Land use and transport modelling

PREPARED FOR: Department for Transport

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vlc

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INTRODUCTION

The UK Department for Transport ("DfT") commissioned Veitch Lister Consulting ("VLC") to deliver a technical note that documents our recent experience with land use and transport modelling.

The following four sections of this technical note are structured as follows:

- *Section 1.0* presents a framework for modelling land use and transport outcomes. This framework links a simplified spatial general equilibrium ("SGE") model to a conventional macroscopic ("strategic") transport model. These models run iteratively until an equilibrium is found in both.
- *Section 2.0* applies the modelling framework described in Section 1.0 to a an illustrative case study, namely Cross River rail ("CRR") in Brisbane. We investigate the sensitivity of travel demands to land use modelling assumptions, such as the elasticity of housing supply and agglomeration economies.
- *Section 3.0* discusses economic appraisal in the presence of land use change. We document why the conventional "rule-of-half" approximation that is commonly used in economic appraisal is invalid in the presence of land use change and discuss several potential alternative appraisal methodologies.
- *Section 4.0* outlines emerging frontiers in quantitative spatial modelling ("QSM"), such as spatial scope, dynamic models, heterogeneity, urban development, work from home, and vehicle ownership.

To finish, we note that this technical note is designed to be concise and remain at a high-level. For this reason, we refer to other relevant studies, rather than discussing their implications in detail.

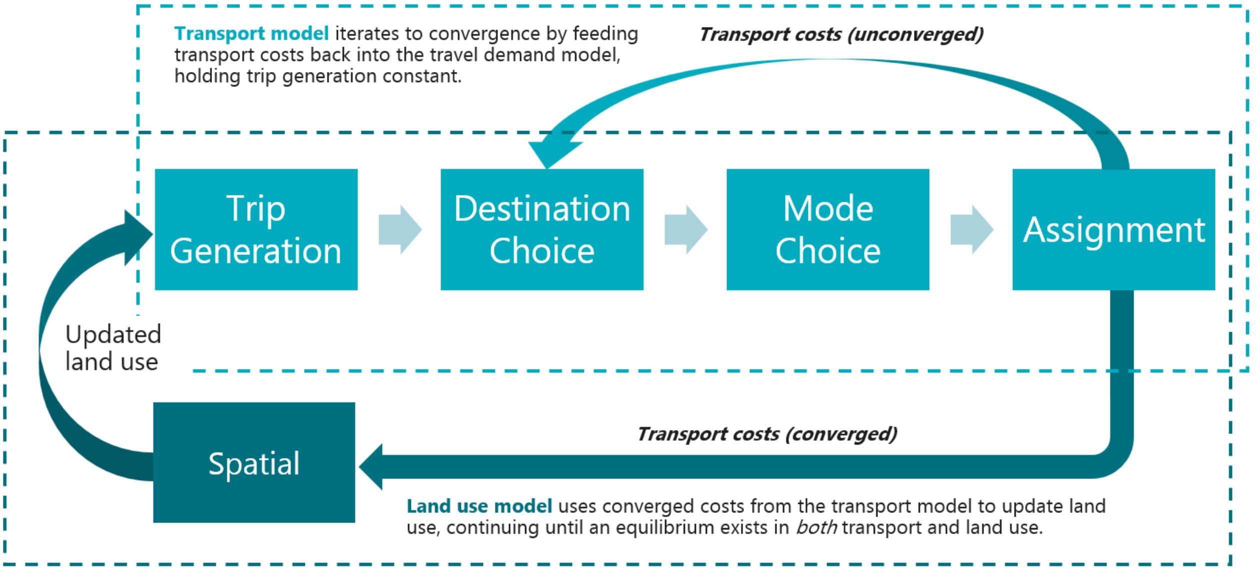
1.0 LAND USE AND TRANSPORT MODELLING

This section presents a framework for modelling land use and transport outcomes. The framework links a spatial general equilibrium model ("SGE") to a conventional macroscopic ("strategic") transport model, building on a class of quantitative spatial models ("QSM") that have become widely used in the economic literature over the last decade.

1.1 GENERAL MODELLING FRAMEWORK

VLC's land use model ("Spatial") is linked to a conventional four-step macroscopic ("strategic") transport model, per Figure 1-1. In this framework, information on transport costs and land use ("demographics") flows iteratively between the transport and land use models until both models are in equilibrium.

Figure 1-1 Linking land use and transport models



The modular structure of this modelling framework has three main advantages:

- First, convergence implies a joint equilibrium in both transport and land use decisions, whereby people have no incentive to change their choice of route, mode, destination, and/or location.
- Second, we can replicate the conventional "static" approach to modelling and appraisal by not calling the land use model – in which case land use is fixed, as we do below in in Section 2.0.
- Third, and more generally, the modular structure also allows the land use and transport models to be developed and operated separately, such that they can be swapped out when required or desired.

This modelling framework is thus best understood as a conventional strategic transport model that is connected to a land use model. Section 1.2 discusses the operation of the land use model in more detail, while the assumptions that underpin the transport model are discussed in Appendix A.

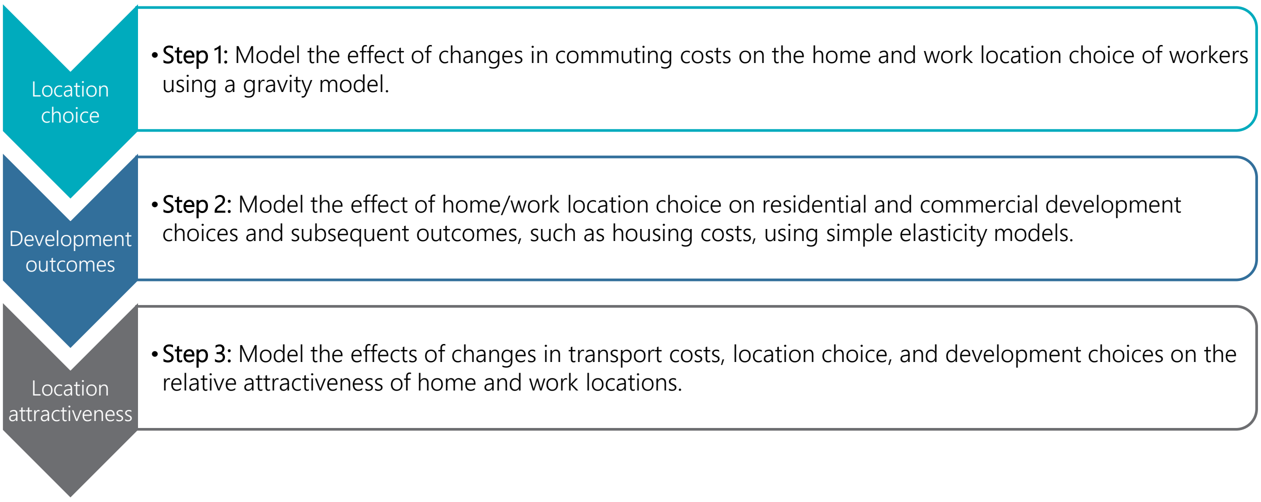
1.2 THE LAND USE MODEL

VLC's land use model, Spatial, draws on the Spatial General Equilibrium (SGE) model developed in Ahlfeldt et al (2015), where workers' choice of home and work location is endogenously determined with commuting costs, residential amenities (home location), and workplace productivity (work location).[1]

Since its publication, the model in Ahlfeldt et al (2015) has inspired many extensions and adaptations, such as Severen (2019).[2] Together, this body of economic literature has given rise to a new class of so-called Quantitative Spatial Models ("QSM"), which distinguish themselves from earlier CGE models primarily through their levels of spatial detail, e.g. number of zones. The spatial detail of QSM, in turn, allows them to generate richer and arguably more realistic insights into the effects of transport and land use policies.

