Spatial Economic Dynamics and Transport Project Appraisal

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James Lennox

Centre of Policy Studies,
Victoria University

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Address: Centre of Policy Studies, Victoria University, PO Box 14428, Melbourne, Victoria, 8001
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Spatial economic dynamics and transport project appraisal

Dr James Lennox[1]

[1]Centre of Policy Studies, Victoria University, Melbourne, Australia

Abstract

Transport infrastructure is costly to build and very long-lived. Major projects are expected to enhance accessibility, which over time, is likely to affect the distribution of population and employment. In a Dynamic Spatial Equilibrium (DSE) model, the timing and location of a project's direct costs and benefits can be explicitly represented. Effects of both construction and operational phases are captured in a forward-looking spatial general equilibrium with costly adjustment. Not only are dynamic responses of direct interest to policymakers, but they have crucial implications for welfare analysis.

In this paper, we present a flexible DSE model incorporating dynamics of internal migration and occupation choice, and intra-period spatial linkages via commuting and trade flows. We calibrate the framework to Australian data and illustrate its application by modelling a hypothetical fast express rail service in South-East Queensland. In analysing the results, we highlight the roles of general equilibrium effects within and between periods. These are important both to overall welfare benefits and to their distribution.

Transport cost changes are exogenous inputs to our simulation. However, we also discuss the potential to link a DSE model to a four-step strategic transport model to enable fully dynamic Land Use–Transport Interactions (LUTI) simulations.

Keywords: dynamic spatial equilibrium; project appraisal
JEL Codes: R12, R23, R42

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1 Introduction

Australian state and federal governments are forecast to spend $218b on 434 major infrastructure projects from 2021 to 2026 (Infrastructure Australia 2021). Of that, major transport projects located in the largest state capitals account for 73%. Many of these are mega-projects[1] If these projects are worth doing, they must deliver commensurate benefits. As transport infrastructure is long-lasting, benefits accrue over decades and may be enhanced or reduced by their effects on the distribution of population and jobs within and between cities. However, in current Australian practice, such 'land use–transport interactions' (LUTI) are not systematically accounted for in cost benefits analyses (CBA). In this paper, we present a flexible Dynamic Spatial Equilibrium (DSE) model of Australia and demonstrate its application to modelling land use and the wider economic benefits of a hypothetical passenger rail upgrade project. We suggest DSE models as a practical and theoretically sound complement to existing four-step transport modelling, which typically underpin benefit estimates in CBAs.

Governments regularly describe transport mega-projects as city-shaping'[2]. Such claims may easily be dismissed as political rhetorical hyperbole. However, this is not to say that land use impacts do not occur. There is strong empirical evidence to support the hypothesis that major road and rail investments have significant, causal long-run impacts on the distribution of population and/or jobs—i.e. what transport modellers refer to generically as 'land use': see e.g. Kasraian et al. (2016), Xie and Levinson (2010), Levinson (2008), Costa, Zegras, and Biderman (2021), Baum-Snow (2007), Duranton and Turner (2012), Duranton and Turner (2011), and Iacono and Levinson (2016) and many other studies cited therein.

Recent national guidelines on 'land use benefits of transport initiatives' (Department of Infrastructure and Communications 2021) take an ambivalent approach towards modelling land use impacts. The potential relevance and significance of land use impacts are accepted. However, impacts are cast as being: (i) highly contingent on the existence of appropriate 'supporting conditions' (e.g. land use zoning); and (ii) highly uncertain, relative to 'conventional' transport benefits. If transport projects

[1] In Australia, transport mega-projects are usually defined as those costing over A$1b, although many now exceed A$5b.

[2] Melbourne's Metro Tunnel (https://bigbuild.vic.gov.au/projects/metro-tunnel), Metro City and Southwest in Sydney (https://www.nsw.gov.au/media-releases/metro-construction-on-track-new-milestone) and Cross-River Rail in Brisbane (https://statements.qld.gov.au/statements/81498) have been described this way, to give just three examples. Websites accessed 25/03/2022.

were completed in months and delivered benefits over a few years, these would be strong arguments in favour of assuming fixed land uses. However, large projects can take many years to plan and build and may yield benefits for many decades. Within these time frames, many constraints on land use should properly be regarded as endogenous. The predictive power of transport models will also break down, as travel demands, transport preferences and technologies change. When simulating impacts two or three decades hence, both land use and transport modelling inevitably involve considerable uncertainties.

A further argument in favour of considering LUTI more systematically is the conventional reliance on a future fixed 'base case' land use. Australian Transport Assessment and Planning (ATAP) guidelines (Infrastructure and Transport Ministers 2022) frame the base case as a neutral point of reference against which different transport projects can be objectively assessed and compared. While it is true that using a common base case enables direct comparisons between projects, it does not follow that such comparisons are neutral. Firstly, any future base case provides a somewhat arbitrarily chosen picture of the future. A different base case produced using different methods and/or assumptions might increase or reduce the benefits of a particular transport project. While this issue cannot be avoided, it might be mitigated by developing several qualitatively different base cases and requiring projects to be assessed against all of them. Secondly, base case land uses are typically developed to account for the land use impacts of committed transport projects. However, this is usually achieved using opaque, *ad hoc* methods, not formal LUTI modelling. Moreover, projects may sometimes be assessed against a base case into which they have already been factored, given that business cases for major projects are frequently completed after governments have committed to them (Terrill, Emslie, and Moran 2020).

This paper presents a novel approach to modelling land use impacts of transport projects. Urban and regional dynamic spatial general equilibrium (DSE[3]) models are well suited to modelling the response of land uses to changes in transport costs. DSE models embed a dynamic discrete choice model, based on random utility theory, within a dynamic spatial general equilibrium framework. From a practical perspective, they can capture the slow dynamic response of land uses, which are due to the sizeable costs incurred by households and workers relocating or switching industries, and to the costs of adjusting housing and other fixed capital stocks. Theoretically,

[3]There remains some variation in terminology used to refer to this class of models and no acronym is in wide use. We adopt 'DSE' here, noting that 'DSGE' conventionally refers to the dynamic stochastic general equilibrium models used in macroeconomics.

they provide a micro-founded framework for welfare analysis at aggregate and disaggregated levels.

Our DSE model of the Australian economy builds primarily on Caliendo, Dvorkin, and Parro (2019, henceforth, CDP) who present a model with trade and intermediate uses in multiple sectors and Warnes (2020) who develops an urban DSE model featuring commuting as well as intra-urban migration. In CDP, households are *ex ante* identical and choose between locations and industries. In Warnes, there are two distinct household types: high and low skill. We take a different approach again, with *ex ante* identical households choosing between locations and occupations, but indifferent to their industry of employment. We also allow for productivity spillovers dependent on effective job density, as is standard in urban spatial models (see e.g. G. Ahlfeldt, Redding, and N. Sturm D. M. W. 2015).

To illustrate how changed transport costs affect land uses in our model, we simulate the introduction of a (hypothetical) 'fast express' service on South-East Queensland's Gold Coast Line. We calibrate the DSE model to distinguish 354 ABS Statistical Area Level 2 (SA2) regions in the South-East Queensland (SEQ) study area and 100 SA3 or SA4 regions covering the rest of Australia. There are five production sectors, plus housing. We simulate the model for 160 2.5-year periods.[4]

Our simulation results show that the fast express service broadly favours additional population growth around suburban stations and additional job growth in the inner city. We hold the national but not the SEQ population fixed, thus gains come only partly at the expense of other areas within SEQ, with additional migration from the rest of Queensland and Australia also playing a role. These changes unfold slowly. Roughly half the land use adjustment is seen within ten years of rail operations beginning in 2026, but small effects persist even beyond 2056. Some adjustment also occurs in anticipation of gains in accessibility.

In our illustrative simulation, transport cost changes are exogenous inputs to the DSE model. However, we argue that both transport costs and land uses should be considered to be endogenous variables of an urban and regional system. In urban transportation modelling, the classic four-step transport model remains the work-horse model. These models involve iterative simulation of: (1) trip generation; (2) trip distribution; (3) mode choices; and (4) route assignments. They have a degree of theoretical coherence with DSE models, drawing on random utility theory to model e.g.

