, we treat the congestion of buses as if all congestion costs were directly borne by passengers. While vehicle-related costs are directly borne by bus companies, we assume that these are passed on to passengers. In this case, our specification is essentially equivalent to a more detailed one distinguishing congestion costs on the supply side from those on the demand side.

$$\tilde{X}_{PTrans,i} = \xi_{PTrans} X_{PTrans,i} \left(X_{MetLnd} X_{PTrans}^{-\eta_{PTrans}} \right)^{\gamma_{PT}} . \tag{1.13}$$

$$\gamma_{Car} = 0.4, \quad \gamma_{Bus} = 0.4, \quad \gamma_{Train} = -0.33, \quad \gamma_{PTrans} = -0.35 .$$

Quantity and (below) price variables pertaining to mobility services, as opposed to mobility inputs, are indicated by tildes. Individual use is distinguished from aggregate use with an i subscript. Note that individuals face constant returns to their own travel inputs, but aggregate returns are decreasing or increasing in the cases of with negative or positive externalities respectively. More work is required to calibrate the *eta* and *gamma* parameters (the *xi* are scaling factors implied by the database) but for the purposes of our illustrative simulations, we choose the following values:

$$\eta_{Car} = 1, \quad \eta_{Bus} = 1, \quad \eta_{Train} = 1, \quad \eta_{PTrans} = 1 .$$

$$\gamma_{Car} = 0.4, \quad \gamma_{Bus} = 0.4, \quad \gamma_{Train} = -0.4, \quad \gamma_{PTrans} = -0.4 .$$

User prices are found from individuals' first order conditions. Aggregate demands for mobility are equal to individual demands multiplied by the number of individuals. These are easily recovered using the fact that the number of individuals is equal to the ratio of aggregate to individual input quantities. We obtain the following equations for prices and quantities in percentage change form:

$$\tilde{x}_{Car} = \left(1 - \eta_{Car}\gamma_{Car}\right) x_{Car} + \gamma_{Car} x_{MetLnd} , \tag{1.14}$$

$$\tilde{p}_{Car} = p_{Car} - \gamma_{Car} \left(x_{MetLnd} - \eta_{Car} x_{Car} \right) , \tag{1.15}$$

$$\tilde{x}_{Bus} = x_{Bus} + \gamma_{Bus} \left(x_{MetLnd} - \eta_{Bus} x_{Car} \right) , \tag{1.16}$$

$$\tilde{p}_{Bus} = p_{Bus} - \gamma_{Car} \left(x_{MetLnd} - \eta_{Car} x_{Car} \right) , \tag{1.17}$$

$$\tilde{x}_{Train} = \left(1 - \eta_{Train}\gamma_{Train}\right) x_{Train} + \gamma_{Train} x_{MetLnd} , \tag{1.18}$$

$$\tilde{p}_{Train} = p_{Train} - \gamma_{Train} \left(x_{MetLnd} - \eta_{Train} x_{Train} \right) , \tag{1.19}$$

$$\tilde{x}_{PTrans} = \left(1 - \eta_{PTrans}\gamma_{PTrans}\right) x_{PTrans} + \gamma_{PTrans} x_{MetLnd} , \text{ and} \tag{1.20}$$

$$\tilde{p}_{PTrans} = p_{PTrans} - \gamma_{PTrans} \left(x_{SubLnd} - \eta_{PTrans} x_{PTrans} \right) . \tag{1.21}$$

Taking car-based mobility as an example, the intuition behind these equations is as follows. The term $\left(1 - \eta_{Car}\gamma_{Car}\right)$ is less than one. Consequently, a given percentage increase in private inputs as measured by x_{Car} will result in a smaller percentage increase in car-based mobility as measured by $\tilde{x}_{Car}$, due to the resulting increase in congestion costs. On the other hand, expansion of the road network as measured by x_{MetLnd} will increase the efficiency with which inputs of fuel, vehicles, etc. can be transformed into car-based mobility. The situation is reversed in the case of rail and the public transport composite.

