Spatial economic dynamics and transport project appraisal

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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—many of them mega-projects[1] located in the largest state capitals—account for 73%. Given their immense cost, it is crucial that transport mega-projects yield commensurate economic benefits. Determining this, is the purpose of a project business case and, particularly, a cost benefit assessment (CBA). However, current Australian transport modelling practice generally gives limited consideration to a phenomenon that may significantly alter the net benefits of a major project: in the long term, changes in transport costs are likely to affect the spatial distribution of population and jobs within and between cities.

Governments regularly describe transport mega-projects as city-shaping'[2]. Made by politicians, such claims may well be exaggerated. Nevertheless, there is strong empirical evidence to support the general 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. Baum-Snow (2007), Costa et al. (2021), Duranton and Turner (2011, 2012), Iacono and Levinson (2016), Kasraian et al. (2016), Levinson (2008), Xie and Levinson (2010) and many other studies cited therein.

Recent national guidelines on 'land use benefits of transport initiatives' (Department of Infrastructure & Communications, 2021) take an ambivalent and arguably incoherent

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[1] These are commonly defined as projects costing over A$1b, but many 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.

approach to modelling land use impacts of transport projects, and their consequences for both transport and wider economic benefits. The potential relevance and significance of land use impacts is accepted. Yet 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. However, base case land use projections that run several decades into the future are a key input to modelling these conventional benefits. Not only are these inputs a product of land use modelling, but they typically attempt to account for land use impacts of previously committed transport projects.[3] Supporting conditions for land use change impacts are relevant considerations. However, these conditions are neither static nor entirely exogenous. Finally, transport models are not immune to substantial uncertainties. Consider, for example, how the current shift to frequent working from home affects estimation of commuting trip generation rates. We suggest that a better approach would be to accept that both endogeneities and uncertainties are pervasive, and to employ the best models of *both* land use and transport systems available to us.

This paper presents a novel approach to modelling land use impacts of transport projects. Urban and regional dynamic spatial general equilibrium (DSE[4]) 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, 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 et al. (2019, henceforth, CDP) who present a model with trade and intermediate uses in multiple sectors, Kleinman et al. (2021, henceforth, KLR) who add dynamics of investment and capital accumulation, and Warnes (2020) who develops an urban DSE model featuring commuting as well as intra-urban migration. A novel feature is that we incorporate capital adjustment costs to explain local variation in gross rates of return, away from steady-state. In KLR, intertemporally optimal consumption–savings decisions of ‘immobile capitalists’ resident in each region plays a similar role.

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 re-

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[3] Business cases for major projects are all to frequently completed *after* governments commit them (Terrill et al., 2020). Base case land use projections might therefore even reflect transport impacts of the very project being appraised. On the other hand, the transport demands implied by base case land use projections certainly be considered by proponents of new projects.

[4] There remains some variation in terminology used to refer to this class of models and no acronym is in wide use. For convenience, we adopt ‘DSE’ here; noting that ‘DSGE’ is already used in reference to macroeconomic dynamic stochastic general equilibrium models.

gions covering the rest of Australia. There are five production sectors, plus housing. We simulate the model for 160 2.5-year periods.[5]

Our simulation results show that the fast express service broadly favours additional population growth around suburban stations and additional jobs 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 teh 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. We note also that there are real anticipatory effects: some migration into areas seeing accessibility gains occurs prior to 2026.

In our illustrative simulation, transport cost changes are exogenous inputs to the DSE model. However, our initial argument was that both transport costs and land uses should be considered as 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. 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). We suggest that it is similarly feasible and practical to link a DSE model with a suitable transport model.

Model

Residents' choice sets include N regions of residence and work and J industries. In practice, a few regions do not permit residence, and not all industries operate in all regions. Residents may also choose not to work. For simplicity of notation, that choice is indicated by an industry index of zero.

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[5] 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.