In essence, VLC's land use model "Spatial" has three core elements, as summarised in Figure 1-2.

Figure 1-2 Three core elements of Spatial



First, Spatial models the effect of commuting costs on the home and work location choices of commuters, where commuting costs are sourced from a transport model. Importantly, we assume a "closed city", where the number of people and jobs is held constant over the model extent. Second, Spatial models the effect of changes in home and work location choice on population and employment density, which has flow on effects for development choices and associated outcomes, like housing costs. Third, we model the combined effects of changes in transport costs and development outcomes on the attractiveness of locations.

Spatial iterates through these three steps to find a partial equilibrium in land use that is conditional on commuting costs from the transport model. Once this partial equilibrium in land use is found, then Spatial updates the "demographic" inputs into the transport model, which can then be re-run to generate updated transport costs that then feed back into the next iteration of Spatial, per Figure 1-1. In updating the demographic inputs, Spatial holds the total number of people and jobs constant as well as the total number for households types and occupation/industry categories.

[1] Ahlfeldt, G. M., Redding, S. J., Sturm, D. M., & Wolf, N. (2015). The economics of density: Evidence from the Berlin Wall. Econometrica, 83(6), 2127-2189.

[2] Severen, C. (2019). Commuting, labor, and housing market effects of mass transportation: Welfare and identification. The Review of Economics and Statistics, 1-99.

1.3 MODEL PARAMETERS

Table 1-1 summarises the main parameters that are used in the land use model. In our experience, the following parameters are the most important:

- *The commuting cost semi-elasticity, ν,* controls the sensitivity of home/work location choice to transport costs, and varies significantly depending on the context and its estimation. As such, we would recommend carefully estimating this parameter using local data. In our experience, we have found it important to account for measurement error in travel times and transport costs.[3]
- *The price elasticities of housing costs and commercial floor space, $\beta_{1,r}$ and $\beta_{1,c}$,* control the extent to which changes in demand for locations flow through to prices. These elasticities reflect the combined effects of physical and regulatory constraints on development, which can vary over space and time. Ideally, these elasticities would be estimated using local data and linked to regulatory restrictiveness.
- *Worker homogeneity parameter, ε,* controls the degree of homogeneity in the population, which in turn defines the extent to which shocks, e.g. changes in transport costs due to a project, have similar effects on the population. Higher values of ε imply the population of workers is more homogenous such that shocks have more global (less localised) effects, and vice versa.

[3] Donovan, S., de Graaff, T., & de Groot, H. L. (2023). An inexact science: Accounting for measurement error and downward bias in mode and location choice models (No. TI 2023-011/VIII). Tinbergen Institute Discussion Paper.

Table 1-1: Land use model parameters

Parameter		Value	Explanation / Source
ν	Commuting cost semi-elasticity	Varies	Measures the effects of commuting costs on home/work location choice. The value of the parameter is not scale free, hence depends on how commuting costs are measured.
$\beta_{1,r}$	Price elasticity of housing w.r.t. population density	0.200	Values are sourced from the literature. We find similar elasticities in quite different contexts (e.g. France and New Zealand) and when estimated using different methodologies (e.g. rents versus prices).[4] A normal range for $\beta_{1,r}$ is 0.15-0.30, where lower values indicate housing prices are less sensitive to demand (i.e. supply is more responsive).
$\beta_{1,c}$	Price elasticity of commercial floor space w.r.t. employment density.	0.075	Values are sourced from the literature, although this is admittedly somewhat thinner than that for residential price elasticities.[5] A normal range for $\beta_{1,c}$ is 0.05-0.10.
ϕ_r	Spillovers from commercial rents to residential rents.	Varies	Assumed. This parameter controls the extent to which changes in commercial rents affect residential rents. That is, the relative extent to which policy allows the two markets to be integrated. We expect that the normal range for ϕ_r is 0.00-0.50, although this would ideally be estimated.
ϕ_c	Spillovers from residential rents to commercial rents.	Varies	Assumed. This parameter is analogous to that above but controls the extent to which changes in residential rents affect commercial rents. Normal range for ϕ_c is 0.00-0.50, although these effects may not be symmetric.
β_2	Housing cost share	0.25	Sourced from estimates reported in the literature.[6] Although there will be some cross-country variation, this variation is often relatively small. We would expect ranges for β_2 0.20—0.30; α_1 0.60—0.70; and α_2 0.05—0.15. In a model that allowed for heterogeneity in workers or industries, them β_2, α_1, and α_2 could vary between workers/industries. Compared to white-collar workers, we would expect blue-collar workers, for example, to have higher values for β_2, which implies that they will be more sensitive to changes in housing costs.
α_1	Labour cost share	0.65	
α_2	Floorspace cost share	0.10	
ε	Worker homogeneity	3.50	Values can be sourced from the literature or estimated.[7] A likely range is 2-7, with lower values indicating more heterogeneous populations.
ϵ_A	Agg. elasticity in production w.r.t employment density	0.03	Sourced from the literature.[8] Normal range for ϵ_A is 0.01—0.07.
ϵ_B	Agg. elasticity in consumption w.r.t population density	0.02	Sourced from the literature.[9] Normal range for ϵ_B is 0.01—0.03.
γ	Elasticity of home amenity, w.r.t. non-work transport costs.	-1.00	This parameter denotes the effect to which changes in non-work transport costs affects the relative attractiveness of locations. Estimated from data, with a 95% credibility interval of -0.50 to -1.50.

[4] See, e.g., Combes, P. P., Duranton, G., & Gobillon, L. (2019). The costs of agglomeration: House and land prices in French cities. The Review of Economic Studies, 86(4), 1556-1589 and Donovan, S., de Graaff, T., Grimes, A., de Groot, H. L., & Maré, D. C. (2022). Cities with forking paths? Agglomeration economies in New Zealand 1976–2018. Regional Science and Urban Economics, 95, 103799.

[5] Koster, H. R., Van Ommeren, J., & Rietveld, P. (2014). Agglomeration economies and productivity: A structural estimation approach using commercial rents. Economica, 81(321), 63-85.

[6] Donovan, S., de Graaff, T., Grimes, A., de Groot, H. L., & Maré, D. C. (2022). Cities with forking paths? Agglomeration economies in New Zealand 1976–2018. Regional Science and Urban Economics, 95, 103799.

[7] Koster, H. R., Tabuchi, T., & Thisse, J. F. (2022). To be connected or not to be connected? The role of long-haul economies. Journal of Economic Geography, 22(4), 711-753.

[8] Donovan, S., de Graaff, T., de Groot, H. L., & Koopmans, C. C. (2021). Unraveling urban advantages—A meta-analysis of agglomeration economies. Journal of Economic Surveys.

[9] Donovan, S., de Graaff, T., Grimes, A., de Groot, H. L., & Maré, D. C. (2022). Cities with forking paths? Agglomeration economies in New Zealand 1976–2018. Regional Science and Urban Economics, 95, 103799.