The CES demand and price equations for the top level of the transport demand system nesting are

$$\tilde{x}_{Car} = x_{UrbMob} - \sigma_{UrbMob}\left(\tilde{p}_{Car} - \tilde{p}_{UrbMob}\right), \tag{22}$$

$$\tilde{x}_{PTrans} = x_{UrbMob} - \sigma_{UrbMob}\left(\tilde{p}_{PTrans} - p_{UrbMob}\right), \text{ and} \tag{23}$$

$$p_{UrbMob} = S_{Car}\tilde{p}_{Car} + \left(1 - S_{Car}\right)\tilde{p}_{PTrans}. \tag{24}$$

For bus and train modes of public transport, they are

$$\tilde{x}_{Bus} = x_{PTrans} - \sigma_{PTrans}\left(\tilde{p}_{Bus} - p_{PTrans}\right), \tag{25}$$

$$x_{Train} = x_{PTrans} - \sigma_{PTrans}\left(p_{Train} - p_{PTrans}\right), \text{ and} \tag{26}$$

$$p_{PTrans} = S_{Bus}\tilde{p}_{Bus} + \left(1 - S_{Bus}\right)p_{Train}. \tag{27}$$

For private car use, they are

$$x_{MotVeh} = x_{Car} - \sigma_{Car}\left(p_{MotVeh} - p_{Car}\right), \tag{28}$$

$$x_{Fuel} = x_{Car} - \sigma_{Car}\left(p_{Fuel} - p_{Car}\right), \text{ and} \tag{29}$$

$$p_{Car} = S_{Fuel}p_{Fuel} + S_{MotVeh}p_{MotVeh}. \tag{30}$$

Illustrative simulations

Unconstrained land supply

We construct a ‘plain vanilla’ scenario of economic growth by assuming a 2% annual growth in labour productivity with zero population growth. Other exogenous parameters of the model such as industry-specific productivity are constant over time. The supply of suburban land is perfectly elastic and adjusts so that the land price tracks the consumer price index (CPI) in each region. It is assumed that this land has no other productive use and more particularly, the total supply of agricultural is fixed independently of the suburban land supply.

We simulate this scenario with four different versions of the model:

- The reference (REF) simulation excludes both externalities of transport demands and zero travel time costs.
- The externalities (EXT) simulation includes positive and negative externalities of transport demands but travel time costs are zero.
- The time costs (TIM) simulation includes positive travel time costs but excludes externalities of transport demands.
- The externalities and time costs (E&T) simulation accounts for both positive and negative externalities of transport demands and for travel time costs.

