



Integrating a computable general equilibrium model with the four-step framework

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Abstract

In the transport policy development process, four-step models are commonly used to estimate transport costs and flows based on representations of travel demands and networks. However, these models typically do not account for broader changes in the economy, which may significantly shift travel patterns in the case of larger transport projects. LUTI models are often applied to simulate changes in land-use patterns, and regional production function models have been used to estimate changes in production, but these methods rely on fixed economic parameters that may not capture the structural economic changes induced by large transport projects. In a separate line of development, computable general equilibrium (CGE) models, which simulate entire economies, have been increasingly applied to estimate the magnitude and distribution of economic impacts from transport improvements both spatially and through markets, including GDP and welfare. Some CGE models are linked with transport network models, but none incorporate detailed networks or generate a complete set of travel demands. This paper presents an integrated CGE and transport model that generates household and freight trips and simulates a detailed road network for different time periods, such that the transport submodel can be calibrated and run as a conventional transport model. The model provides a tool for the rapid strategic assessment of transport projects and policies when economic responses cannot be assumed to remain static. In the model, the CGE submodel simulates the behaviour of households and firms interacting in markets, where their behaviour takes trip costs into account. The model then generates trips as a derived demand from agent activities and assigns them to the road network according to user equilibrium, before feeding back trip costs to the CGE submodel. The model is then tested by simulating the WestConnex motorway project under construction in Sydney, with results showing significant increases in welfare for regions close to the improvements. Further development of the model is required to incorporate land-use and mode choice.

Keywords Four-step model · Computable general equilibrium model · Strategic transport planning · Transport appraisal · Transport demand

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Introduction

Since the advent of the four-step transport planning framework in the 1950s, there has been a drive to incorporate linkages between transport networks and the broader economy. The simplest four-step models assume that origin–destination (OD) demands for trip assignment remain static as transport networks change. For small changes, this assumption is most likely realistic, but larger ones can lead to fundamental shifts in economies and travel demand. For example, improvements in travel time savings may lead to migration, changes in employment patterns, increased attractiveness of shopping regions and so forth.

One method of incorporating OD demand elasticity is to update the generation, distribution and mode split steps using travel times from the assignment step. Land-use transport interaction (LUTI) models (Wegener 2004) achieve this by simulating changes in land-use patterns resulting from changes in travel times or accessibility indicators, and then recalculating travel demand from the new land-use patterns. While this can allow for the partial equilibration of land markets, there is still a reliance on fixed economic parameters for markets other than transport and land as well as of prices for all markets.

Unabated population growth, urbanisation, and increase in consumption leads to higher pressure on transport services. In addition, changes in the production structure and economic patterns also can influence transport demand over time. As a result, a new body of research focuses on transport modelling, defined by the creation of transport input–output (IO) models at the urban and regional scale, where authors used IO, gravity, and SCGE approaches to model inter-regional freight demand (Ivanova 2014).

Furthermore, there is increasing interest in understanding the welfare gains and losses that occur due to market imperfections and technological externalities, known as wider economic impacts (WEIs). These are not captured in the conventional consumer surplus metric used in cost benefit analyses, whether driven by classic four-step modelling structures or contemporary activity-based models.

Computable general equilibrium (CGE) models have been adapted in recent years to analyse the economic effects of transport and to quantify WEIs (Wangsnæs et al. 2016). A CGE model comprises a set of equilibrium equations representing supply and demand in every market in a given economy. These equations are built from fundamental microeconomic models of household (consumer) and firm (producer) behaviour, and thus a CGE model can provide a wide array of welfare, price and GDP outputs. They can also be used to identify the eventual distribution of impacts both spatially and through markets from the equilibration of the entire economy.

CGE models for transport are typically applied to estimate productivity gains from transport improvements, where transport costs determine regional demand and freight costs (Robson et al. 2018). Some formulations represent household travel demand as well, in which case transport costs influence household decisions on where to live, work and shop. In most models, transport costs are static parameters calculated by a transport model. There are a limited number of models with feedback between CGE and transport submodels such that the CGE model generates demand for the transport model, and the transport model generates transport costs for the CGE model (Shahraki and Bachmann 2018).

This type of CGE model with endogenous travel costs provides a basis to develop an extended four-step planning model that accounts for a fuller range of economic responses. Since CGE models are simulators of economies, it is possible to generate trips at a very fundamental level—as a *derived demand* from the activities of households and firms, whose behaviour is determined from utility and profit maximisation models.

A key advantage of linking these two models is that the one model could then be used to estimate both the magnitude and distribution of economic impacts, rather than relying on exogenous transport and economic models, generating a faster and richer set of outputs for strategic planning. The two-fold benefit towards both CGE and transport modelling practice would be that the transport model provides a complete endogenous response of transport costs for the CGE model, and the CGE model provides an endogenous economic response for the transport model.

However, very few, if any, existing CGE models with endogenous transport costs represent transport networks in such detail (Robson et al. 2018). For example (Broecker et al. 2004) modelled Socio-Economic and Spatial Impacts of EU Transport Policy using regional transport model linking to the CGE for the entire European Union. Transport models in the four-step framework are required to handle detailed networks, incorporate different time periods and generate a complete set of travel demands (including household and freight) to model transport costs accurately and at a resolution that permits the analysis of physical changes in infrastructure. Instead, existing CGE models with endogenous transport costs mostly represent sketch networks at the geographical scale of the CGE model, which are generally much coarser than the scale of travel zones in a four-step model, making the analysis of physical changes more difficult. Furthermore, existing models tend to only generate trips that are relevant to their model behaviour, e.g. commuting and shopping trips for an urban CGE model, or freight trips for a regional CGE model. Without representing the full set of travel demands, transport costs do not reflect those observed in the actual network.

This paper presents an integrated CGE and transport model that generates household and freight trips and simulates a detailed road network for different time periods. It is conceptually distinct from the model in Robson and Dixit (2017a) in that the transport submodel can be calibrated and run as a conventional transport model. Compared to that model, the transport submodel is new in that it is formulated separately, generates freight trips and allows for different geographies and time periods between the submodels. The CGE submodel in this paper is an extended version of the submodel in Robson and Dixit (2017a) by adding foreign market and government agents. Above all of these modifications, the Robson and Dixit work was based on a mixed complementarity formulation which was restricting the usage of the model for large scale problems. This is now relaxed in the proposed formulation of this paper.

This structure provides a universal platform for modelling the economy and transport networks together, which can be extended for land-use. The model is calibrated for the Sydney transport network and economy, and is tested by simulating the WestConnex motorway project currently under construction. At this stage, the model does not simulate mode choice, but can be implemented in future models. The proposed model paves the path of development of transport-based CGE models. This suggests a paradigm shift from CGE-based transport models, which are typically limited in terms of the level of complication that can be borrowed from a transport model such as number of zones/links of a realistic transport network or properties of the travel demand model. In introducing a transport-based CGE model, the transport aspects of the proposed formulation can be seen as an object-oriented structure which can be easily plugged in if needed without requiring many changes in the CGE model. As such, the proposed transport-based CGE model can better accommodate transport related policies to assess their effectiveness and robustness. Compared to the existing literature, Fig. 1 shows where the current paper stands in literature and the gap it fills with proposing transport-based CGE model.