[4]This very long time horizon ensures that the model economy converges very close to its true long-run steady-state solution. This aids convergence and also avoids any contamination of results of interest by terminal effects.

mode choices, and modelling road traffic assignment as a decentralised user equilibrium. We have previously contributed to the development of a land use–transport interaction (LUTI) modelling system for Victoria (VLUTI), in which a spatial computable general equilibrium (SCGE) model is coupled to a simplified version of the Victorian Integrated Transport Model (VITM) (Le et al. 2021). After discussing our simulation results, we sketch out a practical approach to linking a DSE model with a four-step transport model to form a fully dynamic LUTI modelling system.

2 Model

We distinguish N spatial units in the national economy in which people may reside and/or work, J industries and K occupations. We index spatial units by r or s, industries and the goods or services they produce (including housing) by i or j, and occupations by k or l. Time is discrete and indexed $t = 0, 1, 2, \ldots$. The economy is populated by profit-maximising firms and forward-looking, utility-maximising households.

Within each sector, firms produce goods or services using a Cobb-Douglas technology with constant returns to scale. They demand intermediate inputs, occupational labour and a local fixed factor. Firms in the first $J-1$ sectors produce goods or services that can be traded both between spatial units and internationally. This trade is shaped by spatial frictions, which we associated with freight costs for goods, and business or private travel costs for services. In the Jth sector, non-tradable housing services are produced using only intermediates and a fixed factor.

Each household is endowed with one unit of labour per period. Before the start of each period, a worker–household chooses her next occupation and place of residence. Switching occupation and/or residence may entail large pecuniary and/or psychic costs, which we assume to be time-invariant. She then chooses a place of work, taking into account spatial differences in occupational wage rates and commuting costs. During the period, she supplies her unit of occupational labour at her work location and consumers housing and shops for goods and services from her residential location.

For computational tractability of the model, we assume that a worker in a given occupation and location is indifferent to her industry of employment. We have the same motiviation for splitting the choice problem into two stages. To mitigate the lack of explicit dynamics in workplace choices, we suggest that a period length of several years is most appropriate.

The government sector is not explicitly represented. However, we do represent a wide variety of direct and indirect taxes (and subsidies).

Government transfers in kind to households (e.g. much healthcare and education provision) and even public goods (e.g. public order) are represented as subsidies to household consumption. The advantage of this is that the spatial distribution of demands automatically follows that of households, while we also make explicit the financing of these expenditures through taxation.

2.1 Workplace choices

The indirect flow utility function of a household in occupation k, residence r, and workplace s at time t is

$$\mathrm{u}_t^{krs} = {\epsilon_{\mathrm{u}}}_t^{krs} \frac{m_t^{krs}}{\mathcal{P}_t^r d_t^{rs}}, \tag{1}$$

where for given (k, r), ${\epsilon_1}_t^{krs}$ are individual-specific shocks associated with workplace choice, m_t^{krs} is after-tax income and d_t^{krs} reflects the dis-utility of commuting. The local consumption price index faced by all local households resident in r is $\mathcal{P}_t^r$.[5]

For tractability, we assume that each worker receives gross non-wage income in proportion to her wage income. However, we allow that taxes on wage and non-wage income may differ by place of residence. After-tax income is given by

$$m_t^{krs} \equiv \left({\tau_{\mathrm{L}}}_t^r + {\tau_{\mathrm{K}}}_t^r \Upsilon_t\right) w_t^{ks}, \tag{2}$$

where w_t^{ks} is the local occupational wage rate, ${\tau_{\mathrm{L}}}_t^r$ and ${\tau_{\mathrm{K}}}_t^r$ are income tax powers for wage and non-wage income respectively and Υ_t is the endogenously determined economy-wide ratio of non-wage income net of investment to wage income.

We assume a Cobb-Douglas sub-utility function for consumption for all households, so the ideal price index for consumption each spatial unit is

$$\mathcal{P}_t^r = \prod_{i=1}^{J} \left(\frac{{\tau_{\mathrm{C}}}_t^{ir} P_t^{ir}}{\alpha_{\mathrm{C}}^{ir}} \right)^{\alpha_{\mathrm{C}}^{ir}}, \tag{3}$$

with

$$\sum_i \alpha_{\mathrm{C}}^{ir} = 1. \tag{4}$$

[5] Note that we do not include a variable for residential amenity. In our final formulation of the model, time-constant levels of amenity would cancel out. However, it would be straightforward to add an amenity variable if desired to simulate exogenous changes.

The $\tau_{\mathrm{C}t}^{ir}$ are consumption tax (or subsidy) powers and P_t^{kr} are local delivered prices of tradable goods and services or the price of (non-tradable) housing services. We assume that households consume their entire after-tax income. Given the assumed form of the sub-utility function, household expenditure shares on goods and services are equal to α_{C}^{ir}.

We assume that the workplace shocks $\epsilon_{\mathrm{u}t}^{krs}$ are drawn from an i.i.d. Fréchet distribution with shape parameter ε_k. The expected flow utility associated with an occupation–residence pair prior to drawing an individual workplace shock is given by

$$U_t^{kr} = \left(\sum_s \left(\frac{m_t^{krs}}{\mathcal{P}_t^r d_t^{rs}} \right)^{\varepsilon_k} \right)^{1/\varepsilon_k}. \tag{5}$$

The variable U_t^{kr} summarises the *ex ante* attractiveness of each occupation–residence pair and so will feature in the solution of the household's dynamic problem, which we present next.

Integrating over individuals yields commuting destination probabilities conditional on place of residence (for details of the more general static location choice problem, see e.g. G. Ahlfeldt, Redding, and N. Sturm D. M. W. 2015). For workers in occupation k and residence r, the probability of commuting to workplace s in period t is given by

$$\psi_t^{krs} = \left(\frac{w_t^{ks} d_t^{krs}}{U_t^{kr}} \right)^{\varepsilon_k}. \tag{6}$$

We can then calculate the average wage of a resident worker as

$$W_t^{kr} = \sum_{s=1}^{N} \psi_t^{krs} w_t^{ks}. \tag{7}$$

From 2, the average income of occupational workers by place of residence is then

$$M_t^{kr} = (\tau_{\mathrm{L}t}^{\ r} + \tau_{\mathrm{K}t}^{\ r} \Upsilon_t)\, W_t^{kr} \tag{8}$$

2.2 Internal migration and occupational choices

Given an occupation–residence pair (k, r) in period t, the household's lifetime utility is given by the Bellman equation

$$\mathrm{v}_t^{kr} = \ln U_t^{kr} + \max_{\{l,q\}_{l=1,q=1}^{K,N}} \left\{ \beta\, \mathbb{E}\left[\mathrm{v}_{t+1}^{lq} \right] + \zeta^{kr,lq} + \nu\, \epsilon_{\mathrm{v}t}^{\ lq} \right\}. \tag{9}$$

That is, the expected flow utility in the current state, plus the expected continuation value from the optimal choice of the next state. Deterministic switching costs are denoted by $\zeta^{kr,lq}$ and individual-specific dynamic shocks by ${\epsilon_{\rm v}}_t^{lq}$. β is the discount factor. As is standard in DEMs, we assume these shocks are distributed i.i.d. in time following a zero-mean Gumbel distribution with shape parameter ν (see e.g. Caliendo, Dvorkin, and Parro 2019).[6] Then, integrating over households' dynamic preference shocks, one obtains

$$V_t^{kr} = \ln U_t^{kr} + \nu \log \left(\sum_{l=1}^{K} \sum_{q=1}^{N} \exp \left(\beta V_t^{lq} + \zeta^{kr,lq} \right) \right). \tag{10}$$

As shown in Caliendo, Dvorkin, and Parro (2019), the share of (k, r) households switching to (l, q) is given by

$$\mu_t^{kr,lq} = \frac{\exp \left(\beta V_{t+1}^{lq} - \zeta^{kr,lq} \right)^{1/\nu}}{\sum_{k'=1}^{J} \sum_{q'=1}^{N} \exp \left(\beta V_{t+1}^{l'q'} - \zeta^{kr,l'q'} \right)^{1/\nu}}. \tag{11}$$

Evolution of the resident workforce from one period to the next is given by

$$H_t^{lq} = \sum_{i=1}^{K} \sum_{r=1}^{N} \mu_{t-1}^{kr,lq} H_{t-1}^{kr}, \tag{12}$$

and the number of occupational jobs in each work location is given by

$$L_t^{ks} = \sum_{r=1}^{N} \psi_t^{krs} H_t^{kr}. \tag{13}$$

2.3 Firms, product and housing markets

A variety of tradable intermediate goods or services are produced by monopolistically competitive firms operating within each industry sector. These firms' production requires labour, land, fixed capital and intermediate inputs. The goods and services consumed by both firms and households are composites of traded intermediate varieties. Each individual variety is sourced from the region that can deliver it at least cost. For simplicity, trade costs have the standard iceberg form, i.e. they are paid for in units of the product supplied. Goods and services may be sourced not only from

[6] Note that idiosyncratic shocks in the dynamic problem are more important, relative to deterministic factors, the larger the value of ν. In the static sub-problem, they are more important the smaller the value of ε.

within Australia, but may be imported and exported internationally. As in Kleinman, Liu, and Redding (2021), we model the production of housing services as a special case in which (i) no labour is used and (ii) trade costs are infinite. Also, housing services are consumed only by households.