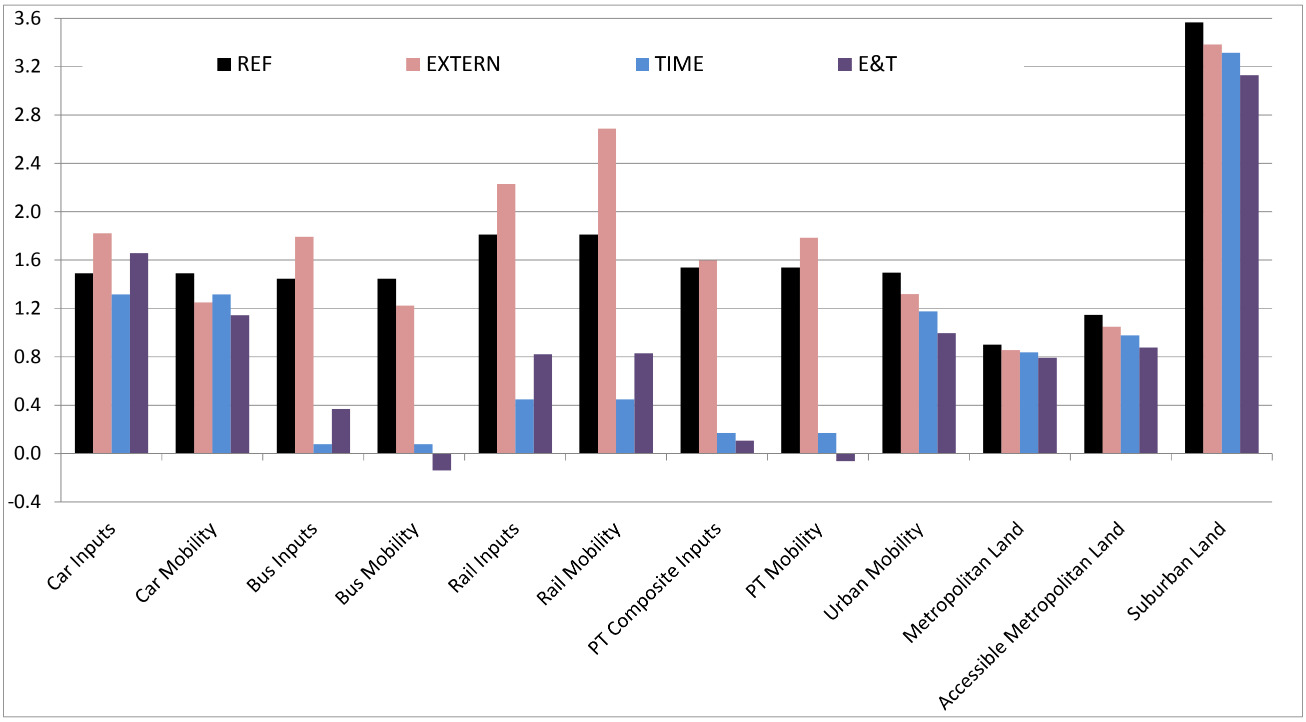

Figure 3 - Growth in transport use in NSW with unconstrained land supply

In figure 3, average annual percentage changes in travel costs, mobility and urban land use are shown for New South Wales (NSW), Australia's largest state. Results for other states and territories are qualitatively similar because common parameters were assumed for the purposes of these illustrative simulations. In the figure, 'cost' refers to the change in (the real value of) cash costs in the REF and EXT simulations and to the changes in combined cash and time costs in the TIM and E&T simulations. 'Mobility' for the individual transport modes can be most easily understood as representing person-kilometres for each individual transport mode, but may also encompass non-cash/non-time attributes of travel (e.g. comfort).

In the REF simulation, costs move together with mobility growth, since externalities are not accounted for. Growth in all transport modes is similar because there is little differentiation of cost pressures amongst modes on the supply side. The increase in overall urban mobility is driven by rising incomes and is associated with expansion of the suburban land area. Urban mobility increases 1.50% p.a. while suburban land area increases 3.56% p.a. The ratio of these rates is 0.42, which is close to the 0.4 elasticity of mobility with respect to land that was calculated from equation (1.9).

In the EXT simulation, introduction of road congestion costs and positive demand density externalities in public transport slow the rate of increase of urban mobility and of suburban land area relative to the REF simulation. Congestion costs make car and bus travel less efficient in delivering mobility by increasing the costs (which are cash only in this simulation) per person-kilometre. Consequently, the growth of expenditure is faster than in the previous simulation, while the growth of mobility is slower. For the rail mode and for the public transport composite, the Mohring effect works in the opposite direction. However, because car is by far the dominant transport mode, the road congestion effects dominate and both overall urban mobility and suburban land use rise more slowly than in the REF simulation.