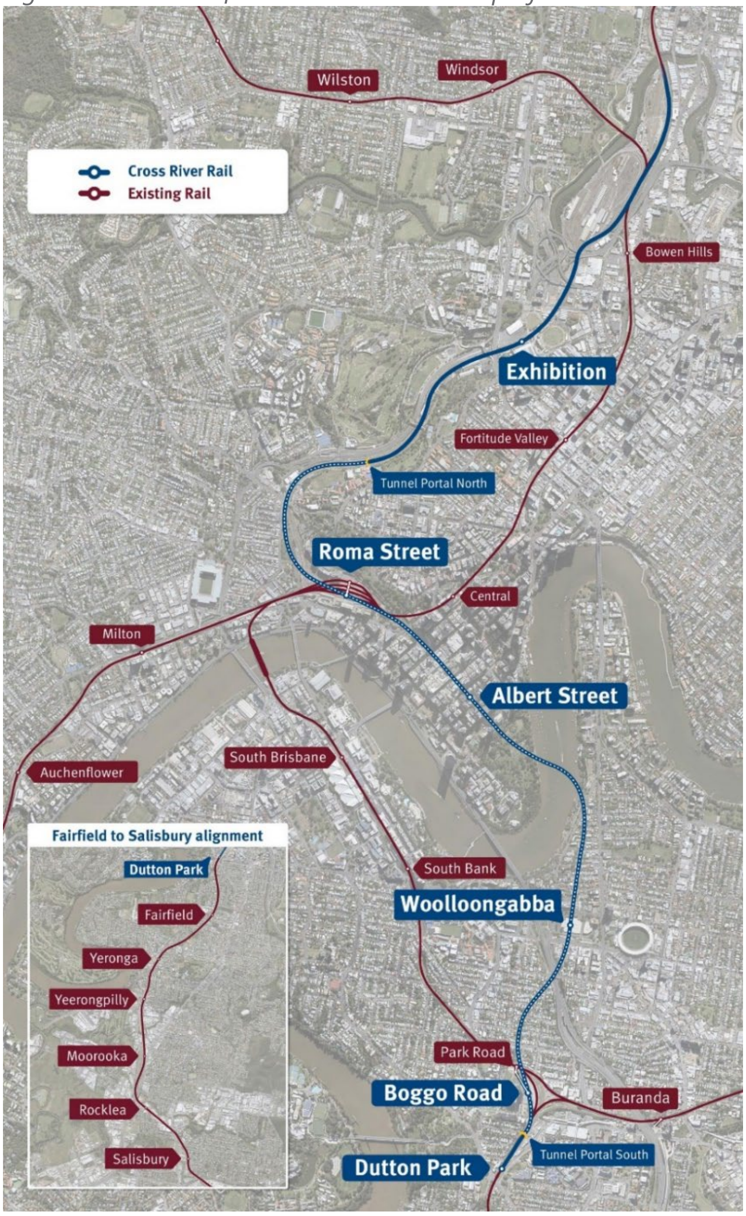
2.0 AN ILLUSTRATIVE CASE STUDY

This section applies the land use and transport modelling framework described in Section 1.0 to a case study. In doing so, we assess the sensitivity of travel demands to land use change and the sensitivity of land use change to underlying model assumptions.

2.1 PROJECT CONTEXT

Cross River Rail ("CRR", or "the project") is a major rail infrastructure project that is currently under construction in Brisbane, Queensland, Australia. CRR involves the construction of a new rail tunnel under the Brisbane River to connect to the city centre, as illustrated in blue in Figure 2-1.

Figure 2-1 Context for the Cross River Rail project



CRR seeks to meet growing travel demands, alleviate congestion, and improve connectivity across the wider South East Queensland region. Key components of the CRR project include:

- *Enables higher service frequencies.* CRR alleviates existing bottlenecks and provides additional capacity that will enable higher frequencies across the entire heavy rail network.
- *Additional stations.* CRR delivers new / upgraded stations at Albert Street, Exhibition, Woolloongabba, and Boggo Road as well as Pimpama, Hope Island and Merrimac (Gold Coast).

Through this combination of higher frequencies and additional stations, CRR serves to greatly increase the accessibility of the rail network, not just in Brisbane's city centre but also further afield.

2.2 MODELLED SCENARIOS

We model the effects of CRR in 2031 for the following three scenarios:

1. Base Case (no CRR)
2. Project Case (with CRR) but without land use change ("static land use")
3. Project Case (with CRR) and allowing for land use change ("dynamic land use")

We then undertook two sensitivity tests of Scenario 3, in which we changed key parameters in the land use model, specifically:

3.A *"Upzoning" land use around train stations.* In this sensitivity test, we consider the potential effects of upzoning. This involved reducing the price sensitivity of housing costs and commercial floor space in zones that were within 500m of train stations by 50%.

3.B *Allowing for agglomeration effects.* In this sensitivity test, we allowed for agglomeration effects in both production (affects wages) and consumption (affects home amenities). In the interests of simplicity and stability, we assume these agglomeration effects arise via changes in density.

Further details on key modelling assumptions are provided in Appendix A.

2.3 MAIN RESULTS

2.3.1 TRAVEL DEMANDS

Effects on travel demands are summarised in Figure 2-1. In Scenario 2, we see the effects of CRR on transport outcomes while holding land use fixed. In Scenario 3, we then allow for land use to change, before Scenarios 3A and 3B consider the effects of upzoning and agglomeration economies, respectively.

Table 2-1: Effects on travel demands

Outcome	Mode	Scenario				
		1	2	3	3A	3B
Daily trips	Rail	358,000	405,200	415,300	415,700	417,500
	Bus	573,000	542,700	547,700	547,800	549,000
	Active	4,340,500	4,334,100	4,346,900	4,347,200	4,350,100
	Car	12,112,600	12,103,100	12,076,600	12,076,000	12,070,800
% change	Rail	-	13%	16%	16%	17%
	Bus	-	-5%	-4%	-4%	-4%
	Active	-	0%	0%	0%	0%
	Car	-	0%	0%	0%	0%

We find that allowing for land use change and agglomeration economies has quite significant effects on travel demands: Whereas Scenario 2 suggests that the project would serve to increase daily rail boardings by approximately 13% when holding land use fixed, this increases to 17% in Scenario 3B. We also observe a small increase in active mode travel and a small reduction in bus travel when allowing for land use change. In contrast, upzoning appears to have relatively modest effects.

2.3.2 POPULATION AND EMPLOYMENT

To illustrate the effects on land use, Figure 2-2 and Figure 2-3 compare the % change in population and employment, respectively, at the zonal (SA2) level between Scenarios 1 and 3. That is, between the Base case and the Project case when we allow for land use change. In Figure 2-2, we observe the CRR leads to a decentralisation in population, with a shift to the periphery of the rail network in the north, west, and south of the region. Conversely, Figure 2-3 reveals that employment centralises into locations in the city centre that are now significantly more accessible by rail, with reductions elsewhere.

The magnitude of the change in employment appears to be relatively modest, although we note that the 2016 Census records approximately 122,000 people as being employed directly in the Brisbane city centre zone with close to 300,000 employed in other zones adjacent to the city centre. As such, even a 5-10% increase in employment in the wider city centre is significant as it implies that CRR might lead to an additional 15,000 to 30,000 jobs to locate in the wider Brisbane city centre.