The household's static problem

Given a sector of employment i, a place of residence r, and place of work q, a resident's indirect flow utility function is given by

$$\mathrm{u}_t^{irs} = \begin{cases} {\epsilon_1}_t^{irq} \dfrac{B_t^r \left(1 - {\tau_{\mathrm{h}}}_t^r\right) w_t^{irq} d_t^{irq}}{P_t^r} & 0 < i \leq J \\ \dfrac{B_t^r m_t^r}{P_t^r} & i = 0. \end{cases} \tag{1}$$

where ${\epsilon_1}_t^{irq}$ are Fréchet-distributed shocks associated with commuting choices, B_t^r measures residential amenities, ${\tau_{\mathrm{h}}}_t^r w_t^{irq}$ is after-tax wage income, $d_t^{irq} < 1$ reflect commuting costs measured in terms of utility, P_t^r is the local consumption price index, $i = 0$ refers to non-participation in the labour market and m_t^r is associated replacement wage. The replacement wage is financed by income from taxes, net of subsidies, and capital income remaining after investment expenses and net international outflows. In an extension to this basic model (to be described in the full paper) we also allow for a form of frictional unemployment.

The ideal consumption price index is:

$$P_t^r = \prod_{k=1}^{J} \left(\frac{\left(1 + {\tau_{\mathrm{c}}}_t^{kr}\right) p_t^{kr}}{\alpha_{\mathrm{c}}^{kr}} \right)^{\alpha_{\mathrm{c}}^{kr}} . \tag{2}$$

where ${\tau_{\mathrm{c}}}_t^{kr}$ are consumption tax rates and p_t^{kr} are local delivered (or shopped) prices of tradable goods and services and (non-tradable) housing services and α_{c}^{kr} are corresponding expenditure shares.

Within each period, all households allocate their income to tradable goods, services and housing to maximise their utility subject to their budget constraint. Having drawn their idiosyncratic shock, working households additionally choose the workplace that maximises their flow utility. The Fréchet shocks are i.i.d. with shape parameter ε^i. Lower values of ε^i imply more dispersed shocks, thus a larger role for idiosyncratic relative to deterministic factors in workplace choices.

The household's dynamic problem

An individual household incumbent in residence locality–sector pair (i, r) at time t has a lifetime utility given by

$$\mathrm{v}_t^{ir} = \max_{\{s\}_{q=1}^{N}} \{\mathrm{u}_t^{irq}\} + \max_{\{j,s\}_{j=0,s=1}^{J,N}} \left\{ \beta \, \mathbb{E} \left[v_{t+1}^{js} \right] + \zeta^{ir,js} + \nu {\epsilon_2}_t^{js} \right\}. \tag{3}$$

The first term is the household's maximised flow utility, as described above.[6]. The second term is the household's maximised discounted continuation value, net of both deterministic switching costs ($\zeta^{ir,js}$) and zero-mean, Gumbel-distributed idiosynratic shocks, i.i.d.

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[6] Note the slight abuse of notation here: for $j = 0$, no discrete choice is made.

in time (${\epsilon_2}_t^{js}$).The parameter ν controls the dispersion of idiosyncratic shocks. A higher value ν means that idiosyncratic factors play a larger role relative to flow utilities in future periods and switching costs. The weight placed on future relative to current utilities is determined by the period discount factor (β).

Assuming that the ${\epsilon_1}_t^{irq}$ are drawn and static choices made at the beginning of each period while the ${\epsilon_2}_t^{js}$ drawn and dynamic choices made at the end of the preceding period, these two problems are separable Warnes (2020). In the static problem, 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. Ahlfeldt et al., 2015). The dynamic model can then be solved with expected flow utilities for each residence and industry (including non-employment) taking the place of the actual flow utilities in regional DSE models (e.g. CDP, KLR). One then obtains