Firms' unit costs are given by

$$p_t^{ir} = \left(A_t^{ir}\right)^{\alpha_{\mathrm{V}}^i} \left(\frac{\tau_{\mathrm{K}t}^{ir} r_t^{ir}}{\alpha_{\mathrm{K}}^i}\right)^{\alpha_{\mathrm{K}}^i} \prod_{k=1}^{K} \left(\frac{\tau_{\mathrm{L}t}^{ir} w_t^{kr}}{\alpha_{\mathrm{L}}^{ikr}}\right)^{\alpha_{\mathrm{M}}^{ikr}} \prod_{i=1}^{J-1} \left(\frac{\tau_{\mathrm{M}t}^{ijr} P_t^{jr}}{\alpha_{\mathrm{M}}^{ij}}\right)^{\alpha_{\mathrm{M}}^{ij}}, \tag{14}$$

where the sector average level of productivity A_t^{ir} will be further specified below, the rental price of capital is r_t^{ir}, and input tax powers on capital, labour and intermediates are $\tau_{\mathrm{K}t}^{ir}$, $\tau_{\mathrm{L}t}^{ir}$ and $\tau_{\mathrm{M}t}^{ijr}$ respectively. Given limitations of sub-national datasets, we assume that the Cobb-Douglas exponents are independent of region, excepting those for the different types of occupational labour. The coefficients on inputs sum to one. These correspond to firms' (tax-inclusive) input cost shares. For convenience, we denote the cost share for value added as

$$\alpha_{\mathrm{V}}^i \equiv \alpha_{\mathrm{K}}^i + \sum_{k=1}^{K} \alpha_{\mathrm{L}}^{ikr}. \tag{15}$$

As is commmon in urban economic models, we make sector average productivity a function of effective job density. As suggested by empirical findings (S. Groot and H. L. d. Groot 2020), we assume that only higher-skilled workers contribute to these productivity spillovers. We take these to be workers in the first $K_{\mathrm{H}} < K$ occupations. Thus, productivity is given by

$$A_t^{ir} = \bar{A}^{ir} \left(\sum_{s=1}^{N} \sum_{k=1}^{K_{\mathrm{H}}} \exp\left(-\varrho g_t^{rs}\right) L_t^{ks}\right)^{\chi_i} \tag{16}$$

where $\bar{A}^{ir}$ captures differences in location-specific, time-invariant fundamentals, ϱ is a distance-decay factor, and χ_i is the elasticity of productivity to effective high-skilled job density.

The cost of composite goods is given by

$$P_t^{is} = \Gamma^{is} \left(\sum_{r=1}^{N+1} \left(\frac{p_t^{ir} t_t^{irs}}{\left(A_t^{ir}\right)^{\alpha_{\mathrm{V}}^i}}\right)^{-\theta^i}\right)^{-1/\theta^i} \tag{17}$$

where $t_t^{irs} \geq 1$ is the iceberg trade cost, θ^i is the shape parameter for the distribution of firm-specific productivity levels and Γ^{is} is a constant related to the distribution.[7]

In this equation, import prices in domestic currency (f.o.b.) are equal to

$$p_t^{i,r} = p_{\mathrm{F}t}^{\,i}/e_t, \quad r = N+1 \tag{18}$$

where $p_{\mathrm{F}t}^{\,i}$ is the exogenous foreign price and e_t the nominal exchange rate (expressed as units of foreign currency per unit of domestic currency). We do not allow for import duties in the model, as these are negligible in Australia. However, trade frictions may incorporate various border costs, e.g. phytosanitary controls.

The share of goods or services sourced from each region is given by

$$\pi_t^{irs} = \frac{\left(p_t^{ir} t_t^{irs} / (A_t^{ir})^{\alpha_{\mathrm{V}}^{i}}\right)^{-\theta^i}}{\sum_{r'=1}^{N+1} \left(p_t^{ir'} t_t^{ir's} / \left(A_t^{ir'}\right)^{\alpha_{\mathrm{V}}^{i}}\right)^{-\theta^i}}. \tag{19}$$

As noted above, trade in housing is infinitely costly, so in equations 17 and 19, all $r \neq s$ terms in the summations are zero.

2.4 Market clearing

For each good or service, market clearing requires that

$$Y_t^{ir} = \sum_{s=1}^{N+1} \pi_t^{irs} X_t^{is} \tag{20}$$

where Y_t^{ir} is the value of industry output in each spatial unit (or imports for $r = N+1$) and X_t^{is} is the combined value of intermediate, investment and final demands in each spatial unit (or exports for $r = N+1$) at market prices.

Aggregate local demands are equal to

$$X_t^{ir} = \sum_{j=1}^{J} \frac{\alpha_{\mathrm{M}}^{ij} Y_t^{jr}}{\tau_{\mathrm{M}t}^{\;ijr}} + \frac{\alpha_{\mathrm{I}}^{i} I_t^{r}}{\tau_{\mathrm{I}t}^{\;ir}} + \sum_{k=1}^{K} \frac{\alpha_{\mathrm{C}}^{ir} M_t^{kr} H_t^{kr}}{\tau_{\mathrm{C}t}^{\;ir}}, \quad r = 1, \ldots N. \tag{21}$$

As we do not model the accumulation of capital, matching the data requires either reclassifying investment demands as consumption (as in CDP) or specifying investment demands exogenously. We opt for the latter

[7] For a detailed exposition of the theory underlying the model of production and trade, see CDP and works cited therein. In our final formulation of the model, the constant Γ^{is} will cancel out.

approach for two reasons. Firstly, we intend ultimately to extend the present model to incorporate the accumulation of fixed capital, as in Kleinman, Liu, and Redding (2021). Secondly, distinguishing investment demands provides a natural way to specify public investments in transport infrastructure, which will be a key component of our simulation. We exogenise aggregate local investment I_t^r and assume these investment goods are produced using a common Cobb-Douglas technology with parameters $\alpha_{\mathrm{I}}^{i}.$ and tax powers $\tau_{\mathrm{I}t}^{ir}$ on investment inputs.

The market value of exports responds to c.i.f. prices in foreign currency

$$X_t^{ir} = E_0^{ir}\left(e_t \tau_{\mathrm{X}t}^{\ i}\right)^{-\theta_i}\left(P_t^{ir}\right)^{1-\theta_i}, \quad r = N. \tag{22}$$

where E_0^{ir} are constants reflecting the initial prices and market value of exports and $\tau_{\mathrm{X}t}^{\ i}$ are taxes on exports. Note that in reality, what appear as taxes on exports are predominantly payments of domestic indirect taxes by foreign visitors to Australia.