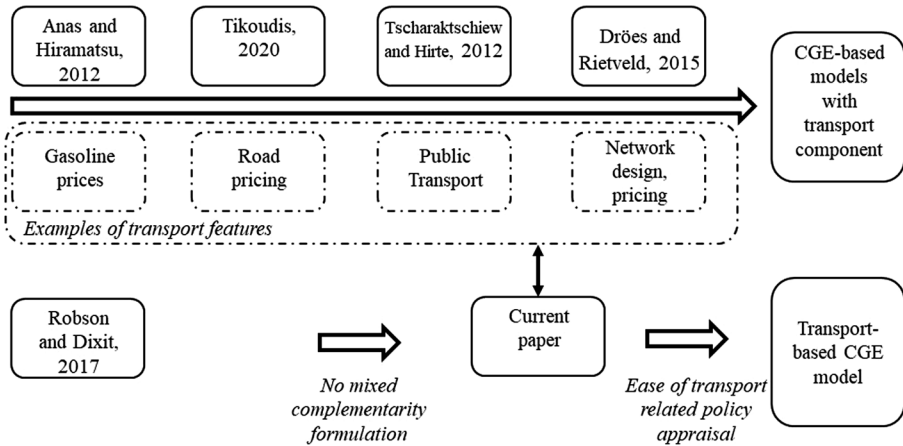


Fig. 1 A comparison between the existing literature and the current paper (Anas and Hiramatsu 2012; Tikoudis 2020; Tscharaktschiew and Hirte 2012; Dröes and Rietveld 2015)

In this paper, “**Literature review**” section reviews existing CGE models for transport. “**Methodology**” section develops the integrated model and discusses its assumptions. “**Calibration**” section describes data for the model calibration and details the calibration process. “**Application**” section describes the model application. “**Results and discussion**” section presents and discusses the results of the model application. “**Conclusion**” section concludes the paper.

Literature review

CGE models originate from the fields of IO modelling and general equilibrium theory. In the 1930s and 40s, Leontief (1941) developed a model to predict the required production levels of industries in an economy to meet a given final demand, based on a matrix of inter-industry commodity flows (an IO table). Johansen (1960) extended this model to include prices, which enabled behavioural models of households and firms to be introduced to the framework. Meanwhile, models of the economy were being developed in the field of general equilibrium theory, in particular the Arrow–Debreu model (1954), which the solution algorithms of Scarf (1973) made operational. However, the IO approach started to dominate by the 1980s due to its flexibility, and the terms and concepts of the two streams of literature effectively merged. CGE models from this era, such as ORANI (Dixon et al. 1982), became prominent for a range of high-level economic issues such as the setting of trade, tax and labour policies.

Many different fields have developed CGE models for transport with their own theory and practices. Robson et al. (2018) defined three main categories: urban CGE models, regional CGE models, and congestion and externality CGE models. Urban CGE models borrow more from the general equilibrium literature to simulate urban economies and incorporate urban-scale characteristics such as land-use and congestion. While early urban CGE models were theoretical in nature, more recent examples such as RELU-TRAN have been applied in real cities to study issues such as fuel prices, congestion tolling and job growth from infrastructure investment (Anas 2013). CGE models at the regional scale,

including spatial CGE models, spatial price equilibrium-based (SPE) CGE models and new economic geography-based (NEG) CGE models, focus more on the economic impacts of inter-regional freight costs. Spatial CGE models are spatial extensions of conventional CGE models, and thus draw significantly from the IO literature. These have been developed for a diversity of applications globally, including in Europe (Bröcker 1998), North America (Wittwer 2017) and Asia (Kim et al. 2004a). NEG-based CGE models simulate the formation of urban agglomerations through industries with imperfect competition and increasing returns to scale. Some of these have been developed extensively for transport appraisal, such as the RAEM (Ivanova et al. 2007) family of models used to estimate WELs in the Netherlands. Finally, congestion and externality CGE models are generally non-spatial, but represent travel commodities and household travel demand in detail to calculate congestion externalities. All of these fields have models that contain useful aspects for developing a CGE model that is aligned with the four-step transport planning model.

Shahraki and Bachmann (2018) identified three key aspects of CGE models that relate to transport networks: transport costs, network behaviour and trip generation. In spatial CGE models, transport costs are incorporated as a margin for industries to move goods from their region of production to their region of use. These margins are provided by an explicit transport industry in a full model. However, an alternative approach first proposed by Samuelson (1954) and popularised by the NEG literature (Fujita et al. 1999) is to assume that a portion of the transported good is used up in proportion to the freight cost (the ‘iceberg assumption’). While this method is computationally simpler, it can lead to serious misspecifications in production (Tavasszy et al. 2011). The transport costs themselves are normally outputs from an exogenous transport model without feedback from the CGE model.

In contrast, many urban and congestion/externality CGE models, as well as RAEM (Ivanova et al. 2007) and a few other regional models, represent household travel demand either as a commodity itself or derived from household activities. These trips can then be simulated in a transport model to determine demand for the travel commodity or underlying activity in the CGE model. Congestion and externality CGE models such as Mayeres’ model (2000) tend to have the most detailed household travel demands, but due to their non-spatial nature, cannot simulate congestion in transport networks other than through a single increasing function relating travel demands to costs. On the other hand, urban CGE models such as RELU-TRAN (Anas and Liu 2007) and Rutherford and van Nieuwkoop’s model (2011) are linked with traffic assignment models as they generate OD demands from household activities. In an iteration of RELU-TRAN, a CGE submodel is run to generate OD demands, which are then fed into a traffic assignment submodel to determine routing and travel costs for the next iteration of the CGE submodel. Rutherford and van Nieuwkoop’s model instead combines the CGE and traffic assignment submodels into a single mathematical problem. To do this, the model uses a multi-commodity flow (MCF) form of user equilibrium (UE) assignment, which can be expressed as a mixed complementarity problem and combined with the CGE submodel equations. There are also equivalent integrated CGE and transport models for freight trip generation in the SPE CGE literature such as Friesz et al.’s model (1994), but few, if any, models generate both household and freight trips.

Models such as RELU-TRAN (Anas and Liu 2007) and Rutherford and van Nieuwkoop’s model (2011) resemble the four-step framework, but lack detailed transport networks or the generation of a complete set of trips. Robson and Dixit’s model (2017a), based on Rutherford and van Nieuwkoop’s structure, generates a fuller set of trips (commuting, shopping and leisure), but only at the daily level. Another set of trips to consider is

business trips, which is included in the RAEM model (Oosterhaven et al. 2001; Knaap and Oosterhaven 2011).

In summary, existing CGE models developed for transport applications have generally retained an economic focus, with a gradual relaxation of fixed transport cost assumptions through incorporating link congestion functions or separate transport network models. However, in almost all these cases, the transport models are somewhat additional to the CGE models, and thus lack emphasis on the necessary features required in transport modelling. These include separate geographies between the CGE and transport models to enable the simulation of detailed transport networks, rather than sketch networks, a full set of household and freight trip purposes, and the incorporation of different time periods for modelling the road network.

The proposed framework can easily incorporate population and employment modifications. The size and distribution of the population is captured in the model through household agents, where each household represents the people living in each combination of residence location, workplace location and employment industry. The size of each household agent is driven by their endowments of time and capital, with each household's endowment being the sum of the endowments of the represented population. Population forecasts can therefore be incorporated by adjusting the endowments of each household for each forecast year. For example, if a region's population is forecast to double (with employment and income distributions remaining the same), the endowments of the corresponding households can be doubled to forecast travel demand. This also enables a comparative static analysis for each forecast year by running the model both with and without the infrastructure/policy change. Likewise, workforce forecasts can be incorporated by adjusting the endowments of the corresponding households, except by employment region and industry rather than by residence region which is analogous to using the Pissarides search model (Pissarides 2000) in RAEM. However, unlike population forecasts, overall levels of employment are determined endogenously through modelling the labour-leisure decision and do not need to be modelled externally. Further, this model is designed so that mode split behaviour can be added without great difficulty, for example using an MNL model (resulting in a logsum calculation of trip costs) or CES function at the trip generation and trip cost stages of the framework.