Figure 2-2 Effects of CRR on population – Percentage change between Scenarios 1 and 3

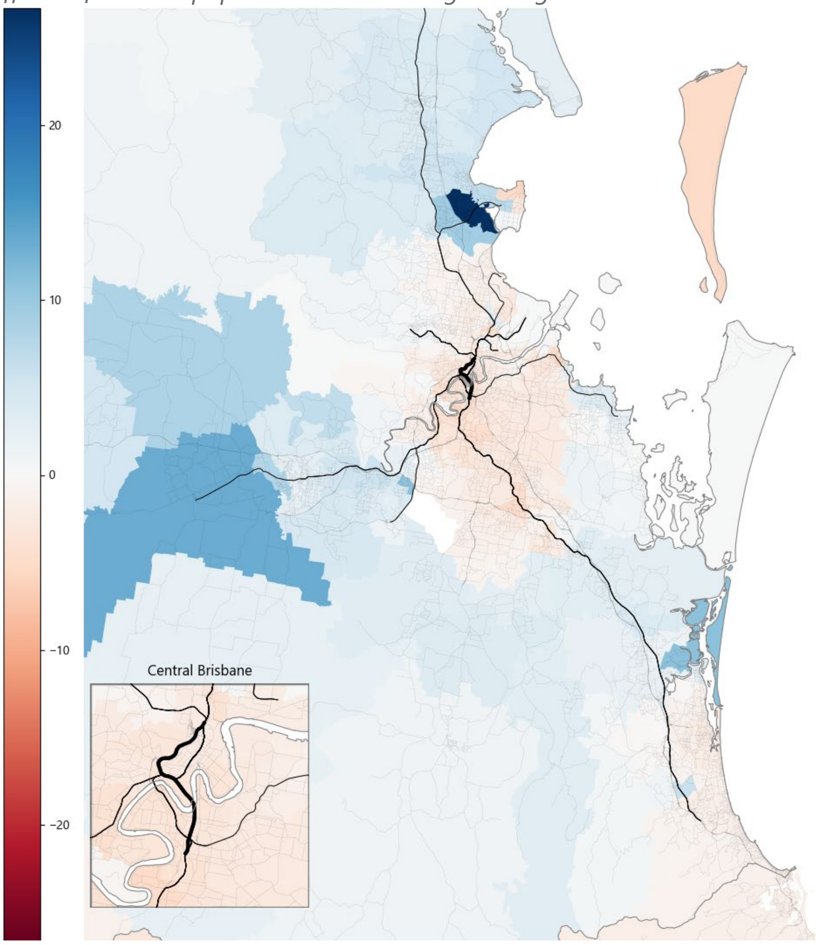
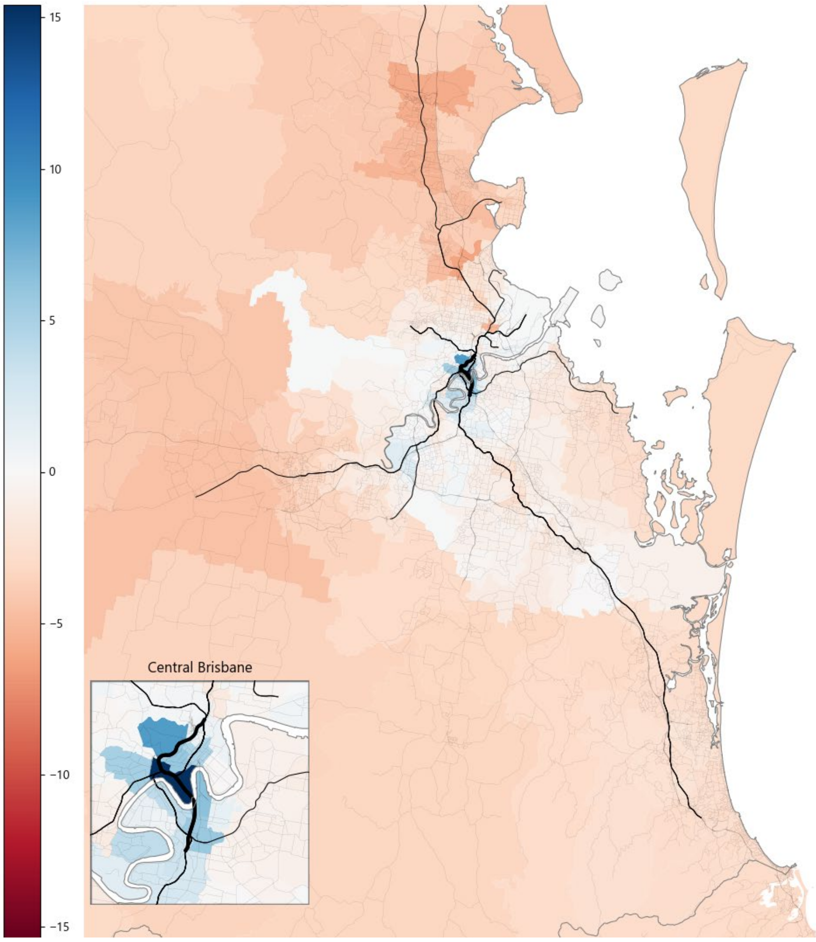


Figure 2-3 Effects of CRR on employment – Percentage change between Scenarios 1 and 3



2.3.3 ECONOMIC APPRAISAL

Table 2-2 summarises the economic appraisal of CRR in Scenarios 2 and 3, where we apply the conventional ATAP guidelines for economic appraisal, which are broadly analogous to the UK DfT's Transport Appraisal Guidance ("WebTAG") that is used in the UK. The results of the economic appraisal suggest that simply allowing for land use to change leads to a 22% increase in conventional economic benefits in Scenarios 3.

Table 2-2: Effects on economic benefits

Benefits	Scenario				% change vs S2		
	2	3	3A	3B	S3	S3A	S3B
User benefits	276	326	324	338	18%	17%	23%
Private vehicle user travel time savings	*55*	*60*	*59*	*62*	*11%*	*8%*	*13%*
Vehicle operating costs (VOC)	*70*	*96*	*95*	*103*	*38%*	*36%*	*47%*
Private vehicle user travel time reliability	*5*	*5*	*5*	*5*	*11%*	*8%*	*12%*
Public transport user travel time savings	*147*	*165*	*165*	*168*	*12%*	*12%*	*15%*
Safety related benefits	8	16	17	19	102%	111%	140%
Vehicular externalities	2	6	6	7	150%	157%	197%
Total economic benefits	**286**	**348**	**347**	**364**	**22%**	**21%**	**27%**

The relatively large increase in safety related benefits, vehicular externalities, and vehicle operating costs likely reflects how the CRR diverts car travel from congested urban road corridors to rail. In Scenario 3A benefits fall slightly, before increasing to 27% in Scenario 3B when agglomeration economies are allowed for.

2.3.4 MODEL CONVERGENCE

Neither ATAP (2022) nor WebTAG provide advice on convergence in linked land use and transport models. In lieu of formal guidance, we seek at least the same minimum level of convergence advised in UK DfT (2020) for demand/supply gap in strategic transport models (i.e., 0.1%).