For local labour markets, market clearance requires

$$w_t^{kr} L_t^{kr} = \sum_{i=1}^{J} \frac{\alpha_{\mathrm{M}}^{ikr} Y_t^{ir}}{\tau_{\mathrm{L}t}^{\ ir}}, \tag{23}$$

while for land markets, the condition is simply

$$r_t^{ir} N_t^{ir} = \frac{\alpha_{\mathrm{K}}^{i} Y_t^{ir}}{\tau_{\mathrm{K}t}^{\ ir}}. \tag{24}$$

2.5 Taxation and the distribution of capital and transfer income

Total net revenues from taxes (and subsidies) on intermediate inputs, investment, consumption and exports is

$$\mathcal{R}_{\mathrm{C}t} = \sum_{i=1}^{J}\left[\sum_{r=1}^{N}\left(\sum_{j=1}^{J}\frac{\tau_{\mathrm{M}t}^{\ ijr}-1}{\tau_{\mathrm{M}t}^{\ ijr}}\alpha_{\mathrm{M}}^{ij} Y_t^{jr} + \frac{\tau_{\mathrm{I}t}^{\ ir}-1}{\tau_{\mathrm{I}t}^{\ ir}}\alpha_{\mathrm{I}}^{i} I_t^{r}\right.\right. \tag{25}$$

$$\left.\left. + \sum_{k=1}^{K}\frac{\tau_{\mathrm{C}t}^{\ ir}-1}{\tau_{\mathrm{C}t}^{\ ir}}\alpha_{\mathrm{C}}^{ir} M_t^{kr} H_t^{kr}\right) + \left(\tau_{\mathrm{X}t}^{\ i}-1\right) X_t^{i,N+1}\right]. \tag{26}$$

Total net revenue from factor input taxes (and subsidies) is

$$\mathcal{R}_{\mathrm{F}t} = \sum_{r=1}^{N}\sum_{i=1}^{J}\left(\frac{\tau_{\mathrm{L}t}^{\ ir}-1}{\tau_{\mathrm{L}t}^{\ ir}}\left(\sum_{k=1}^{K}\alpha_{\mathrm{L}}^{ikr}\right) + \frac{\tau_{\mathrm{K}t}^{\ ir}-1}{\tau_{\mathrm{K}t}^{\ ir}}\alpha_{\mathrm{K}}^{i}\right) Y_t^{ir}. \tag{27}$$

Total gross revenue from taxes on household income is

$$\mathcal{R}_{\mathrm{H}t} = \sum_{r=1}^{N} \left(1 - \tau_{\mathrm{L}t}^{\,r} + \left(1 - \tau_{\mathrm{K}t}^{\,r}\right) \Upsilon_t\right) \omega_t^{kr}. \tag{28}$$

The ratio of non-wage to wage income is

$$\Upsilon_t = \frac{\mathcal{R}_{\mathrm{C}t} + \mathcal{R}_{\mathrm{F}t} + \mathcal{R}_{\mathrm{H}t} - B_t + \sum_{r=1}^{N} \left(\sum_{i=1}^{J} r_t^{ir} N_t^{ir}\right) - I_t^r}{\sum_{r=1}^{N} \sum_{k=1}^{K} w_t^{kr} L_t^{kr}}. \tag{29}$$

where the term B_t represents the net outflow of income abroad. We simply identify this with the balance of trade and exogenise it by making e_t endogenous. This firstly allows us to account for the trade imbalance in the data. Secondly, we can change B_t in our simulation of a transport project to reflect initial foreign borrowing to finance the project, followed by interest repayments.

2.6 Exact hat or calibrated share form

A central difficulty in modelling migration and trade is that transition costs and spatial frictions are difficult to observe. However, migration and trade flows are more easily observed. By reformulating their model in terms of ratios of variables at $t+1$ to t, CDP show that unobservable, time-invariant migration costs cancel out, as do trade costs. Assuming relative changes in trade costs are observed, trade costs may be time-varying. They refer to this model formulation in ratios as 'dynamic hat algebra'. Much the same approach has long been used in the computable general equilibrium modelling literature, where it is referred to as the 'calibrated share form'.[8] In this section we present the equations relating to dynamic choices, commuting, trade and spillovers in their exact hat form. The remaining equations are either trivially converted into this form (e.g. 14)) or are used in their levels form (e.g. 20).

For dynamic transitions, the equations are identical to those in CDP, except that flow utility is differently specified, due to the inclusion of commuting:

$$\mu_{t+1}^{kr,lq} = \frac{\mu_t^{kr,lq} \left(\dot{V}_{t+2}^{lq}\right)^{\beta/\nu}}{\sum_{l'=1}^{J} \sum_{q'=1}^{N} \mu_t^{kr,l'q'} \left(\dot{V}_{t+2}^{l'q'}\right)^{\beta/\nu}}, \tag{30}$$

[8]Note that the ratios described here are in fact 'dot' variables in CDP. Their 'hat' variables are ratios of these dot variables in the policy versus the base case. This second stage yields further theoretical insights, but is not important to the numerical solution of the model.

and

$$\dot{V}_{t+1}^{kr} = \dot{U}_{t+1}^{kr} \left(\sum_{l=1}^{J} \sum_{q=1}^{N} \mu_t^{kr,lq} \left(\dot{v}_{t+2}^{lq} \right)^{\beta/\nu} \right)^{\nu} \tag{31}$$

where, for any variable, $\dot{X}_{t+1} \equiv X_{t+1}/X_t$.

For commuting, the change in expected residence utility is

$$\dot{U}_{t+1}^{kr} = \left(\sum_s \left(\psi_t^{krs} \frac{\dot{m}_t^{krs}}{\dot{P}_t^r \dot{d}_t^{rs}} \right)^{\varepsilon_k} \right)^{1/\varepsilon_k}. \tag{32}$$

and in workplace shares is

$$\psi_{t+1}^{krs} = \left(\frac{\dot{m}_{t+1}^{krs}}{\dot{U}_{t+1}^{kr} \dot{P}_{t+1}^r \dot{d}_{t+1}^{rs}} \right)^{\varepsilon_k} \psi_t^{krs} \tag{33}$$

For trade, the equations are identical to those in CDP. However, we do not observe trade flows between small sub-national spatial units, therefore base year flows are constructed using model equations in levels with estimates of trade frictions based on transport costs and parameters from the literature. Initial trade source shares π_0^{irs} can then be updated as follows:

$$\pi_{t+1}^{irs} = \pi_t^{irs} \left(\frac{\dot{p}_t^{ir} \dot{t}_t^{irs}}{\dot{P}_{t+1}^{is} \left(\dot{A}_t^{ir} \right)^{\alpha_{\mathrm{v}}^i}} \right)^{-\theta^i}, \tag{34}$$

and

$$\dot{P}_{t+1}^{is} = \left(\sum_{r=1}^{N+1} \pi_t^{irs} \left(\frac{\dot{p}_t^{ir} \dot{t}_t^{irs}}{\left(\dot{A}_t^{ir} \right)^{\alpha_{\mathrm{v}}^i}} \right)^{-\theta^i} \right)^{-1/\theta^i} \tag{35}$$

Spillovers can be thought of as the result of flows of information, knowledge, and know-how. Again, these are unobserved, so we construct the base year flows using model equations in levels, transport costs and parameters from the literature. Initial source shares for the effective density experienced in a location are given by

$$\vartheta_0^{rs} = \frac{\exp\left(-\varrho g_0^{rs}\right) L_0^{ks}}{\sum_{q=1}^{N} \sum_{k=1}^{K_{\mathrm{H}}} \exp\left(-\varrho g_0^{rq}\right) L_0^{kq}}. \tag{36}$$

These shares and the associated spillover effects can be updated as follows:

$$\vartheta_{t+1}^{rs} = \vartheta_t^{rs} \frac{\exp\left(\varrho\left(g_t^{rs} - g_{t+1}^{rs}\right)\right)}{\dot{\Theta}_{t+1}^{r}} \frac{\sum_{k=1}^{K_{\mathrm{H}}} L_{t+1}^{ks}}{\sum_{k=1}^{K_{\mathrm{H}}} L_t^{ks}}, \tag{37}$$

and

$$\dot{\Theta}^{r}_{t+1} = \sum_{s=1}^{N} \vartheta^{rs}_{t} \exp\left(\varrho\left(g^{rs}_{t} - g^{rs}_{t+1}\right)\right) \frac{\sum_{k=1}^{K_{\mathrm{H}}} L^{ks}_{t+1}}{\sum_{k=1}^{K_{\mathrm{H}}} L^{ks}_{t}}. \tag{38}$$

Changes in productivity are then given by

$$\dot{A}^{ir}_{t} = \left(\dot{\Theta}^{r}_{t+1}\right)^{\chi_i}. \tag{39}$$

2.7 Calibration

2.7.1 Database

Counts of workers by occupation, place of work, current and five-year lagged place of residence are obtained from the 2016 Census (ABS 2016a). Additionally, counts of workers by current and five-year lagged occupations are obtained from the Australian Longitudinal Census Dataset (ACLD) (ABS 2016b). The latter is based on a 5% sample across census years. The model database is constructed at the level of Australian Statistical Geography Standard (ASGS) 2016, Statistical Area 2 (SA2) (ABS 2016c), sub-major occupational groups from the Australian and New Zealand Standard Classification of Occupations (ANZSCO) (ABS 2019b) and Australia New Zealand Standard Industry Classification (ANZSIC) Divisions (ABS 2013). For simplicity, we abstract from international migration. Internal migration flows are therefore adjusted to compensate for these missing inflows and outflows.