Activity-based modelling is a more recent class of travel demand modelling that simulates the daily activities and corresponding movements of individuals, providing far greater detail than conventional four-step models. To the authors' knowledge, there are no examples of integrated CGE and activity-based models for travel demand, although there are examples of integrated CGE and microsimulation models such as Bourguignon et al. (2005). It may be possible to develop such a model, but due to the additional complexity of activity-based models, the required computing time may be prohibitive.

Methodology

The proposed model is an integrated CGE and transport model that generates both household and freight trips and can simulate different geographical scales and time periods between the submodels. Four-step models typically have high spatial detail, with travel zones under 1 km² in size to load demand precisely onto links. A range of time periods are also usually simulated as travel patterns vary significantly throughout the day. On the other hand, a CGE model grows rapidly as the number of regions increases, and becomes

unwieldy at the number of zones required in a four-step model. Even if it were possible, it is debatable whether spatial variances in economic conditions justify CGE modelling at the travel zone level. In this model, the CGE submodel is an extended version of the submodel in Robson and Dixit (2017a), while the transport submodel is significantly different.

In terms of the structure of integration, unlike the model in Robson and Dixit (2017a) which was formulated as a single mixed complementarity problem, this model comprises separate CGE and transport submodels. In terms of the structure of integration, unlike the model in Robson and Dixit (2017a) which was formulated as a single mixed complementarity problem, this model comprises separate CGE and transport submodels in which the model tends toward equilibrium due to negative feedback reactions. The change is in view of tests that were conducted on the original model—when the transport network was scaled up, solvers for the MCF UE assignment formulation slowed considerably and often could not converge. In contrast, conventional assignment algorithms could solve the same networks in minutes due to their ability to adjust volumes across multiple links (path flows). As a result, the submodels have been split into explicit models, despite the original structure potentially affording efficiencies in allowing a solver to find the fastest solution path between the two submodels.

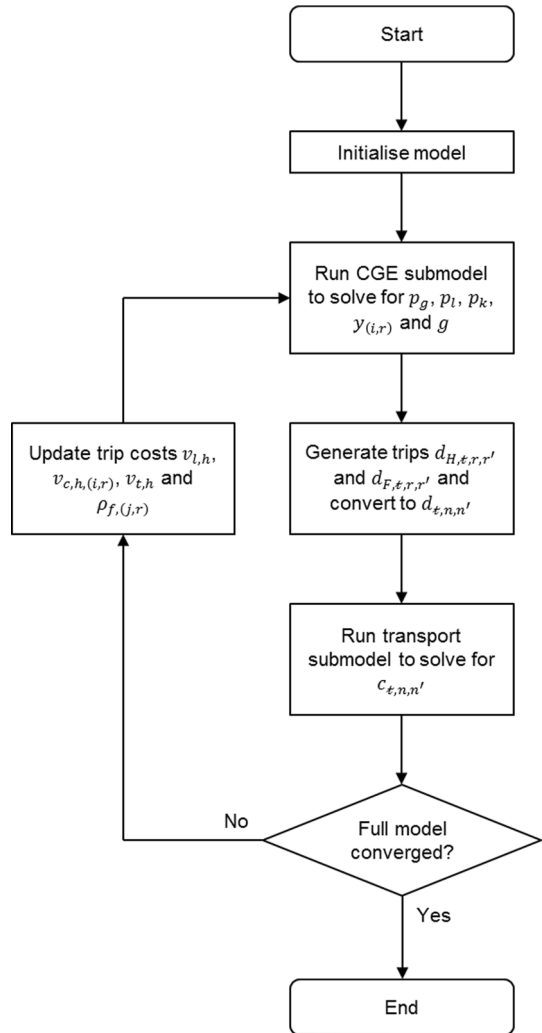
Both the CGE and transport submodels are static. The model is calibrated to a baseline equilibrium that is replicated when the model is run without changes. When an economic or transport parameter is changed, the model calculates a counterfactual equilibrium representing the long-term state of the economy, which provides a consistent basis for measuring impacts and comparing proposals. This is founded on the assumption that markets and transport networks tend towards equilibrium over time through the adjustment of prices and routing respectively. Any parameter in the CGE and transport submodels can be changed, including the structure of the transport network, yielding corresponding changes in prices, outputs, travel demand and trip costs.

Model structure

Figure 2 shows the structure of the model, which is implemented as a script in the mathematical programming software AMPL (Fourer et al. 2003). The model begins by running the CGE submodel to simulate the behaviour of households and firms interacting in markets over a set of regions R . A solution of the CGE submodel is characterised by a set of prices $p_{g,(i,r)}$, $p_{l,(i,r)}$ and p_k , firm outputs $y_{(i,r)}$ and tax collection g as described in “CGE submodel” section. Household activities in the CGE submodel are facilitated by commuting, shopping and leisure-associated vehicle trips, each of which costs time as given by the transport submodel ($v_{l,h}$, $v_{c,h,(i,r)}$ and $v_{l,h}$ for commuting, shopping and leisure respectively). This generates a set of daily household vehicle OD demands $d_{H,t,r,r'}$ between and within regions R , as in the first three steps of the four-step model. In addition, firms source their inputs from different regions as well as their own region, and therefore must purchase a freight service $\rho_{f,(j,r)}$ in proportion to travel time to transport commodities from their region of production to region of use. This generates a further set of freight vehicle OD demands $d_{F,t,r,r'}$ between and within regions R .

In the next stage of the model, the daily household and freight OD demands between and within regions R are converted into a set of OD demands between travel zones Z for time periods T . The trips are then assigned to the road network (N, L) in the transport submodel according to user equilibrium for each time period. Finally, the trip costs $c_{t,n,n'}$ are converted back to daily time prices for household activities and freight requirements for

Fig. 2 Model flowchart



firm production in the CGE submodel. Please note that the model does not incorporate time as a production input so changes in non-transport production time cannot be reported.

When changes in the CGE and transport submodel variables fall below a specified critical gap between iterations of the full model, the model is considered to have converged. The remainder of “[Methodology](#)” section details each stage of the model.

CGE submodel

The CGE submodel is an extended version of the one in Robson and Dixit (2017a). The submodel comprises a set of simultaneous nonlinear equations that are parameterised by travel time prices and freight requirements from the transport submodel. Commodity flows from the CGE submodel are then used to generate trips for the transport submodel.

At any equilibrium, the established CGE model represents an economy with an excess demand function and a non-zero price vector. With a finite number of equilibria, the economy has a general equilibrium configuration (Mas-Colell et al. 1995). The model is based on the Arrow–Debreu development economy, which features competitive markets with no restrictions on free-market operation and atomistic competition. The CGE model’s output function is a nested Constant Returns to Scale (CRS) Constant Elasticity of Substitution (CES) function with a regular structure, which was borrowed from the ORANI model (Dixon et al. 1982). The proportion of intermediate input demands between regions is fixed, and the Armington (1969) assumption of imperfect substitution between regional sources of goods is applied. The developed CGE model does not have a variable closure (fixed closure with no variability in closure), also known as a long-term closure, as it contains the same number of variables and equations (all macro variables endogenous).

Online Appendix A provides a full listing of the model sets, parameters, variables and equations. For the CGE model, all of the variables defined in Online Appendix A—Table A.4 are endogenous, while all of the parameters defined in Online Appendix A—Table A.2 are exogenous. Online Appendix C details the derivation of the CGE submodel equations, including the demand and supply equations of the economic agents.

The agents and commodities of the CGE submodel are built from two fundamental sets that govern the scope of the model:

- A set of regions R .
- A set of industries I , with one industry $i_T \in I$ specified as a transport industry to provide freight services. The remaining industries form set $J = I \setminus \{i_T\}$.