$$V_t^{ir} \equiv \mathbb{E}\left[\mathrm{v}_t^{ir}\right] = U_t^{ir} + \nu \log\left(\sum_{j=1}^{J}\sum_{s=1}^{N} \exp\left(\beta V_t^{js} + \zeta^{ir,js}\right)\right). \tag{4}$$

and

$$U_t^{ir} \equiv \mathbb{E}\left[\mathrm{u}_t^{irq}\right] = \frac{B_t^r \Omega_t^{ir}}{P_t^r}, \quad \Omega_t^{ir} \equiv \left(\sum_{s=1}^{N} E^{iq}\left(w_t^{iq} d_t^{irs}\right)^{\varepsilon^i}\right)^{1/\varepsilon^i}. \tag{5}$$

where E^{iq} are the means of the Fréchet shocks and Ω_t^{ir} can be interpreted as the inclusive value of employment options for workers in each industry, at each place of residence. The latter are thus closely related to but more general than employment accessibility measures that are often produced by transport models.

Static and dynamic allocations of labour

In each period, conditional on choosing industry i and residence r, the probability of commuting to workplace q in period t is given by

$$\psi_t^{ir,s} = \left(\frac{E^{iq} w_t^{is} d_t^{irq}}{\Omega_t^{ir}}\right)^{\varepsilon^i}. \tag{6}$$

These conditional probabilities can be readily computed from ABS Census counts of workers by place of usual residence and place of work. Note that these data actually measure phenomena broader than ‘commuting’ in the usual sense of regular (if not daily) travel between the home and workplace. As an extreme example, some very distant OD pairs are associated with fly-in fly-out working arrangements. For convenience though, we will refer to any travel arrangements that may connect a place of residence and work as commuting.

Between periods, the share of (i, r) households switching to (j, s) is

$$\mu_t^{ir,js} = \frac{\exp\left(\beta V_{t+1}^{js} - \zeta^{ir,js}\right)^{1/\nu}}{\sum_{k=1}^{J}\sum_{q=1}^{N} \exp\left(\beta V_{t+1}^{kq} - \zeta^{ir,kq}\right)^{1/\nu}}, \tag{7}$$

Thus, the evolution of the resident workforce evolves from one period to the next is given by

$$H_t^{js} = \sum_{i=1}^{J} \sum_{r=1}^{N} \mu_{t-1}^{ir,js} H_{t-1}^{ir}. \tag{8}$$

and jobs by place of work are given by

$$L_t^{is} = \sum_{r=1}^{N} \psi_t^{ir,s} H_t^{ir}. \tag{9}$$

These conditional probabilities can also be computed from Census data. The ABS Census data include the current place of usual residence, current industry of work and the place of usual residence five years prior. Additionally, the Australian Census Longitudinal Dataset permits construction of a matrix of transitions between industries. A complete matrix of transitions cannot be directly constructed from these datasets for confidentiality reasons. However, what we expect to be a fair approximation of that matrix can be imputed from the observed margins and various sub-totals using a bi-proportional scaling algorithm.

The fixed transition costs are not observable. Crucially though, they cancel out when the model is reformulated it in terms of proportional changes from one year to the next. This is the so-called 'dynamic exact-hat algebra' developed in CDP.[7] It results in the following equations for the evolution of transition probabilities and lifetime utilities:

$$\mu_{t+1}^{ir,js} = \frac{\mu_t^{ir,js} \left(\dot{v}_{t+2}^{js}\right)^{\beta/\nu}}{\sum_{k=1}^{J} \sum_{q=1}^{N} \mu_t^{ir,kq} \left(\dot{v}_{t+2}^{kq}\right)^{\beta/\nu}}, \tag{10}$$

and

$$\dot{v}_{t+1}^{ir} = \dot{u}_{t+1}^{ir} \left(\sum_{k=1}^{J} \sum_{q=1}^{N} \mu_t^{ir,kq} \left(\dot{v}_{t+2}^{kq}\right)^{\beta/\nu} \right)^{\nu} \tag{11}$$

where $\dot{v}_{t+1}^{js} \equiv \exp(V_{t+1}^{js} - V_t^{js})$ and $\dot{u}_{t+1}^{ir} \equiv \exp(U_{t+1}^{ir} - U_t^{ir})$.