In practice, we cannot use very large tables with multiple cross-classifications directly. With such detailed classifications, most cells will be zero or contain small entries, which the ABS perturbs for reasons of confidentiality. Not only are the small values unreliable, but equivalent subtotals computed from different tables will not be exactly equal. Consequently, we make extensive use of semi-informative priors and bi-proportional scaling to produce our full, self-consistent database. This includes the use of less detailed classifications in one or more levels, e.g. sub-major occupation by industry division by SA4 (i.e. using spatial units two levels above SA2 in the hierarchical classification of the ASGS). For occupational transitions, TableBuilder does not permit cross-classification by geography, but we can distinguish between people who have the same or a different address in the two years. We use the former pattern as a prior for within-SA2 (i.e. occupation-only) transitions and the latter as a prior for between-SA2 transitions.

Wage rates are estimated for sub-major occupations by SA2 from the survey-based Employee Earnings and Hours (ABS 2017) combined with

Census data on employment by place of work and individual income. As the Census provides only counts by broad income bands, we estimate average wages using the mid-points of each band. The Census data are used to estimate unconditional spatial variation in wage rates, which is then corrected for local variation in the composition of 4-digit occupational employment within each sub-major group.

Production technologies, consumption preferences and tax rates are based on national input-output tables (ABS 2019a). For database construction, we assume that the only spatial variation in technology is the occupational composition of labour inputs.

We use estimated transport costs to solve for trade flows between SA2s. As commuting flows are observed, we do not require commuting costs for database construction.[9] However, we use the same methods described here to construct changes in travel costs to characterise our transport project simulation. Given estimated trade costs, we solve the model's trade gravity equations for each good or service in turn. These solutions are constrained by the aggregate demand at each destination and the aggregate supply at each origin. This applies also to international imports and exports. In these cases, the transport costs are the sum of costs to/from the closest seaport (for goods) or airport (for services) plus a large cost to represent transport outside of Australia.

2.7.2 Transport costs

Transport costs for goods are based on road transport only (including ferry links where relevant, most notably between Tasmania and mainland Australia). Driving times are estimated using data from Open Streetmap (OSM) (OpenStreetMap contributors 2017) and shortest path algorithms. It is generally impossible to select any single point as representative of a large area—more so as many SA2s have non-convex geometries. We therefore begin by randomly selecting one origin/destination node for each populated Mesh Block[10] within each SA2. We compute shortest paths between all pairs of Mesh Blocks and define intra- and inter-SA2 times as logsum composites of all relevant individual path times. Our algorithm is coded in C++ and builds on the RoutingKit library of Dibbelt, Strasser, and Wagner (2016).

[9] The data are actually counts of workers by place of usual residence and place of work. They therefore include some phenomena outside of any usual definition of commuting. As an extreme example, some very distant OD pairs are associated with fly-in fly-out working arrangements.

[10] A Mesh Block is the smallest spatial unit in the ASGS, comparable to a US census tract.

To compute changes in travel times associated with our transport project simulation, we recomputed travel times for South-East Queensland only allowing for a second mode: walk-access public transport (PT). For this purpose, we constructed a three-layer network. Origin points are located in the first layer OSM-derived pedestrian network. PT entry nodes link to a middle layer with a headway-based representation of PT services, including waits and transfers between services.[11] The PT layer is linked to a separate pedestrian network permitting final egress to reach the destination node. Composite generalised travel times for SA2 OD pairs are then computed as logsum composites over the two modes for all Mesh Block-level OD pairs.

For trade in services—we assume trade is associated with business or private travel—we adjust the SA2 level matrix of road travel times to allow for the use of air services. Gate-to-gate air travel times between all major and regional airports are compiled manually from results obtained querying the commercial flight planning service webjet.com.au.

2.7.3 Tax rates and behavioural parameters

Tax rates and exponents in consumption and utility functions are calibrated from the database. For other parameters, we adopt values within ranges typically found in the literature.

The 2.5-yr discount factor is $\beta = 0.9$ and the inverse migration elasticity $\nu = 1.8$. This corresponds to a 4% discount rate and an elasticity between the values estimated in Choi (2022) and Caliendo, Opromolla, et al. (2021). For all occupations, we choose a commuting elasticity of $\varepsilon_k = 3.0$, as in Heblich, Redding, and D. M. Sturm (2020). For productivity spillovers, we assume a decay rate $\varrho = 0.33$ and an elasticity of 0.07, based on G. Ahlfeldt, Redding, and N. Sturm D. M. W. (2015). For simplicity, we assume the same elasticity (χ_i) for all sectors. We compute the effective job density considering white-collar workers only.

We assume the marginal elasticity of trade flows with respect to time is 1.25, around the middle of the range typically reported (Caliendo, Parro, et al. 2018).[12] Similarly, we assume a typical value of $\theta_i = 5$ applies in all sectors (*ibid.*). This implies an elasticity of 0.25 between the iceberg cost

[11]Transfers may include walks of up to ten minutes between stops, which are precomputed.

[12]Note that available estimates focus almost exclusively on traded goods, as most rely on international trade statistics.

[12]Note that literature estimates of these parameters relies on international (or in some cases US interstate) trade statistics. Consequently, they are generally limited to goods. Here we apply them to goods and services without distinction.

factors t_t^{irs} and transport times. When estimating the latter for goods, we add a fixed time penalty of 60 minutes to account for loading, unloading, etc.

To calibrate the model, we do not need the iceberg commuting costs $d_t krs$. However, to model effects of a transport project on commuting, we need the estimate changes in these costs. For this purpose, we use the ratio of stylised log sum measures

$$\dot{d}_t^{krs} = \frac{\log\left[0.8\exp\left(-0.1\, t_{\mathrm{Proj},t}^{\mathrm{Car},rs}\right) + 0.2\exp\left(-0.1\, t_{\mathrm{Proj},t}^{\mathrm{PT},rs}\right)\right]}{\log\left[0.8\exp\left(-0.1\, t_{\mathrm{Base},t}^{\mathrm{Car},rs}\right) + 0.2\exp\left(-0.1\, t_{\mathrm{Base},t}^{\mathrm{PT},rs}\right)\right]}, \tag{40}$$

where the t variables are times in minutes (estimated as above) with superscripts Car and PT referring to car and public transport modes respectively, and subscripts Proj and Base referring to project and base cases respectively. We do not differentiate these impacts by occupation (k).

2.8 Numerical solution

Our solution algorithm is based on the nested fixed point algorithm described by Caliendo, Dvorkin, and Parro (2019). Our main modifications to their algorithm are as follows:

- With the introducing of occupations, we lose one-to-one correspondence between labour and product markets. Consequently, we iterate on a vector of local occupational wage rates and fixed factor prices.
- Labour supply is computed by applying commuting probabilities to the resident workforce. Commuting probabilities are also used when computing average occupational wage rates (and thus income) by place of residence. These commuting probabilities are updated in the outer loop used to solve each period equilibrium, applying a continuation factor of 0.5 to achieve stability.
- We find it is more efficient to solve the input-output system using a further nested fixed point iteration rather than by matrix inversion. The matrix is very large, making inversion slow, while the previous solution for the absorption vector provides a good starting point for iterations.
- In both the outer period equilibrium loop (iterating on factor prices) and the outer-most loop (iterating on changes in utilities) we apply the alternate secant acceleration method (Ramière and Helfer 2015). This improves convergence speed and enhances stability relative a fixed continuation factor.

We prepare the model database using a series of Python scripts, making extensive use of the packages Pandas (McKinney et al. 2010) and Numpy (Harris et al. 2020). We implement the model and solution algorithm in C++, making extensive use of the Eigen template library for linear algebra (Guennebaud, Jacob, et al. 2010). We use the C++ cnpy library (Rogers 2018) to read and write Numpy npz files. Figures are produced using Python and Matplotlib (Hunter 2007) and QGIS (QGIS Development Team 2021).

2.9 Baseline economy

The baseline economy is defined in the simplest possible way. The database is constructed with a base year of 2016, as these are the most recent Census data yet available. We fix aggregate population and underlying productivity at the levels in the database. However, initially observed internal migration flows result in net changes in population. Thus, in the baseline simulation, the economy evolves gradually from its initial condition until steady-state levels are reached.