The CGE submodel simulates the behaviour of two core sets of economic agents:

- A set of firms F , with each firm $f \in F$ representing the production activity of industry $i \in I$ in region $r \in R$ such that $F \subseteq I \times R$.
- A set of households H , with each household $h \in H$ representing the people residing in region $r \in R$ and employed in firm $f \in F$ such that $H \subseteq R \times F \subseteq R \times I \times R$.

Furthermore, there are two other economic agents that interact with the households and firms:

- A foreign market agent that provides commodities produced externally (imports) for firm production at a fixed price, and purchases a fixed amount of commodities produced by firms for external use (exports).
- A government agent that collects tax revenue from firm production and redistributes it to households.

Firms and households trade the following commodities in the markets of the CGE submodel:

- A set of goods, with each good representing the output of each firm $(i, r) \in F$. Each good (i, r) has a price per unit $p_{g,(i,r)}$.
- A set of labour commodities, with each labour commodity representing the labour input of each firm $(i, r) \in F$. Labour refers to time that is endowed to households and sold to firms. Each labour commodity (i, r) has a price per unit $p_{l,(i,r)}$.

- Capital, representing the common production capital commodity in the submodel. Capital is endowed to households and sold to firms as per the putty-putty assumption of flexibility between industries and costless movement between regions. Capital has a price per unit p_k .

Firms F also purchase bundles of imports at prices per unit $p_{I,f}$. For simplicity, households are assumed to purchase only local goods, although this assumption can be easily relaxed if necessary.

The economy is assumed to have open markets and perfect competition with constant returns to scale in production such that all economic agents are price takers and firms earn zero economic profit. This form of competition, as opposed to monopolistic competition, was chosen for this particular model to reduce potential issues with multiple equilibria. In addition, welfare measured from the CGE submodel (traditionally used for the measurement of indirect impacts) is not additive with welfare measured from the transport submodel (traditionally used for the measurement of direct impacts), and the CGE submodel should be taken as the single point of measurement of welfare.

The choices regarding labour and capital mobility were made in view of the strategic planning uses of the model. The infinite mobility of capital reflects a long-term perspective where there is sufficient time for it to transform and move as required, for consistency between counterfactual scenarios. Likewise, labour was assumed to be immobile to allow for consistent comparisons between groups of people, and to have the ability to incorporate workforce forecasts. Both of these assumptions will be reviewed in future models.

Households

Households maximise utility subject to both time and monetary constraints. Utility is specified as the nested constant elasticity of substitution (CES) function with constant returns to scale shown in Fig. 3, where consumption refers to the aggregate intake of goods. The chosen nesting structure accords with conventional utility functions in the

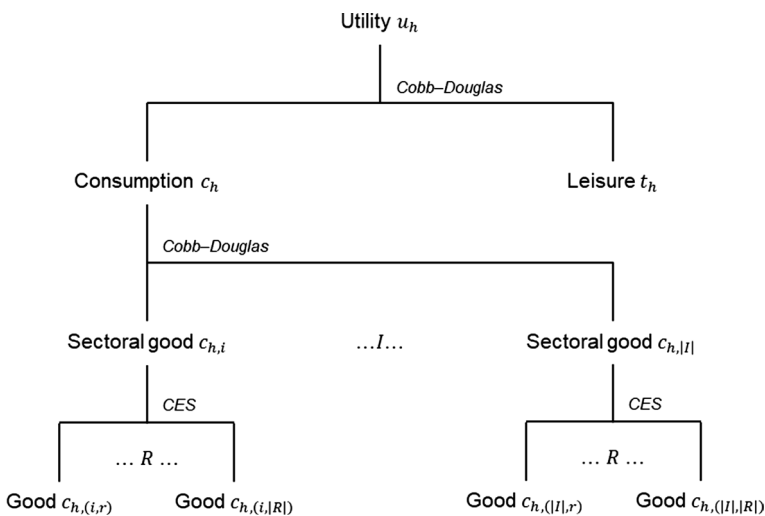


Fig. 3 Structure of utility function

literature in “Literature review” section to fit classic assumptions in microeconomic behavioural modelling and to enable the use of elasticity of substitution parameters from existing models.

At the top level, utility u_h is a Cobb–Douglas combination of consumption c_h and leisure t_h :

$$u_h = c_h^{\alpha_{c,h}} t_h^{\alpha_{t,h}} \tag{1}$$

Consumption itself is a Cobb–Douglas combination of aggregate sectoral goods $c_{h,i}$:

$$c_h = \prod_{i \in I} c_{h,i}^{\beta_{h,i}} \tag{2}$$

Finally, each aggregate sectoral good is a CES combination of goods from each firm $c_{h,(i,r)}$:

$$c_{h,i} = \left(\sum_{r \in R} \gamma_{h,(i,r)} \frac{\sigma_{h,i}^{\sigma_{h,i}-1}}{\sigma_{h,i}} c_{h,(i,r)} \right)^{\frac{\sigma_{h,i}}{\sigma_{h,i}-1}} \tag{3}$$

To purchase goods, households sell their capital endowment $\omega_{k,h}$ and a portion of their daily time endowment $\omega_{t,h}$ as labour l_h . Households are also allocated a share ψ_h of government tax income g . With price index for consumption $p_{c,h}$ and price (wage) for the household’s labour commodity $p_{l,h}$, the monetary constraint is:

$$p_{c,h}c_h = p_{l,h}l_h + p_k\omega_{k,h} + \psi_h g \tag{4}$$

Households are also constrained by time per day. Besides labour and leisure time itself, commuting trips are required to supply labour, shopping trips are required to obtain goods, and leisure-associated trips are required to access activities associated with non-labour time. Together, these trips aim to cover all sources of household travel demand. With travel time prices $v_{l,h}$, $v_{c,h}$ and $v_{t,h}$ given for each unit of labour, consumption and leisure respectively, the daily time constraint is:

$$l_h + t_h + v_{l,h}l_h + v_{c,h}c_h + v_{t,h}t_h = \omega_{t,h} \tag{5}$$

Maximising utility in Eq. (1) subject to constraints in Eqs. (4) and (5) yields demand equations for goods $c_{h,(i,r)}(p_g, p_l, p_k, v_{l,h}, v_{c,h}, v_{t,h})$ and supply equations for labour $l_h(p_g, p_l, p_k, v_{l,h}, v_{c,h}, v_{t,h})$. The derivation of these equations is provided in Online Appendix C. Thus, any decision on where to shop or how to allocate time to labour or leisure depends on travel times.

In addition to the above utility structure, residential location choice is optionally allowed for household agents at the discretion of the analyst. This migration behaviour is not directly integrated into the utility function (for reasons that will be discussed below), and instead operates at a separate level *after* agents receive their utility for each cycle of the model.

The mechanism for migration is as follows. Each agent observes the utilities of all agents that are similar to them in terms of employment but dissimilar in terms of residential location. Any differences in utility would be attributed to location choice (as agents are otherwise homogenous), meaning that agents are inclined to move the region where they expect to receive the highest utility.

Mathematically, the mechanism for migration is as follows:

$$\%_{migration} = \frac{u_{max} - u_{current}}{u_{max}}$$

where $\%_{migration}$ = the percentage of household agents that migrate out of a given region in each model cycle. u_{max} = the maximum utility an agent expects to receive when migrating to the corresponding region. $u_{current}$ = the utility the agent currently expects to receive if they do not migrate.

1. The assumptions behind this mechanism is as follows: Agents are unable to directly observe how changing residential location would influence their utilities, and must instead observe the influence of residential location indirectly via the utilities other agents receive.
2. Agents can accurately and fully observe the received utility of all other agents identical to themselves. This is a necessary condition to assume rational decisions made by agents as the model is not stochastic on the CGE side.
3. Cost of migration is not modelled.