Firms, product and housing markets

We leave a full specification of the production side of the economy and of trade in goods and services for the completed paper. These largely combine and extend the DSE models presented in CDP and KLR.

In brief, 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 housing sector is

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[7] The full dynamic hat algebra actually involves two steps of which we employ only the first: (1) construct equations in ratios of variables between periods; (2) construct equations in ratios of those ratios between policy and baseline simulations.

an exception, in that its outputs are not tradable and production of housing services not require labour inputs. Firms' levels of investment are determined taking into account capital adjustment costs. This is a significant departure from KLR, who suppose the existence in each region of 'immobile capitalists' who allocate gross capital rents between investment and consumption in that same region.

The goods and services consumed by both firms and households are composites of tradable intermediate varieties. For convenience, housing can be considered as a special case in which costs of trade between regions are infinite (KLR). 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 within Australia, but may be imported and exported internationally.

Taxation and the distribution of capital income

In addition to the tax on labour income mentioned above, we allow for various taxes and subsidies on intermediate and final uses of goods and services (e.g. the goods and services tax, excise taxes on fuel and alcohol), on factor inputs (e.g. payroll tax, council rates), on corporate income and on capital investments. If desired, this permits quite specific assumptions to be made regarding funding and financing of project construction and operation. Alternatively, funding by non-distortionary taxation can be modelled.

There is no explicit government sector in the model. Rather, public expenditures on e.g. healthcare and education are treated as if they were actually subsidised private expenditures. We assume that taxes, subsidies and transfers in the model exactly balance.

The external balance allows that the rest of the world has a claim to a share of net primary income. The remaining primary income and transfers are distributed to non-working households. Various assumptions may be made regarding the external balance. In the simplest case, the capital account must have a zero balance in all periods. Alternatively, distributions of capital income may be smoothed over time, allowing the capital account to vary and adjusting net foreign claims on primary income accordingly.

Calibration and solution of the model

Data sources for the transition and commuting matrices were referenced above. Additionally, to calibrate the model we use ABS Input-Output Tables and our own estimates of transport costs. Transport costs are estimated from Open Streetmap (OSM), public transport timetables and air travel times using shortest path algorithms. As very limited data are available on internal trade flows, these are estimated using a gravity procedure that balances supply and demand, accounting for our estimated trade costs.

The DSE model is implemented in C++ and solved using a nested fixed point algorithm. Matrix algebraic computations are implemented efficiently using the Eigen C++ template library (https://eigen.tuxfamily.org). Database preparation and post-processing of results is handled in Python scripts, making use of Pandas and Numpy packages. The C++

cnpy library (https://github.com/rogersce/cnpy) is used to read and write Numpy npz files. We solve the model using a nested fixed point algorithm based on CDP and KLR. Minor modifications are made to handle commuting. Additionally, we introduce an adaptive homotopy method that greatly improves convergence of the solution.

Results (preliminary and incomplete)

Scenario

We simulate the introduction of a hypothetical ‘fast express’ service on SEQ’s Gold Coast Line. 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 effects of the line on road and PT congestion. Consequently, in this paper 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 PT (versus car) mode shares and changes in those shares.

The model database is constructed to represent the economy in 2016. The first simulated period begins in mid 2019. The baseline economy is defined in the simplest possible way: aggregate population and underlying levels of productivity are fixed. Households gain full knowledge of the project at the beginning of period one, after having chosen their residence and industry for that period. The construction phase is 7.5 years, so the operating phase begins in 2026. Operations are represented by a permanent step changes in transport costs and a constant stream of operating and maintenance costs.