Introducing time costs in the TIM simulation makes all forms of mobility more costly, but the effects are much larger for public transport modes (especially buses) than they are for cars. The decrease in car mobility is therefore the net effect of lower overall mobility and substitution from public transport modes to car transport. There is also substitution towards trains from buses, so that the substitution effects on trains are in principle ambiguous (but in practice negative because of the dominance of the car mode) whereas the effects on buses are unambiguously negative. Growth in bus transport is approximately zero in this simulation. As we the case in the EXT simulation, lower growth of urban mobility is accompanied by lower growth in suburban area. As in the RES scenario, changes in cost and mobility are identical because externalities are not modelled.

In the E&T simulation, both travel time costs and positive and negative externalities of transport demands are accounted for. The differences in growth rates relative to the REF simulation are approximately the sum of the differences in the previous two simulations relative to the REF simulation, although there is some non-linearity in the responses. The most notable non-linearity occurs for rail mobility: the growth rate is 0.98% lower than in the REF simulation, whereas the sum of effects from the EXT and TIM simulations would suggest it should be only 0.48% lower. In this simulation, the growth in overall urban mobility is 1.0% while the growth in suburban land is 3.1%. The ratio of the former to the latter is 0.32, compared to the ratio of 0.42 in the REF simulation. Thus, the relative price changes associated with rising time costs and with externalities substantially lower the apparent elasticity of mobility with respect to land area.

Urban growth boundaries

We now consider the effects of imposing strict urban growth boundaries (UBGs) in all regions. We simulate this by holding the quantity of suburban land in each region at its base year level, endogenising the price of suburban land. The impacts of this policy on household mobility and transport use are shown in Figure 3 (as before, focussing on the state of New South Wales). The original growth rates as they appeared in the previous section are shown for reference (solid bars). Changes in growth rates due to the imposition of UBGs are shown by the diagonally striped bars. Results are show for simulations excluding (REF) and including (E&T) externalities and travel time costs.[9]