There is no cost when deciding to migrate between residential locations. There are no costs to purchasing a new property/renting, no income from selling existing property (if any), no time or monetary cost of moving etc. This is due to the lack of a real estate market, which other CGE models have included (Anas and Liu 2007) but lacking in this one as it is primarily a tool for transport appraisal and not for pure economic analysis.

4. Zones have infinite room and can fit infinite number of agents.

The mechanism outlined above is dissimilar to many CGE models that treat migration endogenously within a household agent's utility function, and instead takes the approach that an agent does not include residential location as part of their utility assessment as they are unable to predict their expected utility when moving to a new location. This is done partially because agents are in actuality not able to predict their expected utility, as well as the fact that within the utility function of the household agents as presented in the model, agents are primarily deciding between consumption and leisure. The mechanism between this tradeoff is time, as consumption is the result of time spent working and leisure is the result of time spent *not* working. The choice of residential location does not seem an appropriate third decision to include as it is not a time-based decision.

By separating residential decisions from the endogenous utility function, the migration mechanism trades accuracy for simplicity and flexibility. While it is true that this mechanism is not a highly accurate representation of migration, it has the advantage of being able to be added or removed to the model at will by the analyst, since it is not endogenous to the utility function of the agents. The result is that the analyst can look at short-term effects of economic shocks (such as the construction/improvement of road infrastructure like the WestConnex) as well as gauge the rough long-term effects of such decisions. More detailed migration models can be included in future work, but for this study, the current formulation is believed to be sufficient.

Firms

Firms maximise profits subject to a monetary constraint, but since firms earn zero economic profit, their behaviour is modelled as a cost minimisation problem with production levels determined from market equilibrium. Production is specified as the nested constant

elasticity of substitution (CES) function with constant returns to scale shown in Fig. 4. Like the utility function in “Households” section, the chosen nesting structure accords with conventional production functions to fit classic microeconomic assumptions and enable elasticity of substitution parameters to be borrowed from existing models.

At the top level, output y_f is a Leontief (perfect complements) combination of intermediate inputs from each industry other than transport $x_{g,f,j}$, imports $x_{I,f}$ and a primary factor composite $x_{p,f}$:

$$y_f = \min \left(\frac{x_{g,f,j}}{\mu_{g,f,j}} \forall j \in J, \frac{x_{I,f}}{\mu_I}, \frac{x_{p,f}}{\mu_{p,f}} \right) \tag{6}$$

Each intermediate input is a CES combination of goods from each firm $x_{g,f,(j,r)}$:

$$x_{g,f,j} = \left(\sum_{r \in R} \theta_{f,(j,r)} \frac{x_{g,f,(j,r)}^{\frac{v_{f,j}}{v_{f,j}-1}}}{\rho_{f,(j,r)}} \right)^{\frac{v_{f,j}-1}{v_{f,j}}} \tag{7}$$

However, $x_{g,f,(j,r)}$ represents the input of good (j, r) after it has been transported to firm f 's region. This is accomplished by a Leontief combination of the good itself $x_{s,f,(j,r)}$ and a freight margin $x_{m,f,(j,r)}$, where $\rho_{f,(j,r)}$ represents the units of transport required to relocate a unit of good (j, r) from its source to destination:

$$x_{g,f,(j,r)} = \min \left(x_{s,f,(j,r)}, \frac{x_{m,f,(j,r)}}{\rho_{f,(j,r)}} \right) \tag{8}$$

The freight margin is assumed to be proportional to the travel time from source to destination and is supplied by the transport industry in the source region such that:

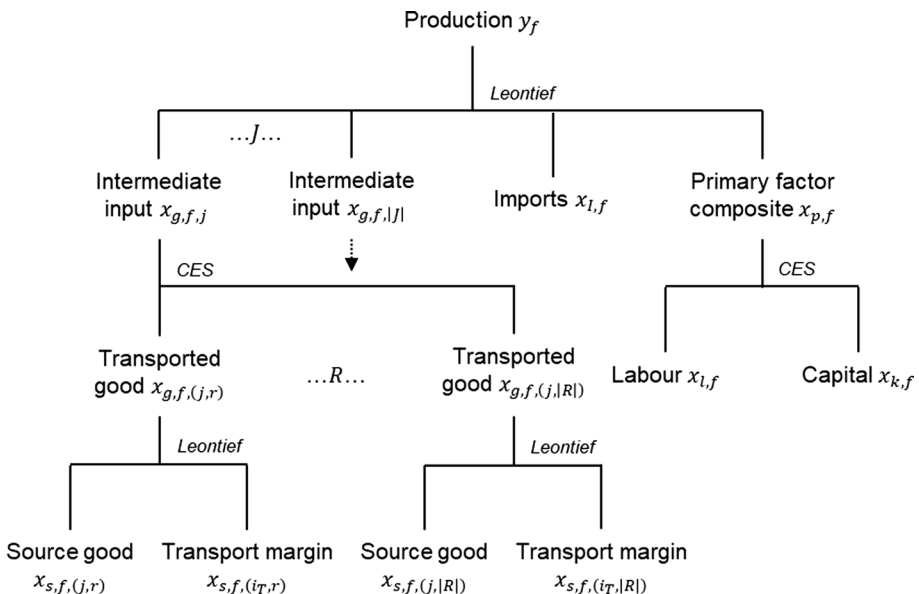


Fig. 4 Structure of production function

$$x_{s,f,(i,r)} = \sum_{j \in J} x_{m,f,(j,r)} \tag{9}$$

The primary factor composite is a CES combination of labour $x_{l,f}$ and capital $x_{k,f}$:

$$x_{p,f} = \left(\zeta_{l,f} x_{l,f}^{\frac{\varphi_f-1}{\varphi_f}} + \zeta_{k,f} x_{k,f}^{\frac{\varphi_f-1}{\varphi_f}} \right)^{\frac{\varphi_f}{\varphi_f-1}} \tag{10}$$

With price index $p_{g,f,j}$ per unit of intermediate input from each industry, price $p_{l,f}$ per unit of imports and price $p_{p,f}$ per unit of primary factor composite, as well as production tax rate π_f , the cost e_f for firm f to produce y_f units of output is:

$$e_f = (1 + \pi_f) \left(p_{l,f} x_{l,f} + p_{p,f} x_{p,f} + \sum_{j \in J} p_{g,f,j} x_{g,f,j} \right) \tag{11}$$

The parameters of $\theta_{f,(j,r)}$ and $\zeta_{l,f}$ which are firm share parameter for intermediate input of good and firm share parameter for labour respectively are estimated using IO tables with the calibration equation defined in Robson (2018). $v_{f,j}$ and φ_f which are the firm elasticity of substitution between regional sources of intermediate inputs and firm elasticity of substitution between labour and capital are taken out from ORANI model (Dixon et al. 1982; Armington 1969).

Minimising the cost of producing y_f units of output in Eq. (11) subject to Eq. (6) yields demand equations for goods $x_{s,f,(i,r)}(y_f, \mathbf{p}_g, \mathbf{p}_l, p_k, \mathbf{p}_f)$, imports $x_{l,f}(y_f, \mathbf{p}_g, \mathbf{p}_l, p_k, \mathbf{p}_f)$, labour $x_{l,f}(y_f, \mathbf{p}_g, \mathbf{p}_l, p_k, \mathbf{p}_f)$ and capital $x_{k,f}(y_f, \mathbf{p}_g, \mathbf{p}_l, p_k, \mathbf{p}_f)$. The derivation of these equations is provided in Online Appendix C.