Long run spatial impacts

Figure 1 show changes in the resident workforce in 2056 while figure 2 shows changes in jobs. The largest changes in population are concentrated around Beenleigh station, while smaller gains are spread more widely in a corridor between Beenleigh and Helensvale, and in parts of inner Brisbane. Gains in jobs tend to be more concentrated than population gains. Some SA2s around Beenleigh station account for the largest job gains, while others see the largest job losses. There are also more widely diffused job gains around the city and inner suburban stations, with slight gains seen in many northern Brisbane suburbs. By contrast, excepting the areas already mentioned around stations, there are slight job losses in most western and southern suburbs, through to the Gold Coast.

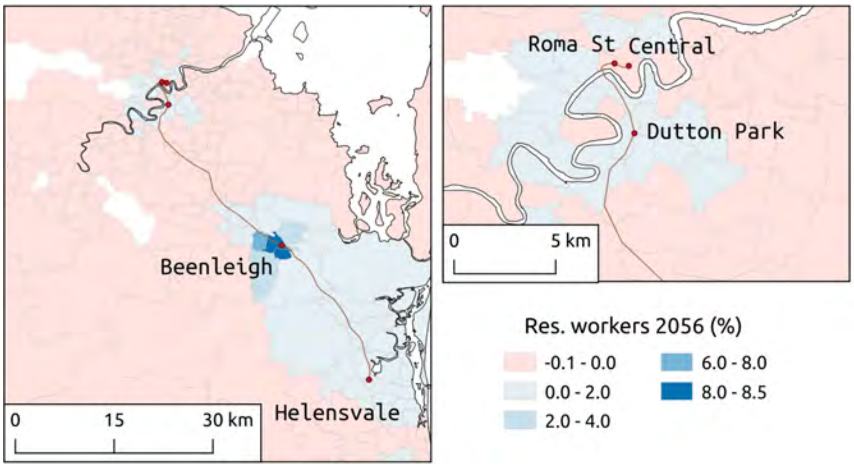

Figure 1: Change in resident workers vs base (2056)

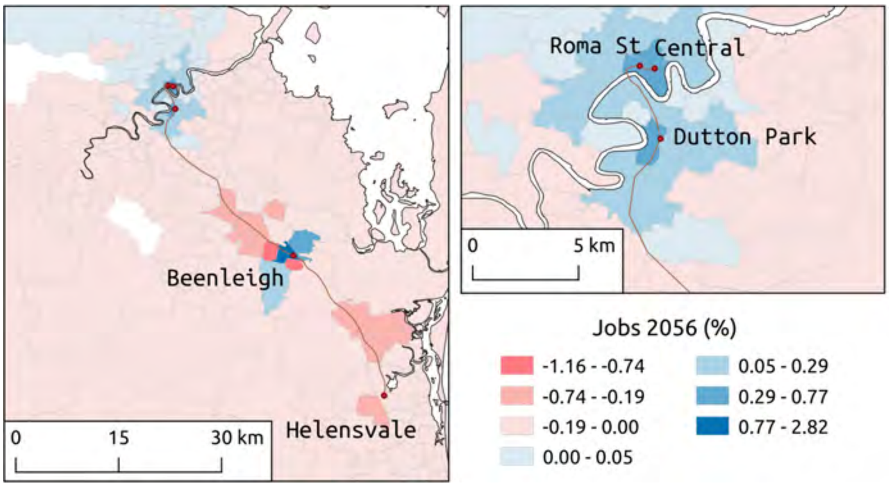

Figure 2: Change in jobs vs base (2056)