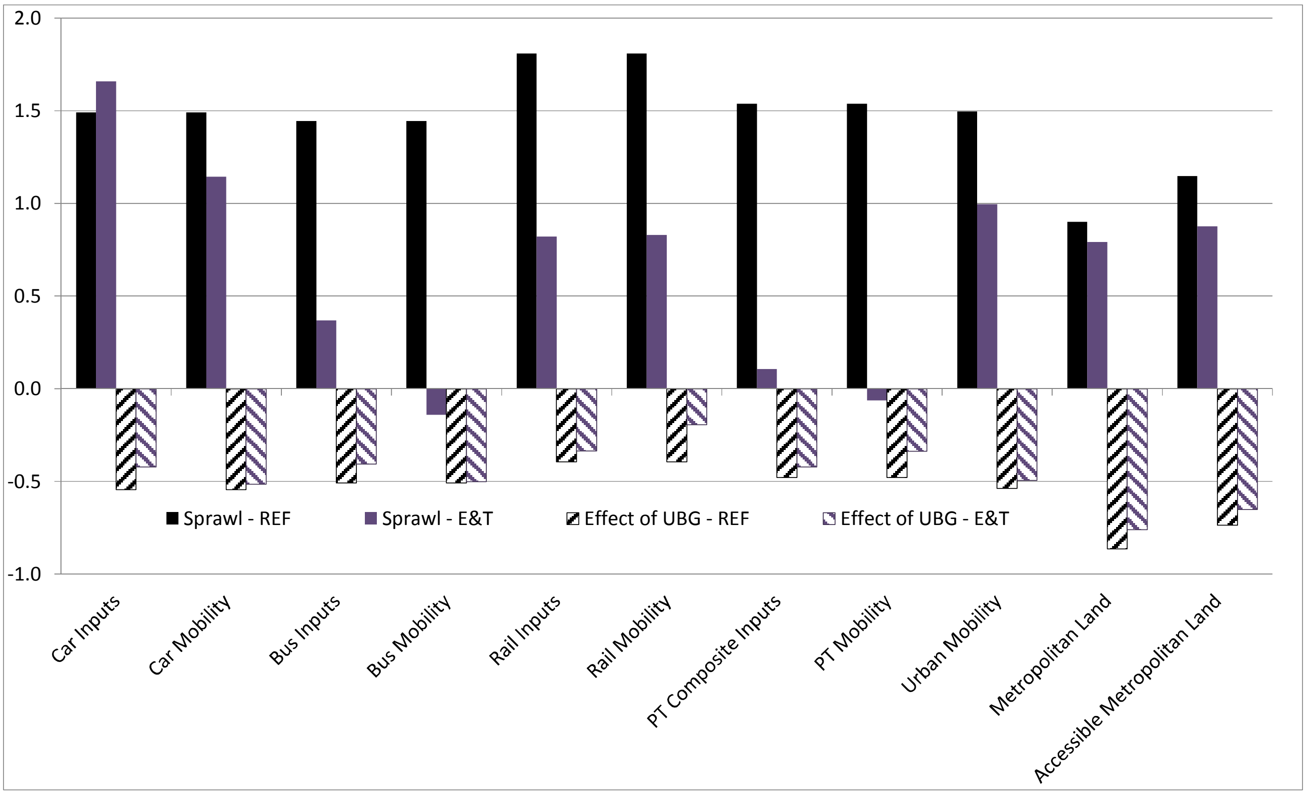

Figure 4 - Growth in transport use in NSW with an urban growth boundary

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[9] Changes in growth of suburban land area are not shown to maximise the scale of the figure, but are, by definition, the negative of those shown in Figure 3, as is also true of the changes in growth of metropolitan land.

The dominant effect of constraining urban area is to reduce annual growth of all forms of urban (household) transport expenditure and mobility. Urban mobility grows in the UBG simulations because even though the metropolitan area is fixed, it can still be accessed more intensively by increasing the length and/or the number of trips. In terms of differences in percentage points of growth, the effects of UBGs on overall urban mobility are slightly weaker when externalities and time costs are considered (E&T) than when they are not (REF). Considered in relative terms though, the effects are large: the growth rate is halved by imposing UBGs in the E&T simulations, whereas in the REF simulations, the higher growth rate is reduced by only a third.

For all transport modes, growth in both costs and mobility fall less (again in terms of differences) when externalities and time costs are accounted for (E&T) than when they are not (REF). However, for the car mode, the reductions in inputs are less than the reduction in mobility whereas for the train mode, the opposite is true. This is because holding the effective land area fixed (the denominator in the definition of external effects), growing mobility increases both negative externalities in road transport and positive externalities in rail transport.

Macroeconomic effects of UBGs

The impacts of imposing UBGs on GDP are shown in Figure 5 for all four model configurations (note the non-zero origin of the vertical axis). While UBGs have negative effects on growth, these are smaller when congestion or time costs are accounted for.

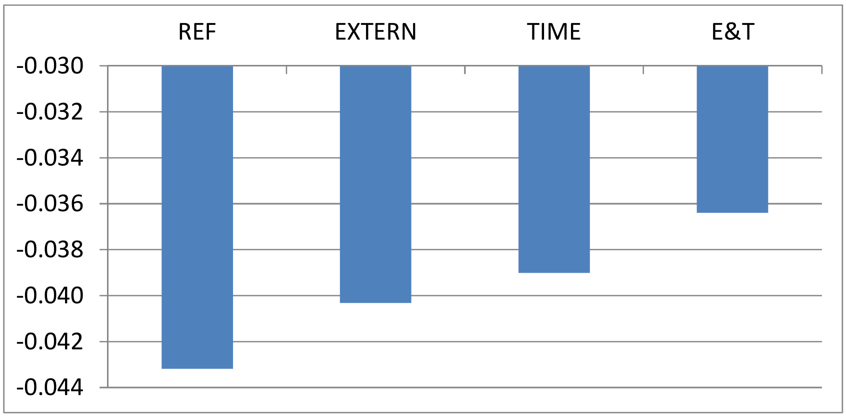

Figure 5 - Percentage change in GDP as a result of imposing UBGs in four model specifications