3 Results

3.1 Scenario

We simulate the introduction of a hypothetical 'fast express' service on SEQ's Gold Coast Line.[13] Our hypothetical service travels between Helensvale (Gold Coast) and Central (Brisbane) via Beenleigh, Dutton Park and Roma St stations. Helensvale to Central takes 28 minutes. Between these same points, the current express service takes 65 minutes but serves nine stations rather than three.

We lack access to a fully-fledged transport model that could account for the effects of the line on road and PT congestion. Consequently, we limit our consideration to: (i) direct PT travel time savings for any trips making use of the line; and (ii) reductions in generalised travel times, taking into account the relative importance of PT versus car travel (see equation 40).

We assume construction takes place over the first three 2.5-year periods of the simulation, and operations commence in the fourth, i.e. from 2026. Aggregate construction costs of A$960m are allocated equally across eight SA2s around stations and ramp up over time, doubling each year. Operating

[13]Note that an actual upgrade of this line is underway, but has the primary aim of doubling passenger capacities between Brisbane and Beenleigh and the Gold Coast. See https://www.tmr.qld.gov.au/projects/logan-and-gold-coast-faster-rail, accessed 29 March 2022.

and maintenance (O&M) costs are assumed to be A$30m p.a., but half of these costs are allocated to a major rail depot at Bowen Hills.

For simplicity, we assume that both the transport benefits and O&M costs will continue in perpetuity. We assume that construction is financed by borrowing on international markets, with each tranche of borrowing repaid as a perpetuity. To fund both debt repayments and O&M costs, income tax rates are increased uniformly.

3.2 Long run land use changes

Figure 1 show changes in the resident workforce in 2056 while figure 2 shows changes in jobs. We choose this year to illustrate the spatial impacts of the project because it allows enough time for most, although not all of the impacts to play out (as will be seen below). It is also a common practice for transport modelling of major projects to be conducted for a year two or three decades out.

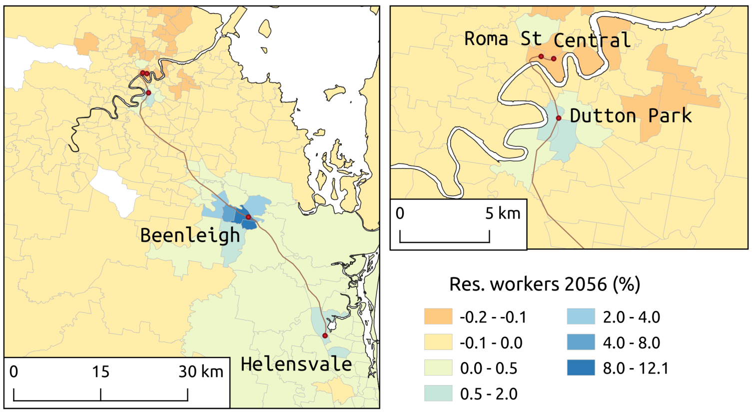

Figure 1: Change in resident workers vs base (2056)

The largest changes in population are concentrated around Beenleigh station. There are smaller gains around Helensvale station and diffused outwards around this southern half of the corridor. There are also small gains around Dutton Park, in Brisbane's inner south. As the national population is fixed, these gains are offset by slight population losses elsewhere, more but not exclusively so from within the SEQ region.

Proportionately, the strongest job gains are concentrated in two SA2s around Beenleigh station. Increases are smaller but more widely diffused around Dutton Park, Roma St and Central stations. Indeed, small job gains are widely spread north of the Brisbane River and in the inner southern suburbs, whereas there are slight job losses further south and in the western

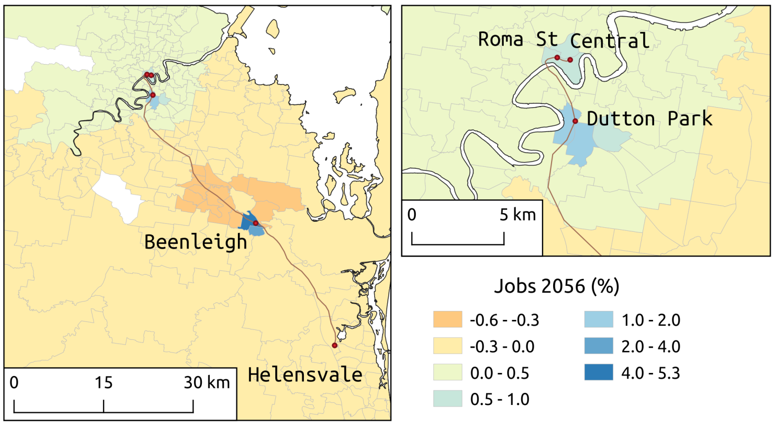

Figure 2: Change in jobs vs base (2056)

suburbs. This includes all SA2s in the southeast that see residential gains, except for the two in Beenleigh mentioned above.

3.3 Land use change dynamics

The movements of residents and jobs seen above occur only slowly. Figure 3 shows percentage changes in resident workers and in jobs by collar and overall in three SA2s around Beenleigh station (top panel) and for the whole of SEQ, the rest of Australia (RoA) and Australia (bottom panel). Note that in the last case, although the total workforce is fixed, the number in each occupation is not.

In the top panel, it is seen that the three SA2s begin to gain residents well before the fast express services begin in 2026. This reflects the combination of high moving costs with the importance of idiosyncratic factors in motivating relocations. If moving costs are high, moves will tend to be infrequent. If idiosyncratic factors and more generally, non-market factors (e.g. household formation or dissolution) are important most moves will not be primarily motivated by changes in transport accessibility or relative prices. However, when choosing a new residential location, households will consider both current and future accessibility and prices.

In the SA2s around the station, the effects of the project are largely played out by 2056. However, regional scale dynamics are slower. In the model, the speed of adjustment is significantly affected by differences in openness to migration. Most metropolitan suburbs are much more open than their parent metropolitan region considered as a whole.

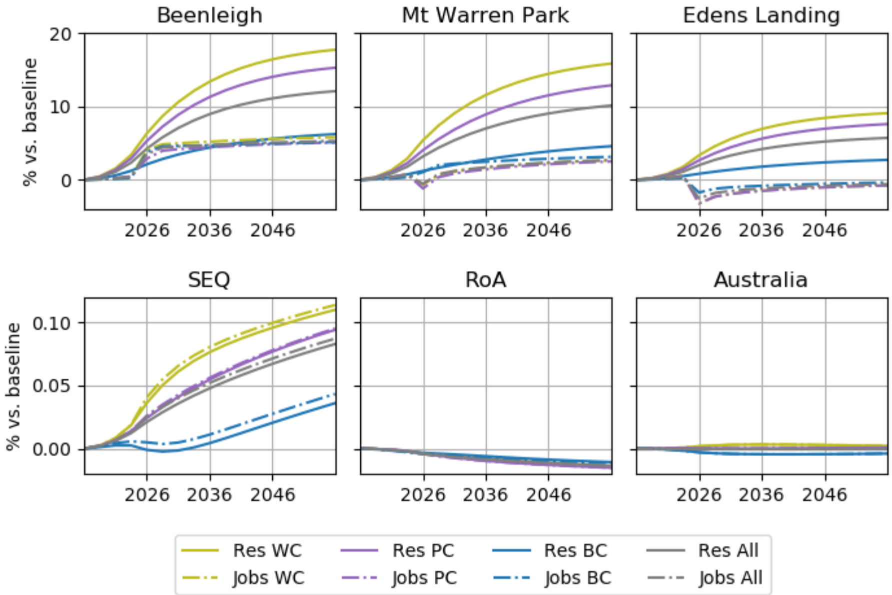

Figure 3: Changes in resident workers and jobs around Beenleigh station (upper panels) and at regional and national scale (lower panels).

3.4 Economic impacts

Figure 4 shows changes in real gross regional product (GRP) and GRP per job in the SEQ and RoA regions. For Australia, changes in gross domestic product (GDP) and changes in the nominal exchange rate are shown.[14] It will be noted that GRP per capita is a measure often used by policymakers. We prefer the measure of GRP per job for two reasons because it has a straightforward interpretation as a measure of single factor labour productivity, making it more interpretable in regions open to commuting.