This gap is calculated using the updated values for transport costs and land use (in this case population and employment) between iterations. We find it helpful to relate these values to transport cost and land use totals in the starting (base case) iteration using the following formula:

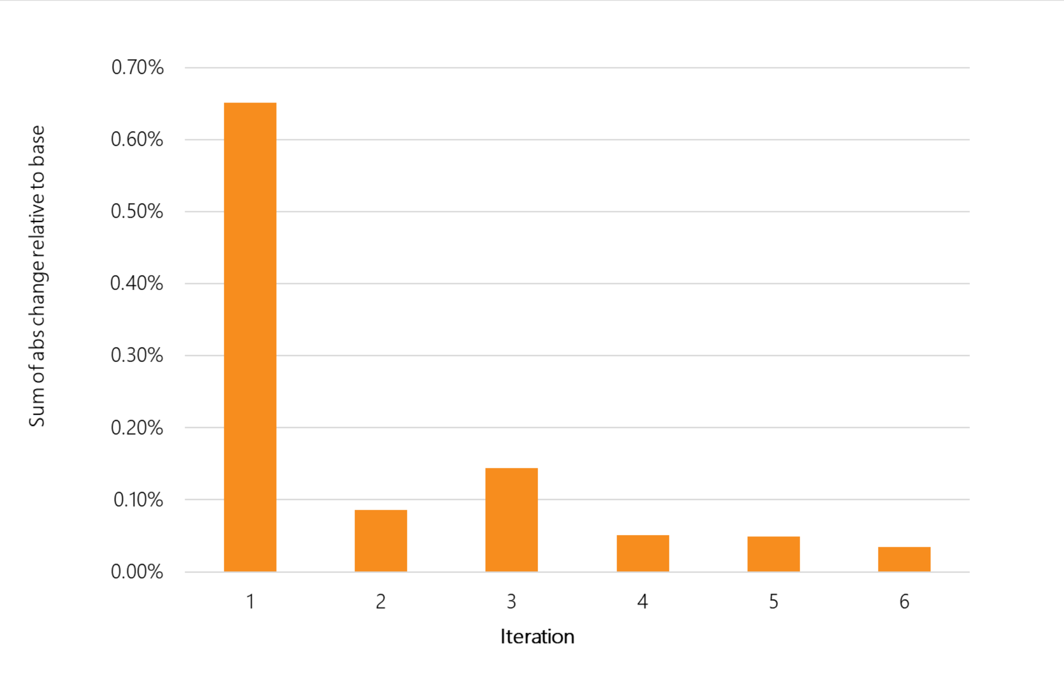
Equation 1

$$Gap_n^k = \frac{\sum_{ij}|k_n - k_b| - \sum_{ij}|k_{n-1} - k_b|}{\sum_{ij} k_b}$$

Where Gap_n^k denotes a standardized measure of convergence for criteria k on iteration n; k_n and k_b denote the metric of interest (e.g., transport costs or land use changes) on iteration n and in the Base, respectively; and ij refers to all zone-to-zone pairs. Differences are calculated as absolute differences.

Figure 2-4 illustrates the transport gap convergence for Scenario 3 over each iteration with the size of the transport cost gap falling below the conventional 0.1% minimum threshold from iteration 3 onwards.

Figure 2-4 Transport gap convergence for Scenario 3b plus upzoning and agglomeration



In previous testing, we have found that the speed of convergence of the integrated land use and transport modelling framework can be improved by averaging ("blending") the change in generalized costs between the current and previous iteration prior to updating the land use outcomes. This has the effect of smoothing the land use response to changes in transport costs, such that the model is less prone to "overshooting".

3.0 ECONOMIC APPRAISAL WITH LAND USE CHANGE

This section documents why we consider the conventional "rule-of-half" approximation used in the economic appraisal of transport projects to be invalid in the presence of land use change. We also outline several potential alternative appraisal methodologies that have been proposed in the literature and discuss our experience with their application.

3.1 APPRAISAL METHODOLOGIES

To estimate economic benefits in the presence of land use change, we have reviewed existing literature and guidance and identified the following four "high-level" methodologies:

1. *Fixed ("Static") land use.* Calculate benefits using the static land use project case scenario and base case scenario, as per standard consumer surplus / rule of half approach. This approach ignores (or places 'below the line') the effects of changes in land use on estimated economic benefits.
2. *Constrained demand curve.* Applies the static land use approach to modelling results from the dynamic land use project case scenario per ATAP (O8, 2021). The difference in benefits is assumed to represent benefits of dynamic land use.
3. *Flexible demand curve.* Calculates benefits using the method proposed in Parker (2013), which presents an adjusted rule of half that accounts for changes in consumer surplus that arise from both shifts in demand due to changes in land use and shifts in supply due to a project.[10]
4. *Logsum measure.* Calculates benefits by applying a logsum measure of consumer surplus to the discrete choice model of household location choice.[11]

The following sub-sections discuss each of these methodologies in turn.

3.1.1 STATIC AND CONSTRAINED DEMAND CURVES

Conventional methods for economic appraisal that are used when land use is fixed (or "static") are not appropriate when land use is allowed to change (or become "dynamic").

The reason for this is that when land use is static, the gross utility of a trip (the utility associated with getting to the destination, plus the utility of using a specific travel mode) does not vary between base and project scenarios. This means the standard consumer surplus ("rule of half") approach can reasonably assume that changes in utility are entirely driven by changes in the transport costs, or supply curve, that users face. Specifically, for a given origin-destination pair and mode, changes to infrastructure and/or services in the project case serves to shift the supply curve, while the demand curve is assumed to remain constant.

However, when land use is allowed to change, for example due to people changing where they live and work, then the gross utility from some trips will change. The findings presented previously in Section 2.3.1 for the case study of CRR show how allowing for land use change can produce materially different travel demands and transport costs than in a static land use case. For these reasons, we argue that under dynamic land use the transport demand curve shifts and the assumptions that underpin the conventional application of rule of

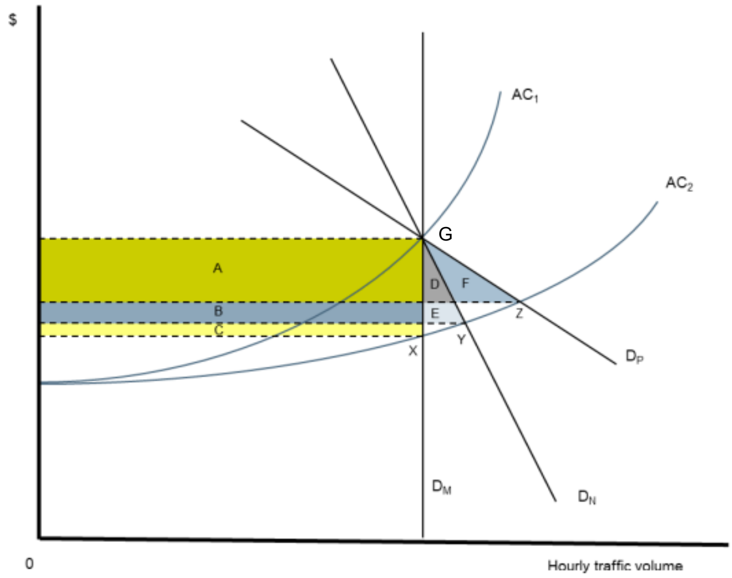
[10] Parker, C. (2013). Appraising transport strategies that induce land use changes (No. 2013/4). New Zealand Institute of Economic Research.
[11] De Jong, G., Daly, A., Pieters, M., & Van der Hoorn, T. (2007). The logsum as an evaluation measure: Review of the literature and new results. Transportation Research Part A: Policy and Practice, 41(9), 874-889.

half do not hold. Put another way, the rule of half does not provide a valid approximation of the benefits, or consumer surplus, which can be attributed to a transport project – alternative methods are needed.