On the one hand, constraining land use reduces the demand for mobility and increases positive externalities in public transport. On the other, it worsens congestion of road transport. The effects of accounting for congestion on the macroeconomic impacts of UBGs are thus theoretically ambiguous in general. In our simulations though, GDP impacts are smaller when these externalities are accounted for. The theoretical effect of accounting for travel time costs in our specification is unambiguous. At the aggregate level, travel time and suburban land are complementary. Consequently, less is forgone by constraining the expansion of suburban land if travel times represent an increasing cost to land use (TIM simulations) than when they do not (REF simulations).

Discussion

Our simulations show the potential to capture some key characteristics of urban economies by means of simple *ad hoc* aggregative relationships between key variables, such as residential land use and mobility, as well as by distinguishing the private and social costs of decisions when these differ markedly, as is the case for urban transportation. Our approach is *ad hoc* in the sense that we do not derive aggregative relationships from spatially explicit micro-foundations. This has some costs: we may be less confident that parameters are 'structural' and we may obtain less insight into particular phenomena. However, it also has benefits: many phenomena can be considered simultaneously and parameters need not be restricted to take mathematically convenient values. For much applied work, these benefits may outweigh the costs.

One further caution is that density, while important, is only one dimension of urban form. Ewing and Hamidi (2014) list four main factors as being relevant in measuring 'sprawl' versus 'compact and connected' development: 'development density' (itself multidimensional); land use mix; activity centring; and street accessibility. The Global Commission on the Economy and Climate (2014) also calls for 'compact and connected development' rather than simply high density development. The recent wave of high-rise residential developments in Melbourne, Australia provide a case study of poorly managed development that achieve extremely high densities at the expense of liveability (Hodyl 2014). Whether it is possible to develop our approach to account in any way for the multiple dimensions of urban form remains a question for further research.

Provided that aggregative relationships are sufficiently stable – particularly with respect to policy variables of interest – the top-down approach presented here may be well-suited to problems where urban form is one of a number of factors that are important. For example, a carbon tax would have strong impacts on urban transport as well as strong impacts on various specific sectors. In the Australian context, it could potentially also involve various adjustments in fiscal arrangements between the federal and state levels of government. The detailed industry structure and comprehensive treatment of taxes and transfers at all levels of government in VURM would be of particular value in such an analysis.

Our characterisation of passenger transport demands highlights the important role of externalities and time costs. A key concern in relation to both pecuniary and time costs that we did not address here is that of fixed costs of users. These include fixed costs of owning and garaging a car, fixed per trip time costs of getting to/from a car park, bus stop or train station, and fixed cost components of public transport fares. These characteristics of transport pricing can have large effects on mode choice. Indeed, it has been suggested that innovations such as vkm-based insurance premia would help to reduce the gap between the marginal social and private costs of private car transport (Litman 2015). Car-sharing schemes can have similar benefits.

Future work

We have presented here only the first steps in our development of the VURM-Cities model. Many things are still missing from the model, of which the following are among the most important:

- Distinguishing urban from ex-urban road transport.
- Accounting for business land use and allowing for competition between business and residential uses.
- Relating urban freight and business transport costs to urban area.
- Refining the treatment of congestion, including effects of and on urban freight and business transport.
- Refining the treatment of positive density externalities associated with public transport.
- Explicitly modelling the stock of urban road infrastructure[10] and specifying rules to describe public infrastructure investment decisions as functions of price and/or quantity variables.
- Considering modelling of other types of externalities in addition to greenhouse gas emissions from transport, which were not reported in this paper but are already accounted for in VURM.
- Allowing for density-dependent technological spillovers within relevant industries.

[10] Whereas rail infrastructure is (implicitly) accounted for as part of the capital of the rail passenger transport sector, most spending on roads is classified statistically as investment of general government and in the VURM model and database, is part of government consumption.

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