GRP for the SEQ region increases as the project attracts more workers and jobs, particularly once it begins operating. At the beginning of the operational phase, there is a small jump in GRP per worker, as the project has some modest productivity benefits. In the longer run though, the dominant effect is the increasing abundance of labour relative to the fixed factors of production. Consequently, GRP per worker falls. The opposite occurs in the RoA region. At the national level, movements of jobs cancel out and we can observe a small increase in GDP as operations begin. Movements in the exchange rate reflect the schedule of foreign borrowing and repayments associated with project financing.

[14]The size of the Australian workforce is unchanged.

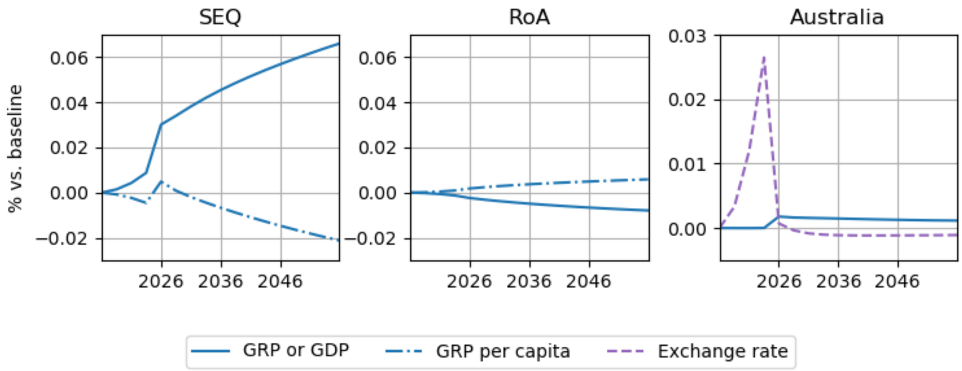

Figure 4: Changes in real GRP or GDP (blue solid lines), GRP per job (blue dash-dotted) or nominal exchange rate (orange dotted).

3.5 Welfare impacts

Figure 5 shows welfare gains for initial incumbents in occupations and places of residence. The top sub-figures show these results for three SA2s around Beenleigh station, where the largest benefits are seen. Notice that blue-collar occupations benefit significantly less than white- and pink-collar occupations. This reflects differences in the spatial distribution of employment opportunities. The fast express rail service improves accessibility to Brisbane's CBD and surrounding areas where white and pink-collar jobs are more highly concentrated. Nevertheless, workers in all occupations benefit significantly. The weighted mean consumption-equivalent welfare in Beenleigh and Mt Warren Park exceeds two percent.

Those who initially reside further from the fast express corridor naturally benefit less from its introduction. Welfare gains tend to decrease with distance from the corridor for two reasons. Firstly, the service may do little or nothing to directly improve accessibility from those areas to jobs and/or services. Secondly, while these residents have the option to relocate to locations where the accessibility gain is greater, these moves are costly.[15] On the other hand, our simulation assumes that all Australian households share the financial costs of the project in proportion to their pre-tax labour income. Thus, on average, benefits exceed costs for initial residents of SEQ, whereas costs exceed benefits for initial residents of RoA. Nationally, benefits exceed costs. These observations apply regardless of initial occupation.

Figure 6 shows regional welfare results in simulations with only (i) changes in travel costs and (ii) only investment and O&M expenditures and

[15]Empirically, migration costs depend on many factors, but these do correlate with distance. More specifically, transport costs affect migration (Morten and Oliveira 2018).

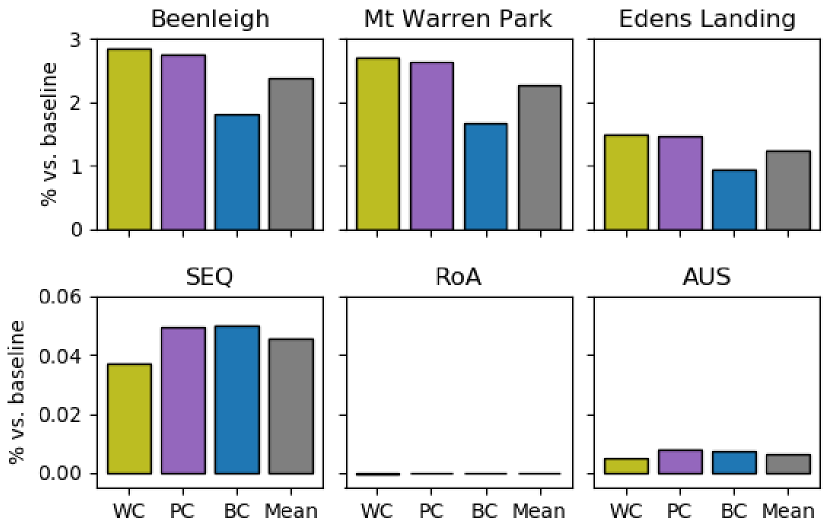

Figure 5: Welfare effects around Beenleigh station (upper panels) and at regional and national scale (lower panels). Initial headcounts used in weighted averages over occupations and/or spatial units.

financing/funding thereof. Looking across the three panels in this figure, the spatial concentration of benefits versus the broad socialisation of costs is evident. In the left panel, differences by occupation should be noted. With regard to project expenditures, blue-collar occupations benefit significantly from increased labour demand related to construction activities. In the middle panel, it should be noted that there are some benefits to residents outside of SEQ, but they are slightly less than the costs. These include intra-period general equilibrium effects and the option of migrating to locations where more direct benefits are obtained.

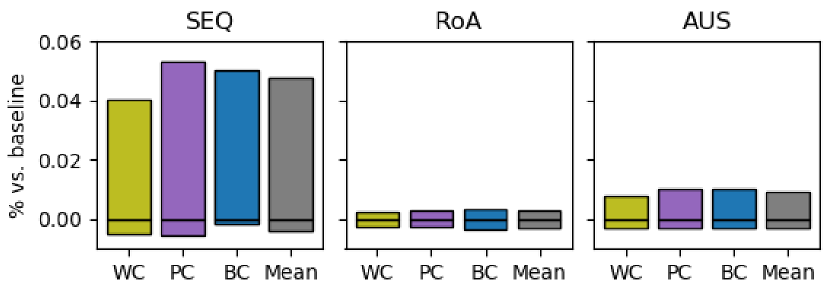

Figure 6: Decomposition of welfare effects into effects of operations (positive bars) and of construction and O&M (negative bars).

Finally, to emphasise the role of costly internal migration and occupational switching relative to other channels, figure 7 shows welfare effects in a model simulating a sequence of steady-state spatial equilibria (SSSE) without dynamic switching of either residence or occupation. The number of workers by residence and occupation is fixed at 2016 levels. Jobs can still shift but the long run labour supply in each location is much less elastic without the mechanism of dynamic choice.

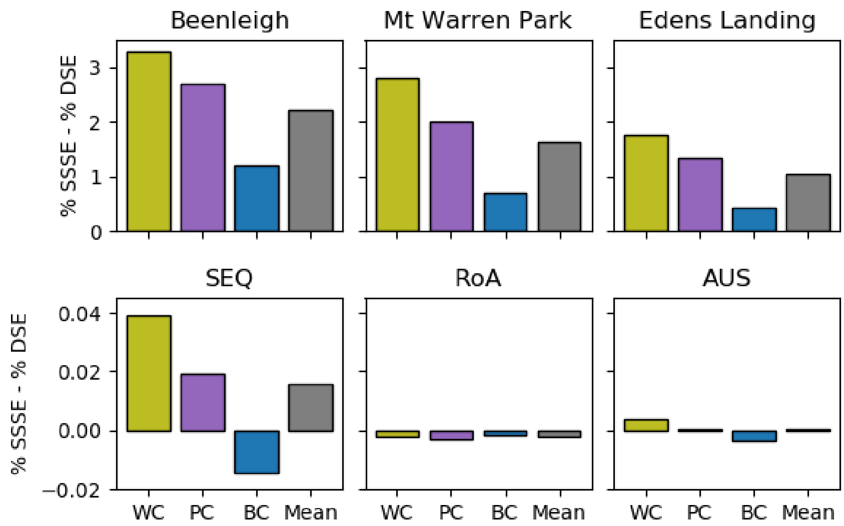

Figure 7: Difference in welfare changes by occupation and overall in a sequence of SSSE simulations relative to DSE simulations.