Foreign markets and government

In the CGE submodel, foreign markets and government are treated in a relatively simple manner. Their incorporation in the model is primarily to establish their structures such that they can be extended as required in future models.

Foreign markets provide a source of imports and export demand. As described in the sections above, the foreign market agent provides imports $x_{l,f}$ to firms at prices $p_{l,f}$. Hence, there is no substitution between imported and local goods, although the volume of imports scales with firm production and changes in the costs of imports are reflected in the costs of goods. Foreign markets also demand quantity $x_{e,(i,r)}$ of each good (i, r) for export.

The government agent imposes an *ad valorem* tax on firm production at rate π_f for firm f . The total tax collected g is then redistributed in full to households at share ψ_h for household h .

Equilibrium

Equilibrium conditions for the goods, labour and capital markets are:

$$\sum_{j \in F} x_{s,f,(i,r)} + \sum_{h \in H} c_{h,(i,r)} + x_{e,(i,r)} = y_{(i,r)}, \quad \forall (i, r) \in F \tag{12}$$

$$x_{l,f} = \sum_{r \in R} l_{r,f}, \quad \forall f \in F \tag{13}$$

$$\sum_{f \in F} x_{k,f} = \sum_{h \in H} \omega_{k,h} \tag{14}$$

The zero profit conditions for firms are:

$$p_{g,(i,r)} = p_{g,f} = (1 + \pi_f) \left(\mu_{l,f} p_{l,f} + \mu_{p,f} p_{p,f} + \sum_{j \in J} \mu_{g,f,j} p_{g,f,j} \right), \quad \forall f \in F \tag{15}$$

Finally, the full redistribution condition for the government agent is:

$$g = \sum_{f \in F} \pi_f \left(p_{l,f} x_{l,f} + p_{p,f} x_{p,f} + \sum_{j \in J} p_{g,f,j} x_{g,f,j} \right) \tag{16}$$

Import prices and export demand are fixed for the foreign market agent.

Trip generation

In the CGE submodel, both household and production activities are facilitated by vehicle trips, with costs derived from the transport submodel. This section describes how these trips are generated for the transport submodel.

Regional household trips

Households undertake three types of trips—commuting, shopping and leisure-associated i.e. all trips other than commuting and shopping—in time periods $t \in T$

A commuting trip is assumed to comprise a daily return journey from the household’s region of residence to their region of employment. With daily trip generation rate $\delta_{l,(r,(i,r'))}$ for each unit of labour, time period proportion $\tau_{o,l,t}$ for outbound legs and time period proportion $\tau_{i,l,t}$ for inbound legs, the number of commuting trips $d_{l,r,r'}$ in time period $t \in T$ from $r \in R$ to $r' \in R$ is:

$$d_{l,t,r,r'} = \sum_{i \in I} \left(\tau_{o,l,t} \delta_{l,(r,(i,r'))} l_{(r,(i,r'))} + \tau_{i,l,t} \delta_{l,(r',(i,r))} l_{(r',(i,r))} \right), \quad \forall r, r' \in R \tag{17}$$

Likewise, a shopping trip is assumed to comprise a daily return journey from the household’s region of residence to the good’s region of production, which is also assumed to correspond with the retail location. A retail sector can be added in calibrating the model to ensure shopping patterns are realistic. With daily trip generation rate $\delta_{c,(r,f),(i,r')}$ for each unit of each good, time period proportion $\tau_{o,c,t}$ for outbound legs and time period proportion $\tau_{i,c,t}$ for inbound legs, the number of daily shopping trips $d_{c,r,r'}$ from $r \in R$ to $r' \in R$ is:

$$d_{c,t,r,r'} = \sum_{f \in F} \sum_{i \in I} \left(\tau_{o,c,t} \delta_{c,(r,f),(i,r')} c_{(r,f),(i,r')} + \tau_{i,c,t} \delta_{c,(r',f),(i,r)} c_{(r',f),(i,r)} \right), \quad \forall r, r' \in R \tag{18}$$

Finally, households are assumed to spend their leisure time in fixed proportions across all regions. With daily trip generation rate $\delta_{t,(r,f),r'}$ for travel to region $r' \in R$ for each unit of leisure, time period proportion $\tau_{o,t,\xi}$ for outbound legs and time period proportion $\tau_{i,t,\xi}$ for inbound legs, the number of daily leisure-associated trips $d_{t,r,r'}$ from $r \in R$ to $r' \in R$ is:

$$d_{t,\xi,r,r'} = \sum_{f \in F} \left(\tau_{o,t,\xi} \delta_{t,(r,f),r'} t_{(r,f)} + \tau_{i,t,\xi} \delta_{t,(r',f),r} t_{(r',f)} \right), \quad \forall r, r' \in R \tag{19}$$

Therefore, the number of household trips $d_{H,t,r,r'}$ in time period $\xi \in T$ from $r \in R$ to $r' \in R$ is:

$$d_{H,t,r,r'} = d_{l,t,r,r'} + d_{c,t,r,r'} + d_{t,t,r,r'}, \quad \forall r, r' \in R \tag{20}$$

Regional freight trips

Production activities of firms involve three types of commodity flows—local trade of goods, imports and exports. All of these flows require corresponding one-way trips in time periods $\xi \in T$. To accommodate imports and exports, an external region r_e is added to the set of regions R , forming set $R_e = R \cup r_e$ to represent trips into and out of the model regions.

Local trade of goods requires freight from the region of production to the region of use. With daily trip generation rate $\delta_{L,(i,r),(j,r')}$ for each unit of good traded and time period proportion $\tau_{L,\xi}$, the number of local freight trips $d_{L,r,r'}$ in time period $\xi \in T$ from $r \in R$ to $r' \in R$ is:

$$d_{L,\xi,r,r'} = \sum_{i \in I} \sum_{j \in J} \tau_{L,\xi} \delta_{L,(i,r),(j,r')} x_{s,(i,r),(j,r)}, \quad \forall r, r' \in R \tag{21}$$

Flows of imports require freight from the external region to the region of use. With daily trip generation rate $\delta_{I,(i,r)}$ for each unit of imports and time period proportion $\tau_{I,\xi}$ the number of import trips $d_{I,\xi,r}$ in time period $\xi \in T$ from the external region to $r \in R$ is:

$$d_{I,\xi,r_e,r} = \sum_{i \in I} \tau_{I,\xi} \delta_{I,(i,r)} x_{I,f}, \quad \forall r \in R \tag{22}$$

Similarly, flows of exports require freight from the region of production to the external region. With daily trip generation rate $\delta_{E,(i,r)}$ for each unit of exports and time period proportion $\tau_{E,\xi}$ the number of export trips $d_{E,\xi,r}$ in time period $\xi \in T$ from $r \in R$ to the external region is:

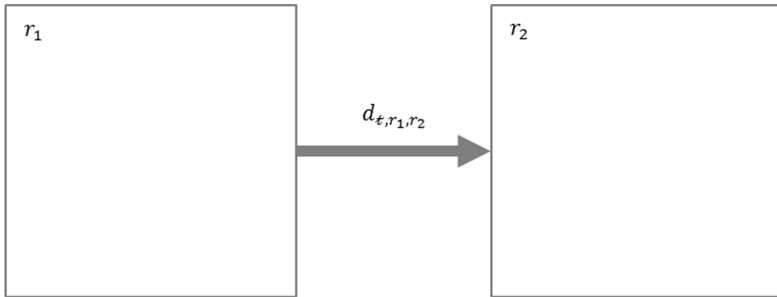
$$d_{E,\xi,r,r_e} = \sum_{i \in I} \tau_{E,\xi} \delta_{E,(i,r)} x_{e,(i,r)}, \quad \forall r \in R \tag{23}$$