Some guidance on economic appraisal in the presence of dynamic land use, such as ATAP (O8, 2021), make simplifying assumptions that seek to constrain the demand curve. This methodology assumes that, for all origin-destination-mode combinations, travel demand is unchanged between land use scenarios unless the transport costs change. In other words, travel demand can change in response to land-use-only change, but the gross utility of the traveller does not change in response to home or work relocation. This implies the demand curve swivels, or rotates on a point, but does not shift inwards or outwards in a more general sense.

Figure 3-1 illustrates this setting, where the dynamic land use demand curve DP has a different slope to static land use demand curve DN, but still assumes that DP must pass through point G in applying the rule of half in calculating user benefits (shaded area), not allowing a vertical or horizontal shift of the demand curve.

Figure 3-1 User benefit calculation with dynamic land use change (ATAP – O8, 2021)



This assumption is convenient because it enables the continued used of conventional methods in which the demand curve is assumed to be fixed. We suggest, however, it is only a valid approximation of the consumer surplus under very specific conditions, where generalised travel costs are the only relevant factor in the household utility function with respect to location choice. In practice, housing costs and a host of other factors may affect the attractiveness of locations and give rise to shifts in the demand curve that are not directly related to changes in generalised travel costs, including rents / land prices and a location's amenity – both of which will be endogenously determined with location choice. In such general situations, we do not expect the demand curve to always pass through point G in Figure 3-1, thereby invalidating this approach.

For these reasons, we suggest that neither Methodology 1 (static land use) nor Methodology 2 (constrained demand curve) are appropriate to economic appraisal in the presence of land use change.

3.1.2 FLEXIBLE DEMAND CURVE

An alternative methodology is developed in Parker (2013), where the calculation of consumer surplus in the presence of land use change allows the demand curve (D_1 in Figure 3-2) to shift from that under static land use (D_0 in Figure 3-2). This acknowledges that home or work relocation can change a travellers' gross utility of a given origin-destination-mode trip. User benefits are calculated as the shaded area, which includes a 'wedge' reflecting the higher willingness to pay for travel on some origin-destinations when people and jobs relocate. We note this methodology extends conventional approaches by treating land use as a related and imperfectly functioning secondary market to transport. In this case, the economic value of changes in the secondary market for land use can be approximated by analysing shifts in the primary demand curve.

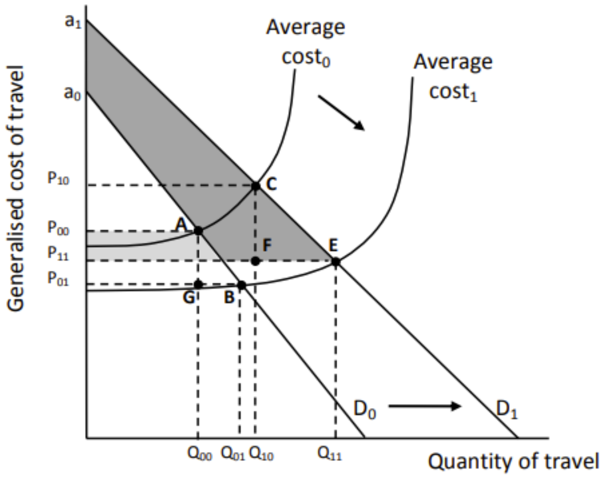
Parker (2013) considers two common functional forms for the demand curve: A linear form, or a log-linear form, which require different adjustments to the standard formula. Our testing of the demand curve shape using Australian data indicates a broadly linear functional form is appropriate. In the case of linear demand curves, user benefits can be calculated using the following adjusted consumer surplus formula:

Equation 2

$$\int_{P_{11}}^{a_1} D_1(P)dP - \int_{P_{00}}^{a_0} D_0(P)dP = \frac{1}{2}(P_{00} - P_{01})(Q_{01} + Q_{00}) + \frac{1}{2}\left[\frac{Q_{11}^2(P_{10} - P_{11})}{(Q_{11} - Q_{10})} - \frac{Q_{01}^2(P_{00} - P_{01})}{(Q_{01} - Q_{00})}\right]$$

Where the nomenclature is illustrated in Figure 3-2 and described in Table 3-1.

Figure 3-2 Consumer surplus approach with shifted (linear) demand curve due to land use change, example of an origin-destination where a project drives land use changes that result in more travel (Parker, 2013)



See Table 3-1 for description of notation.

Table 3-1: Adjusted consumer surplus approach notation (Parker, 2013)

		Transport network (latter subscript) P = transport cost; Q = trips	
		Project case	Base case
Demand source (first subscript)	Demand with dynamic land use (D_1)	P_{11}, Q_{11}	P_{10}, Q_{10}
	Demand with static land use (D_0)	P_{01}, Q_{01}	P_{00}, Q_{00}

3.1.3 LOGSUM MEASURE

Many location choice models, like Spatial, are underpinned by discrete choice models. Under certain assumptions, the results of these models can be used to estimate changes in consumer surplus directly using so-called "logsum" measures.[12] Formally, Ahlfeldt et al (2015) notes the probability that a worker chooses to live and work in locations i and j is given by the following formula:

Equation 3

$$\pi_{ij} = \frac{T_i E_j \left(d_{ij} q_i^{1-\beta}\right)^{-\varepsilon} \left(B_i w_j\right)^{\varepsilon}}{\sum_{r,s} T_r E_s \left(d_{rs} q_r^{1-\beta}\right)^{-\varepsilon} \left(B_r w_s\right)^{\varepsilon}}$$

Where d_{ij} denotes commuting costs between i and j, w_j denores wages paid in work location j; q_i denotes rents in home location i, and B_i denotes the level of residential amenities in home location i (NB: All other parameters in this equation remain invariant between scenarios and hence we do not discuss them here. Interested readers are, however, referred to Ahlfeldt et al (2015) for further details). In this setting, the estimate of the logsum utility arising in a specific scenario is given by:

Equation 4

$$L = \ln\left[\sum_{ij} T_i E_j \left(\frac{B_i w_j}{d_{ij} q_i^{1-\beta}}\right)^{\varepsilon}\right]$$

The difference in the logsum measure, L_{21} between base (1) and a project (2) scenarios is given by $L_{2,1} = L_2 - L_1$. Here, $L_{2,1}$ represents the net change in expected utility over all origin-destination pairs that is attributable to the project, considering the latter's affect on commuting costs, d_{ij}; wages, w_j; rents, q_i; and amenities, B_i (NB: In our model, changes in non-work transport costs are captured in B_i). To monetise the value of the change in welfare, we can multiply $L_{2,1}$ by the inverse of the marginal utility of income, $1/\lambda$.[13]

In theory, we expect logsum measures like this would generate results that are broadly equivalent to that discussed in Section 3.1.2, although they would help capture changes in utility arising from not just changes in supply but also shifts in demand. In practice, however, there are some challenges involved in implementing this method, especially for non-workers whose location choices are not currently modelled directly within Spatial (nor in Ahlfeldt, 2015) but are instead treated as adjuncts to the distribution of workers. For this reason, we see a need for further research into logsum measures, where a preliminary step is the development of an explicit discrete choice mode for the location choices of non-working households.

3.2 PRACTICAL CONSIDERATIONS

In theory, the methodologies presented in Sections 3.1.2 and 3.1.3 have the potential to support the economic appraisal of transport projects in the presence of land use change. In practice, however, several practical considerations still need to be overcome, as documented in Table 3-2.

We do not believe these considerations are likely to be insurmountable. The numerical instability of results from the flexible demand curve, for example, might be overcome through the development and application of methods to convert transport modelling outputs from real numbers into discrete positive integers.