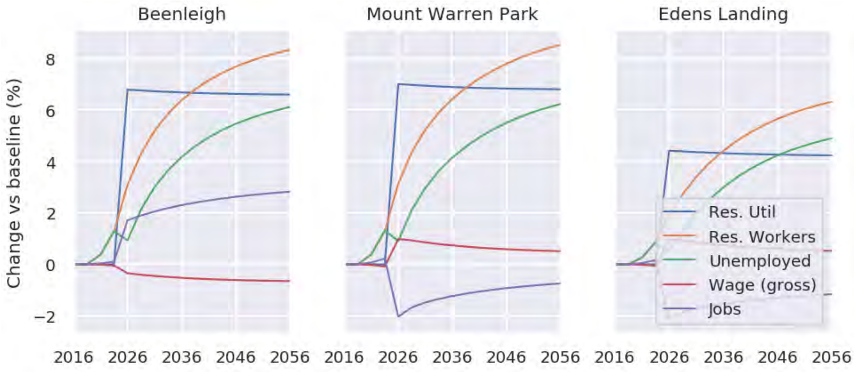

Figure 3: Time paths of resident flow utility, resident workers, unemployed residents, gross wage rate and jobs in key SA2s.

Dynamics

Figure 3 shows the dynamic responses of some key variables in three SA2s around Beenleigh station in which the project impacts are largest. Some gains in population are already apparent appear from 2021, prior to operation. There are large jumps in flow utility, unemployment numbers, and jobs in 2026 as operation begins. Although around half the residential adjustment is completed by 2031, there is some continued growth even beyond 2056 (i.e. after three decades of operation). Changes in job numbers are proportionately smaller than changes in population. Beenleigh and Eden's Landing are two of the SA2s around Beenleigh station in the project actually results in localised job losses 2.

Welfare impacts

Figure 4 shows the welfare impacts for incumbent resident workers. They are highly although not perfectly correlated with the long run population gains, with the largest gains being for persons currently residing near Beenleigh station, but smaller gains throughout Brisbane's outer suburbs and the Gold Coast and in many, but not all inner Brisbane suburbs.

In three key SA2s, figure 5 shows welfare gains by industry. The hatched bars show changes in the value function (equation 4) at time zero. Thus, they represent the gains realised by the initial incumbents in those industries and locations. The lighter bars show changes in the value function in the long-run steady-state, i.e. at a time by which the economy has fully adjusted to the project. Gains are substantially larger for incumbents in industries that are disproportionately concentrated in inner the city centre (e.g. Division M –Professional, Scientific and Technical Services) and thus are relatively more accessible by the fast express than jobs that are more widely dispersed (e.g. Division G –Retail Trade) or clustered in other locations (e.g. Division C –Manufacturing).