Differences are positive for locations and occupations benefiting most directly from the fast express services. That is, nearer stations and for white- and pink-collar occupations. The reason is that the dynamic equilibrium forces tend to erode the direct benefits. For instance, the price of housing services in Beenleigh rises substantially as the local population grows in the DSE simulation. Blue-collar wages tend to rise as more workers opt for white or pink-collar occupations. Conversely, welfare losses in the rest of Australia are larger without migration, because these residents benefit neither from the possibility of migrating to SEQ, nor from the general equilibrium effects of net out-migration in the DSE simulation, including lower prices of housing services and higher wage rates. A final point is that for this project in the DSE economy, switching costs are large enough and the discount rate high enough that aggregate welfare benefits differ little from those in the SSSE economy.

4 Discussion of results

We present a flexible DSE modelling framework, incorporating dynamics of internal migration and occupation choice and intra-period spatial linkages via commuting and trade flows. We calibrate this framework to Australian data, with a spatial, occupational and industry aggregation relevant to our simulation of a hypothetical fast express rail service in South-East Queensland.

The overall ratio of benefits to costs depends not only on the timing of flows of costs and benefits and the discount rate, but also on the speed and costs of economic adjustment in a spatial general equilibrium. Consistent with empirical findings in the literature, our illustrative simulation shows long-run impacts on the distributions of population and jobs. However, the slow and costly adjustment process has important implications for welfare analysis.

Distinguishing both multiple occupations and multiple industries allows representation of heterogeneity that may be important in the context of particular transport projects; for example, in relation to work commuting patterns. In our illustrative simulation, the fast express service provides relatively more benefits to white and pink-collar occupations than to blue-collar occupations. However, the latter benefit from increased labour demand in the construction phase.

The DSE framework allows spatially and temporally explicit representation of both construction and operational phases of a project, as well as its financing and funding. Features omitted from our simple illustrative simulation could easily be incorporated. For example, construction activities often involve significant negative local externalities (e.g. noise) and may temporarily disrupt parts of the transport network.

In presenting the results of our simulation, we focus heavily on the distribution of costs and benefits in space and between occupations. If adjustment is slow, incumbent residents in localities and occupations gaining most from accessibility improvements are likely to capture a large share of the benefits, even when the operational phase has a substantial lead time. This is without considering the additional capital gains of incumbent home owners, from which we abstract in our model.[16] Nevertheless, general equilibrium effects including the ability to migrate internally and to switch occupations are essential to the wider diffusion of benefits amongst the current population.

Even with our simple assumption of full employment, we find that the

[16] Recall that in our model, all households rent and these rents are redistributed in proportion to wage income. In reality, home owners who stay are insulated from these rising rents, while those who move elsewhere will realise a capital gain.

construction phase can have significant welfare impacts for incumbent blue-collar occupations. This further reinforces the benefits of modelling the construction and operational phases within the coherent DSE framework. The framework also captures the macroeconomic impacts associated with construction, operations, and funding. In a general equilibrium, construction and operations involve real resources, which cannot be used elsewhere in the economy. However, the costs to consumption will, realistically, be spread over many decades. While our simple example assumes that these costs are shared nationally, it would be straight-forward to model more realistic cases of state, or shared state and Commonwealth funding.

In the very long run, the impacts on land uses we simulate should be comparable to those that could be produced using simpler, comparative static spatial equilibrium models. However, the dynamics of land use changes in our framework are of interest for several reasons. Firstly, we can quantify the time required for adjustments; or more exactly, to achieve a given percentage of the steady-state changes. Secondly, the medium run impacts may be of independent policy interest. For example, we highlight population changes motivated by changes in accessibility some years in the future.

One limitation of the model as presented is that we omit investments in structures and other fixed capital. This issue is addressed in Kleinman, Liu, and Redding (2021), albeit at the larger spatial scale of US states. A more intractable problem is the 'lumpiness' of (re)developments when considered at relatively fine spatial scales. Realistically, local idiosyncratic factors strongly affect the extent and timing of actual changes. This is a challenging problem that is only beginning to be addressed by urban economists (see e.g. G. M. Ahlfeldt, Albers, and Behrens 2022).

5 Relevance to the practice of transport project appraisal

The simulation presented here illustrates the effects of given changes in transport costs. In practice, these inputs would usually be derived from a four-step strategic transport model. As in Le et al. (2021), this requires producing composite generalised costs from detailed skim matrices that summarise costs by mode and other factors, e.g. travel purpose, time-of-day and day-of-the-week. It may also be necessary to spatially aggregate costs. In our dynamic setting, we need transport cost inputs for each period of the DSE model simulation. This poses some further challenges.

Base case networks for strategic transport models in Australia do not usually extend beyond three to four decades. They are often defined each five years, to coincide with Census years. In project appraisals, a project case is typically compared to a base case in just one or two future periods. A practical dynamic LUTI framework must therefore rely on two strategies, the details of which we leave for future research. Firstly, transport cost changes must be extrapolated beyond the final transport simulation. Changes must eventually converge to zero so, to satisfy the terminal steady-state condition of the DSE model. Secondly, it may well be necessary to interpolate transport cost changes between a limited number of transport simulation years. In this case, a corresponding smoothing of land use changes may be necessary to avoid artefacts or convergence problems in the linked system. It should be noted that transport simulations for all years can be run in parallel, thus simulating many periods need not affect the overall wall-clock time.

There is also a geographic mismatch. Transport models typically cover a single city or broader metropolitan region. Our model covers the whole of Australia and any region of interest is open to migration. The 'external zones' in transport models may satisfactorily represent trips into or out of the modelled region. However, any congestion effects outside of the modelled region will not be modelled. This is important if there is (usually) net in-migration to the modelled region. Other things equal, this will slightly increase congestion in the modelled region but decrease congestion elsewhere. Omitting the latter effect will both exaggerate the regional population change and bias welfare results downwards. A possible solution would be to develop a reduced form model for external congestion effects as a function of external population. Alternatively, one might modify the DSE simulation to artificially fix the total regional population. While this is hard to justify from a theoretical perspective, it would be consistent with the accepted practice in transport project appraisal.

Standard practice in transport project appraisal is to model the operational effects of a project and its impacts on farebox revenues. Investment, operation and maintenance costs are prepared separately. If wider economic benefits of the operational phase are considered, these are typically estimated using simple spreadsheet' models. In a dynamic LUTI framework, all these components are inextricably linked. The necessity of financing and funding is of particular interest. In some project CBAs, a marginal cost of public funds is applied, which is most consistent with our approach (albeit that relaxing our fixed labour supply assumption would yield more plausible results). A fixed transport budget' assumption is less appealing. In our framework, this can only be represented by explicitly specifying where other transport investments are forgone and the effects of that on transport costs.

The greatest challenges relate to the reconciliation of 'bottom-up' estimation of user benefits produced by a transport model with the 'top-down' welfare metric of a DSE model, and the adoption of an explicitly dynamic paradigm for welfare analysis. In transport models, user benefits build up from the costs of individual linkages used in individual trips. Relaxing the assumption of fixed land uses should improve these estimates. As in Le et al. (2021), bottom-up estimates of user costs can be complemented with top-down estimates of wider economic benefits. However, given some fundamental and practically irreducible inconsistencies in the representations of transport demands[17], this 'add-on' approach has its own limitations. Thus, further research on the best way(s) to use the outputs of transport and DSE models is needed.

6 Conclusions and recommendations

This paper presents a flexible DSE model calibrated to Australian data and shows how it may be applied to the economic appraisal of a transport project. In our model, households make forward-looking dynamic choices of residence location and occupation, subject to switching costs. Within periods, local occupational labour markets are linked by costly commutes. Local markets for all goods and services other than housing are linked by trade flows, which are associated with freight or travel costs.

We present an illustrative simulation of a hypothetical fast express rail service between the Gold Coast and Brisbane. As well as modelling changes in transport costs associated with the operational phase, we explicitly represent the timing and location of construction, operating and maintenance activities. Project financing and funding are also explicitly accounted for. Our results highlight the importance of costly internal migration and occupational switching, in addition to interactions in labour and product markets in a dynamic spatial general equilibrium.

In our simulation, we take the changes in transport costs characterising the project's operational benefits as exogenous. Fundamentally though, both transport costs and land uses should be considered as endogenous variables of an urban and regional system. Building on earlier work in a comparative static setting, we suggest how a fully dynamic LUTI modelling system might be developed and outline some of the practical and theoretical challenges involved.

[17] For example, large-scale transport models typically distinguish multiple household types according to factors such as household family composition and car ownership.

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