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[12] de Jong, G., Daly, A., Pieters, M., & Van der Hoorn, T. (2007). The logsum as an evaluation measure: Review of the literature and new results. Transportation Research Part A: Policy and Practice, 41(9), 874-889.

[13] This assumes the marginal utility of income, λ, is constant over the range of incomes that experience changes. For details, see de Jong, G., Pieters, M., Daly, A., Graafland, I., Kroes, E., & Koopmans, C. C. (2005). Using the logsum as an evaluation measure: literature and case study.

Table 3-2: Practical considerations associated with the implementation of appraisal methodologies

Methodology	Practical considerations
Flexible demand curve	• Requires additional assumptions on the functional form of demand curve • Approximates the demand curve from transport and land use outcomes • Numerically unstable (e.g can involve division by small numbers)
Logsum measure	• Requires utility functions for the location choices of the whole population • Requires additional assumptions on the marginal utility of income • Replaces (rather than extends) conventional appraisal methods

4.0 EMERGING FRONTIERS

This section outlines several emerging frontiers in quantitative spatial modelling ("QSM"), such as spatial scope, dynamic models, heterogeneity, urban development, work from home, and vehicle ownership.

4.1 SPATIAL SCOPE

Whereas earlier QSMs focused on metropolitan areas – such as Berlin and Los Angeles in Ahlfeldt et al (2015) and Severen (2019), respectively – more recent research adopts a national spatial scope. Koster (2024), for example, specifies a QSM for the UK that is used to analyse the welfare effects of the Green Belt.[14]

In the context of a medium-sized country like the UK, we see little reason to constrain QSMs to a sub-national scope. Modelling location choices at a national level provides a convenient platform for capturing regional spillovers and interactions, for example domestic migration.

The spatial scope of land use models need not align with transport models—indeed, the former can easily extend beyond the latter. This simply requires that we make assumptions on transport costs in locations outside of the transport model, e.g. they are exogenous and/or specify aggregate speed flow curves.

4.2 DYNAMIC SGE MODELS

Recent economic research has advanced our understanding of dynamic SGE models. The theoretical foundations of these models are rich and robust, relying on discrete choice theory on the one hand, and general equilibrium and microeconomics on the other.

First developed to study trade and migration between regions, dynamic SGE models are increasingly being applied to urban economics and other fields. Davis, Fisher and Varacierto (2021), for example, model the dynamics of migration between US cities.[15] In a recent paper, Lennox (2023) specifies a dynamic QSM ("DSM") and uses it analyse the effects of transport projects.[16] The key advantage of these DSMs is they allow people and firms to anticipate policy changes, such as transport projects and congestion pricing, and respond pre-emptively and consistently, for example by adapting their location choices.

DSMs also open avenues for modelling the implications of housing tenure, e.g. owner-occupation vs. rental, over both space and time. The primary implication of housing tenure in the context of the DSM is that renters and owners are differently affected by current housing costs (i.e. market rents or owners' user costs), since owner-occupied housing is both a source of housing services and an economic asset.

4.3 HETEROGENEITY

Modern QSM will often allow for heterogeneity in workers and firms, for example by occupation and industry. The model deployed in Section 2.0, for example, does allow for differences between blue- and

[14] Koster, H. R. (2024). The Welfare Effects of Greenbelt Policy: Evidence from England. The Economic Journal, 134(657), 363-401.
[15] Davis, M. A., Fisher, J. D., & Veracierto, M. (2021). Migration and urban economic dynamics. Journal of Economic Dynamics and Control, 133, 104234.
[16] Lennox, J. (2023). Spatial economic dynamics in transport project appraisal. Economic Modelling, 127, 106464.

white-collar workers. In applying this model, we have allowed these workers to differ in their housing cost shares (β_2). Other recent studies, like Teulings et al (2018) allow workers to vary by education, thereby capturing potential differences in income and preferences.[17] Allowing for heterogeneity in workers and firms has been found to be useful for generating richer and more realistic insights into a range of policy relevant questions, for example into the distributional effects of transport and land use policies.

4.4 DEVELOPMENT MODELS

Although modern QSMs and DSMs have much more detailed zone structures than earlier CGE models, they nevertheless aggregate spatial economic outcomes, such as wages and rents, to a zonal level. Whereas such levels of spatial resolution are usually sufficient for transport policy purposes, it might not provide a sufficient level of detail to capture the effects of planning policies on urban development outcomes.

For this reason, there may be value in pairing QSMs and DSMs that operate at a zonal level with more detailed “development models” that operate at a parcel level. The latter would seek to provide detailed insights into the effects of planning policies and tax instruments, such as property taxes and development contributions, on the supply of residential and commercial development. This could in turn interact with the demand-side modelling capabilities of QSMs and DSMs.

Using microsimulations grounded in (random utility) microeconomic models, development models could predict, for example, the probabilities that individual sites are developed and to what level of intensity, considering site-specific factors such as planning policies, capital intensity, topography, and ownership as well as zone-specific factors such as prices and demand from the Spatial economic module.

4.5 WORK FROM HOME

Increased uptake of work from home (WFH) following the COVID pandemic also has implications for land use and transport modelling. We distinguish between two types of potential WFH arrangements:

- *People continue with normal employment arrangements*, which have a fixed place of work, but are not required to commute to work every day of the week. In this context, the decision facing workers is whether, on a given day, they commute to work and the main effect of WFH is to reduce commuting costs over the course of the working week compared to the base.
- *People change employment and engage in work that is more readily undertaken from home*, potentially all the time. In this context, the decision facing workers is whether they take such a job, possibly for less job security and/or less pay. As such the effect of WFH will be to reduce commuting costs over the longer term compared to the base.

Distinguishing between these two types of WFH responses is important. The first response, that is, whether to commute to work, seems better addressed in the transport model, potentially as a type of mode choice that may differ by the day of the week. The second response, in contrast, may be better addressed in the land use model as part of a wider model of occupational and industry choice, e.g. occupations and industries may differ in the propensity with which they support remote work arrangements.

[17] Teulings, C. N., Ossokina, I. V., & de Groot, H. L. (2018). Land use, worker heterogeneity and welfare benefits of public goods. Journal of Urban Economics, 103, 67-82.

Recent economic research has touched on these questions. Lennox (2020) uses a QSM to analyse the effects of WFH in Australia and find it leads to centralisation of employment and decentralisation of home locations.[18] Delventhal et al (2022) use a theoretical model to arrive at similar conclusions.[19]

4.6 VEHICLE OWNERSHIP

Integrated land use and transport models provide an opportunity to endogenise household vehicle ownership. Economic research by Mulalic et al (2018) analyses the effects of the Copenhagen metro and finds that people's location choices and vehicle ownership are related, with changes in one affecting the other.[20] Given the significant role of vehicle ownership in transport models, such effects seem likely to be relevant to policy. We also note that, in the context of an integrated land use and transport modelling framework, the updates to demographic inputs could readily be extended to allow for changes to vehicle ownership. We suggest that this would tend to increase the benefits of public and active transport projects.

[18] Lennox, J. (2020). More working from home will change the shape and size of cities. Centre of Policy Studies, Victoria University.

[19] Delventhal, M. J., Kwon, E., & Parkhomenko, A. (2022). JUE Insight: How do cities change when we work from home?. Journal of Urban Economics, 127, 103331.