Therefore, the number of freight trips $d_{F,\xi,r,r'}$ in time period $\xi \in T$ from $r \in R_e$ to $r' \in R_e$ is:

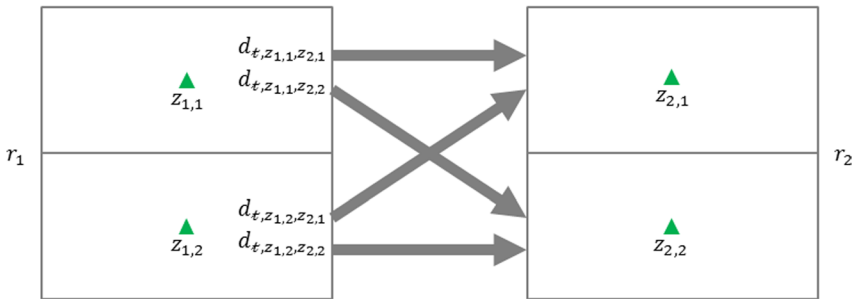
$$d_{F,\xi,r,r'} = \begin{cases} d_{L,\xi,r,r'}, & \forall r, r' \in R \\ d_{I,\xi,r_e,r'}, & r = r_e, \forall r' \in R \\ d_{E,\xi,r,r_e}, & r' = r_e, \forall r \in R \end{cases} \tag{24}$$

Conversion to travel zone trips

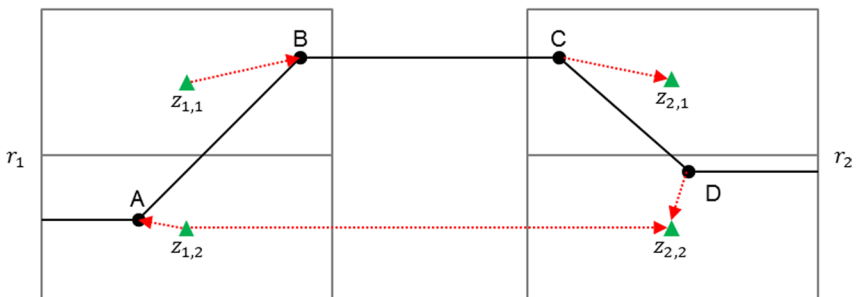
Each region in R is then split into a number of travel zones Z for the transport submodel. In the example in Figs. 5a and 5b, region r_1 has been split into travel zones $z_{1,1}$ and $z_{1,2}$, and region r_2 has been split into travel zones $z_{2,1}$ and $z_{2,2}$. As a result, what was previously one OD pair at the regional level becomes four OD pairs at the travel zone level. Travel zones are also allocated to the external region at access points such as ports,



(a) Regional trips between r_1 and r_2 .



(b) Travel zone trips between r_1 and r_2 .



(c) Network and direct trips between r_1 and r_2 .

Fig. 5 Correspondence between regional and travel zone trips

airports, intermodal facilities and roads that enter and exit the boundary of the modelled regions.

In the model, the two types of OD trips (regional and travel zone) are treated separately, i.e. the regional OD trips are calibrated to a dataset of total household and freight trips by time period, and the travel zone OD trips are calibrated as a transport model with separate household demand (using light vehicles) and freight demand (using both light and heavy vehicles). The two levels of trips are then connected by assuming that demand in the travel zone OD pairs change in the same proportions as their corresponding regional OD pairs. This implies that spatial trip patterns within regions do not vary as the economy shifts. A justification for this assumption is that land use patterns within regions are controlled by local planning laws, and thus are likely to scale together.

From this assumption, the total daily trips at the regional level from the CGE submodel $d_{H,t,r,r'}$ and $d_{F,t,r,r'}$ as split into time periods $t \in T$ may be represented by a separate set of travel zone OD demands for each time period (e.g. hourly flows). These travel zone OD demands need not sum to the total demand from the CGE submodel; they just need to be representative of typical conditions across the time period. In addition, the model allows for travel zone trip patterns to differ between household and freight trips, and therefore the calculations for household and freight trip costs are kept separate.

Furthermore, it may be computationally difficult to simulate the full road network due to the number of iterations required in the full model or the spatial extent of the CGE submodel. Figure 5c shows an example road network $A - B - C - D$ connecting the travel zones, with the centroids represented by the triangles. While a trip from $z_{1,1}$ to $z_{2,1}$ is likely to use the given road network by first accessing node B , travelling from B to C , and then leaving node C , a trip from $z_{1,2}$ to $z_{2,2}$ may travel via local road networks not represented in the model. Therefore, to facilitate the use of more limited road networks, the travel zone OD trips are pre-assigned into:

- A set of direct trips that bypass the road network (N, L) . The cost of a direct trip $c_{d,t,z,z'}$ in time period t from $z \in Z$ to $z' \in Z$ is fixed.
- A set of network trips that are assigned to the road network (N, L) . The cost of a network trip in time period t from $z \in Z$ to $z' \in Z$ comprises a fixed cost $c_{t,z,n}$ from the centroid of z to the nearest node $n \in N$, a variable cost $c_{t,n,n'}$ from n to $n' \in N$ (the nearest node to z'), and a fixed cost $c_{t,n',z'}$ from n' to the centroid of z' .

This pre-assignment is a proposed method to simplify the transport model, which may be required when using previously developed transport networks from existing models, as the integrated CGE and transport model requires multiple iterations to converge to equilibrium. The effect is that route choice and congestion are not simulated for trips that are not likely to use the simulated transport network, according to the pre-assignment criteria, which will likely reduce the magnitude of impacts of congestion. A fraction of local traffic using higher order networks might be considered with adjusting route choices depending on circumstances where travel times are relatively inelastic for small changes in flows.

The loading of trips into the network to determine variable costs $c_{t,n,n'}$ from the transport submodel is captured by the multipliers $\xi_{H,t,r,r',n,n'}$ and $\xi_{F,t,r,r',n,n'}$ for household and freight trips respectively. For freight trips in particular, the multiplier $\xi_{F,t,r,r',n,n'}$ covers the allocation of trips to the external region via access points and also captures the conversion of trips into passenger car units. With the number of regional household OD trips $d_{H,t,r,r'}$ in time period t from r to r' given in Eq. (20), the number of regional freight OD trips $d_{F,t,r,r'}$ in time period

t from r to r' given in Eq. (24) and a set of background trips $d_{B,t,n,n'}$ for preloading into the transport submodel, the number of network OD trips $d_{t,n,n'}$ in time period t from n to n' is:

$$d_{t,n,n'} = d_{B,t,n,n'} + \sum_{r,r' \in R} \xi_{H,t,r,r',n,n'} d_{H,t,r,r'} + \sum_{r,r' \in R_e} \xi_{F,t,r,r',n,n'} d_{F,t,r,r'}, \forall n, n' \in N \tag{25}$$

For each regional OD pair, the total corresponding travel zone OD trips are captured by the multipliers $\eta_{H,t,r,r'}$ and $\eta_{F,t,r,r'}$ for household and freight trips respectively, and the fixed costs for both direct and network trips are captured by the multipliers $\kappa_{H,t,r,r'}$ and $\kappa_{F,t,r,r'}$ for household and freight trips respectively, as explained in “Trip costs” section. Depending on the data used, multipliers may exist for intra-zonal trips stemming from intra-regional activities in the CGE submodel. However, since these trips would have the same origin and destination, their cost would be zero.