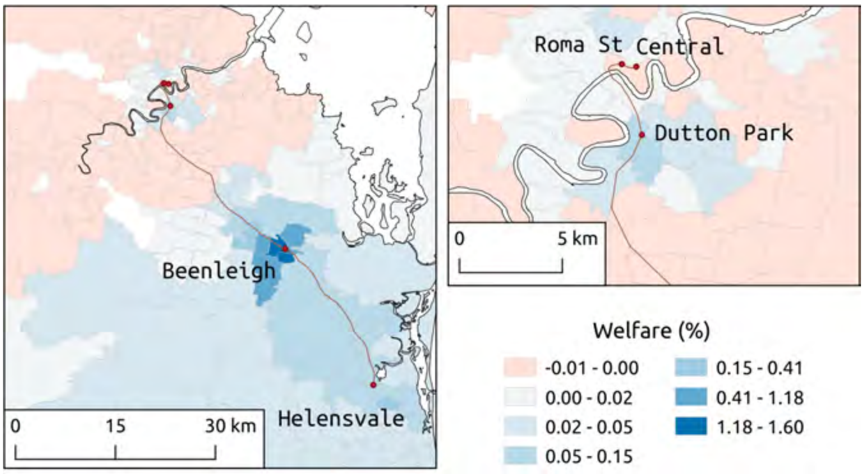

Figure 4: Change in lifetime utility of current residents

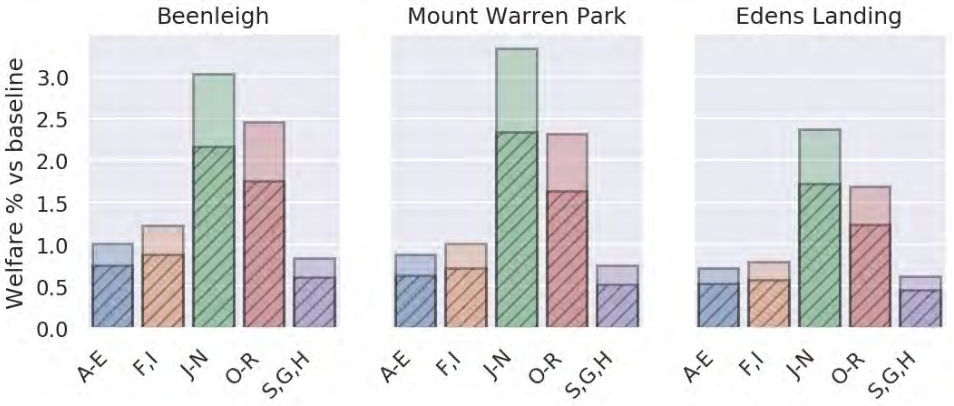

Figure 5: Present value of welfare gains for local incumbents by industry (hatched bars), and in the steady-state

Discussion

We simulate improvements to a radial rail corridor terminating in the CBD of a predominantly monocentric city. It is intuitive then that we see, broadly speaking, residential growth concentrated around suburban stations and jobs growth concentrated in the CBD. Weak residential growth around the Helensvale station partly reflects the much greater distance from Brisbane relative to Beenleigh. However, it may also reflect a limitation of our transport costs estimation. We considered only use of PT with pedestrian access, whereas ‘park-and-ride’ is an important mode for Brisbane and Gold Coast rail stations.

Land use dynamics are slow. Roughly half the impacts on local populations are seen within ten years of operation, but some adjustment continues beyond three decades. Some households move *prior* to the operational phase. This is not primarily due to construction activities but can be explained by the interaction of deterministic factors and idiosynratic moving costs. For example, changes in household composition often motivate a change to a dwelling that is larger, smaller or of a different type. If one is already determined to move house, the marginal costs of also changing location (here, moving between SA2s) is lower. In choosing the new location, one accounts for prospects well beyond the immediate future, since moving again will also be costly.

Welfare impacts are substantially affected by both project timings economic dynamics. As in a simple CBA, discounting reduces the present value of the net benefits accruing in the operational phase relative to the present value of construction costs, which are necessarily incurred earlier. Beyond this though, our DSE model captures real adjustment costs incurred by households (internally migrating and switching industries) and by firms and within the housing sector (adjusting fixed capital stocks) as land uses change. This has consequences for the distribution of costs and benefits. With sizeable adjustment costs, a substantial share of net benefits accrue to the current incumbents in particular locations and industries most directly affected by a project. Additionally, owners of land and fixed capital assets in these same areas may also capture a substantial share of benefits. With households being mobile between locations in our model, we cannot practically track ownership of assets in particular locations. In reality though, incumbent home owner-occupiers are likely to benefit via both channels.

Conclusions and recommendations

Major transport projects should be expected to affect the spatial distributions of population and economic activities. In modelling to support transport project appraisal, both transport costs and land uses should be considered endogenous variables. We present a DSE model of the Australian economy and demonstrate its application by modelling changes in transport costs representing a hypothetical fast express service in SEQ. Our model captures a multitude of direct and indirect economic effects flowing from lower costs of commuting and other travel, including shifts in population and jobs that unfold gradually, over several decades. Our illustrative simulation takes transport costs as exogenous. However, we suggest that it is desirable, feasible and practical to create a dynamic LUTI modelling system by linking a DSE model with a conventional four-step transport model.

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