[20] Mulalic, I., & Rouwendal, J. (2020). Does improving public transport decrease car ownership? Evidence from a residential sorting model for the Copenhagen metropolitan area. Regional Science and Urban Economics, 83, 103543.

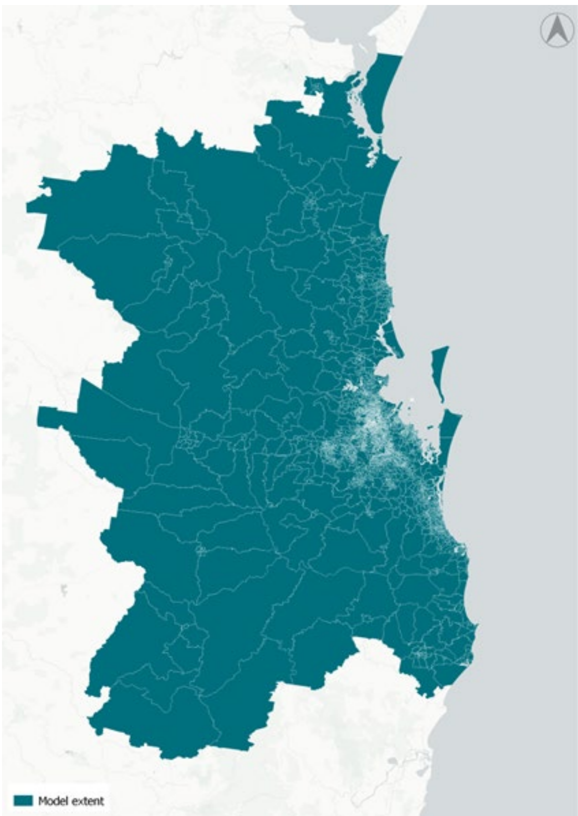
APPENDICES

APPENDIX A TRANSPORT MODELLING ASSUMPTIONS

A.1 TRANSPORT AND LAND USE ASSUMPTIONS

We use the Zenith Strategic Transport Model of South East Queensland (SEQ) ("the Zenith model"). The Zenith model is a multi-modal travel demand forecasting model in which travellers choose their destination, mode, and route depending on transport costs that are, in turn, influenced by transport network conditions. The Zenith model covers the entire SEQ region as well as Northern NSW and comprises of 4,507 travel zones. The granularity of zones increases in urban areas, such as the Brisbane Greater Capital City Statistical Area (Figure 6). The key attributes of the Zenith model are summarised in Table A. 1. In these applications, we run the Zenith model without PT crowding, which provides a better indication of overall latent demand.

Table A. 1 Attributes of the Zenith SEQ model

Model extent	Characteristic	Model treatment
	Modelled day types	Average Weekday Daily Traffic (AWDT). This measure reflects the daily traffic on an 'average weekday' in which schools, universities, and workplaces are all in operation. The model results are not representative of demands during weekends or 'non-average' weekdays (e.g. school holidays).
	Modelled time periods	AM Peak (7am to 9am), PM Peak (4pm to 6pm), and Off-peak (remainder)
	Modes	Walk/cycle, car, light and heavy goods vehicles, bus, train, ferry and light rail
	Freight	Generated by employment and industry in each zone and unique areas such as ports.
	Induced demand	Changes in destination, mode and route choice[21]

Underlying population, employment and enrolment projections for 2031 were based on the Queensland Government Statistician's Office 2018-edition population projections, Queensland Treasury Regional Employment Projections (2010-11 to 2040-41) 2015-edition, and Queensland Government Department of

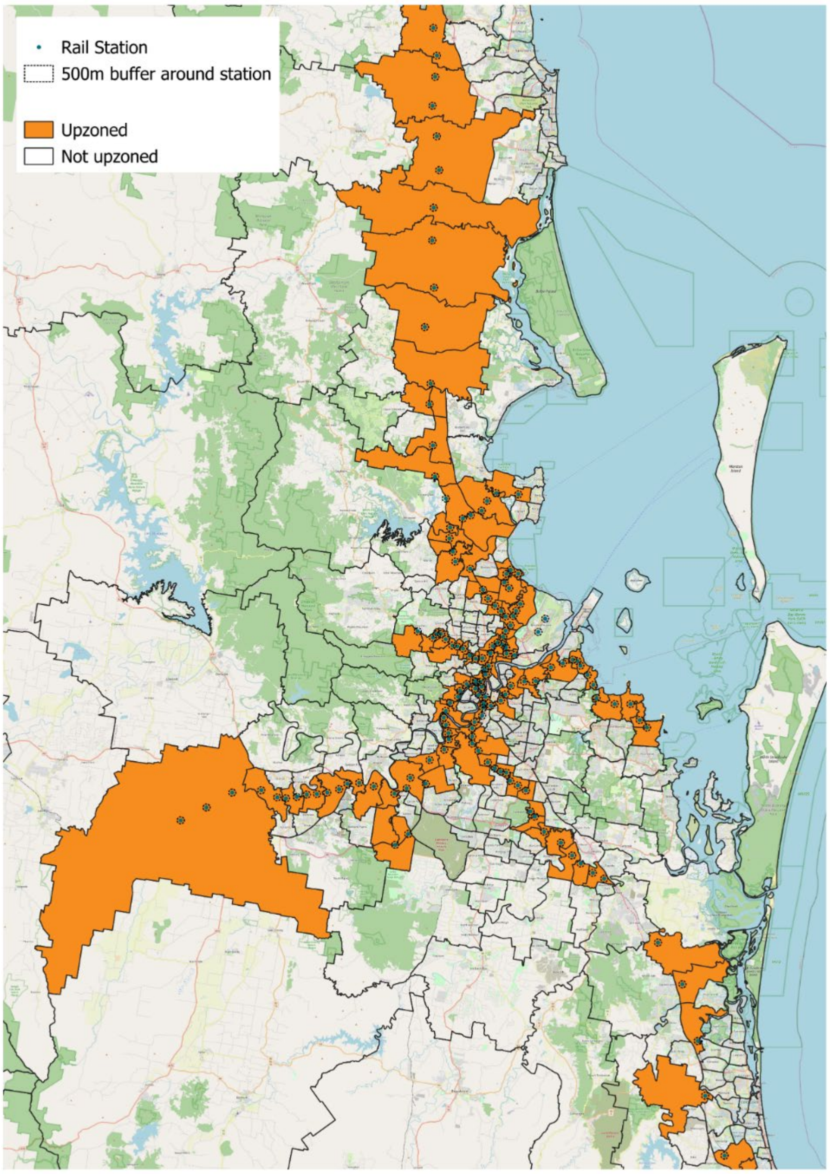
[21] Additional trips, changes in departure time and changes to land use because of the project have not been modelled.

Education data respectively. These projections are kept constant in the Base Case and Project Case when not modelling land use interaction but are allowed to vary in the "with land use modelling" scenario. In the "with land use modelling" Project Case scenario, the adjusted demographics obtained from the land use model are fed into the travel demand model at the beginning of each loop in the process (refer to Figure 1). The resulting transport costs from the transport model are subsequently fed into the land use model. This process was repeated across iterations.

A.2 SENSITIVITY TESTS

The upzoning sensitivity test assumed that the parameters for the price elasticities of residential and commercial floor space were halved in locations that were proximate to stations, as illustrated below.

Figure A. 1 Extent of upzoning around train stations



For the agglomeration economies sensitivity test, we assume agglomeration economies in production and consumption are 0.03 and 0.02, respectively.

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