Transport submodel

Following the generation of network OD trips $d_{t,n,n'}$, the trips are assigned to the road network (N, L) for each time period t in the transport submodel to yield OD costs $c_{t,n,n'}$. In user equilibrium (UE) assignment, every user travelling from n to n' is assumed to independently choose a path that minimises their travel cost. The model is solved by finding an equilibrium set of flows such that each user cannot find a better path (route) that lowers their travel cost, subject to all other users remaining on their current paths. This is known as Wardrop’s First Principle (1952)—as a result, all used paths from n to n' have the same travel cost, which is lower than the travel cost for any unused path.

This model adapts a nonlinear programming formulation of UE assignment from Sheffi (1984), based on the Frank–Wolfe algorithm (2006), that only requires a set of link flows $d_{t,\ell}$, $\ell \in L$ and not the enumeration of paths. The algorithm to solve for a set of OD costs $c_{t,n,n'}$ for each time period $t \in T$ is described in Online Appendix D.

Trip costs

The final stage of the model, prior to the next iteration, is to calculate the travel time prices $v_{l,h}$, $v_{c,h,(i,r)}$ and $v_{t,h}$, as well as the freight requirements $\rho_{f,(j,r)}$ for local trade from OD costs $c_{t,n,n'}$. Freight costs for imports and exports do not impact the CGE submodel as both import prices and export demand are exogenous.

Household trip costs

Firstly, the number of household travel zone trips $d_{H,Z,t,r,r'}$ associated with each regional OD pair is:

$$d_{H,Z,t,r,r'} = \eta_{H,t,r,r'} d_{H,t,r,r'}, \forall r, r' \in R \tag{26}$$

Next, the sum of fixed costs $c_{H,SUM,t,r,r'}$ for the household travel zone trips associated with each regional OD pair is:

$$c_{H,SUM,t,r,r'} = \kappa_{H,t,r,r'} d_{H,t,r,r'}, \forall r, r' \in R \tag{27}$$

Finally, using the variable costs $c_{t,n,n'}$ from the transport submodel, the average OD cost $c_{H,t,r,r'}$ for the household travel zone trips associated with each regional OD pair is:

$$c_{H,t,r,r'} = \frac{c_{H,SUM,t,r,r'} + \sum_{n,n' \in N} \xi_{H,t,r,r',n,n'} d_{H,t,r,r'} c_{t,n,n'}}{d_{H,Z,t,r,r'}}, \quad \forall r, r' \in R \tag{28}$$

The travel time prices $v_{l,h}$, $v_{c,h,(i,r)}$ and $v_{t,h}$ are then:

$$v_{l(r,(i,r'))} = \delta_{l(r,(i,r'))} \left(\sum_{t \in T} \tau_{o,l,t} c_{H,t,r,r'} + \sum_{t \in T} \tau_{i,l,t} c_{H,t,r',r} \right), \forall (r, (i, r')) \in H \tag{29}$$

$$v_{c,(r,f),(i,r')} = \delta_{c,(r,f),(i,r')} \left(\sum_{t \in T} \tau_{o,c,t} c_{H,t,r,r'} + \sum_{t \in T} \tau_{i,c,t} c_{H,t,r',r} \right), \forall (r, f) \in H, (i, r') \in F \tag{30}$$

$$v_{t,(r,f)} = \sum_{r' \in R} \left(\delta_{t,(r,f),r'} \left(\sum_{t \in T} \tau_{o,t,t} c_{H,t,r,r'} + \sum_{t \in T} \tau_{i,t,t} c_{H,t,r',r} \right) \right), \forall (r, f) \in H \tag{31}$$

Freight trip costs

The calculation of regional OD costs for local freight trips parallels that of household trip costs. The number of freight travel zone trips $d_{F,Z,t,r,r'}$ associated with each regional OD pair is:

$$d_{F,Z,t,r,r'} = \eta_{F,t,r,r'} d_{F,t,r,r'}, \quad \forall r, r' \in R \tag{32}$$

The sum of fixed costs $c_{F,SUM,t,r,r'}$ for the freight travel zone trips associated with each regional OD pair is:

$$c_{F,SUM,t,r,r'} = \kappa_{F,t,r,r'} d_{F,t,r,r'}, \quad \forall r, r' \in R \tag{33}$$

Using the variable costs $c_{t,n,n'}$ from the transport submodel, the average OD cost $c_{F,t,r,r'}$ for the freight travel zone trips associated with each regional OD pair is:

$$c_{F,t,r,r'} = \frac{c_{F,SUM,t,r,r'} + \sum_{n,n' \in N} \xi_{F,t,r,r',n,n'} d_{F,t,r,r'} c_{t,n,n'}}{d_{F,Z,t,r,r'}}, \quad \forall r, r' \in R \tag{34}$$

With the amount of freight margin required per unit of trip cost $\epsilon_{(i,r),(j,r')}$, the freight requirement $\rho_{(i,r),(j,r')}$ for firm (i, r) purchasing good (j, r') is:

$$\rho_{(i,r),(j,r')} = \epsilon_{(i,r),(j,r')} \sum_{t \in T} \tau_{L,t} \delta_{L,(i,r),(j,r')} c_{F,t,r,r'} \tag{35}$$

$\forall (i, r) \in F, (j, r') \in J \times R$

Calibration

The proposed model has been calibrated for testing purposes using data for the Sydney transport network and economy. While the data was derived from real measurements, it should be treated as synthetic as it has not undergone thorough validation. The model's performance is assessed by convergence of model parameters over iterations. Five parameters, namely the price of goods, the price of labour, the output of firms, demand, and utility, were chosen and their values were observed during the model run. The percentage change in these variables compared to their values in the previous iteration is computed, and by the third iteration, the variables had reached a point of convergence with less than 0.01 change compared to the previous value in the previous iteration.

Transport submodel calibration

The calibration of the transport submodel was heavily based on the 2011 Sydney Strategic Travel Model (STM) (Bureau of Transport Statistics 2011), which is currently used as the standard four-step transport planning model in Sydney. The 2,404 travel zones in the STM covering the contiguous Sydney urban area were adopted for set Z , as well as the four time periods of 'AM peak', 'interpeak', 'PM peak' and 'night' for set T .

The road network is a condensed version of the 2011 STM network, which originally contained 63,747 links and 25,268 nodes. Even though this network is used in an existing four-step model, the multiple iterations required between the CGE and transport submodels made it necessary to simplify the network to a core structure appropriate for strategic modelling, in order to keep computation times reasonable. This involved removing links that would be insignificant to the model results, combining links where possible and checking for network consistency.

Starting from the original STM network, all links outside the Sydney SA2 regions R as well as all local and sub-arterial roads (and corresponding isolated nodes) were removed. This resulted in a number of extraneous midblock nodes along the remaining arterials, highways and freeways which no longer served any technical purpose. A macro was written to scan through every node in the network, identify midblock nodes and remove them by combining links. Further reductions were made by reclassifying all roads to either arterials or freeways, simplifying freeway interchange structures by combining freeway ramp lanes with mainline lanes, and removing additional midblock nodes along freeways. The final step was to rectify inconsistencies generated in the network that would prevent the model from operating correctly. All loop links (links that had identical start and end nodes), duplicate links (where a set of links shared common start and end nodes), dead-ends and isolated nodes were removed. The final road network for Sydney, shown in Fig. 6, contains 1898 links and 791 nodes representing all of Sydney's arterials and freeways.

Next, the travel zone OD matrices for each time zone were extracted from the STM. Each travel zone centroid was then allocated to the nearest node by Euclidean distance, and approximate travel times by local or arterial roads were compared to allocate the travel zone OD trips into direct or network trips. This provided network OD matrices to enable the calibration of the link parameters. Following a number of runs of the transport submodel in which the link parameters were adjusted until the travel times closely matched those observed in Google Maps, the link parameters were finalised as:

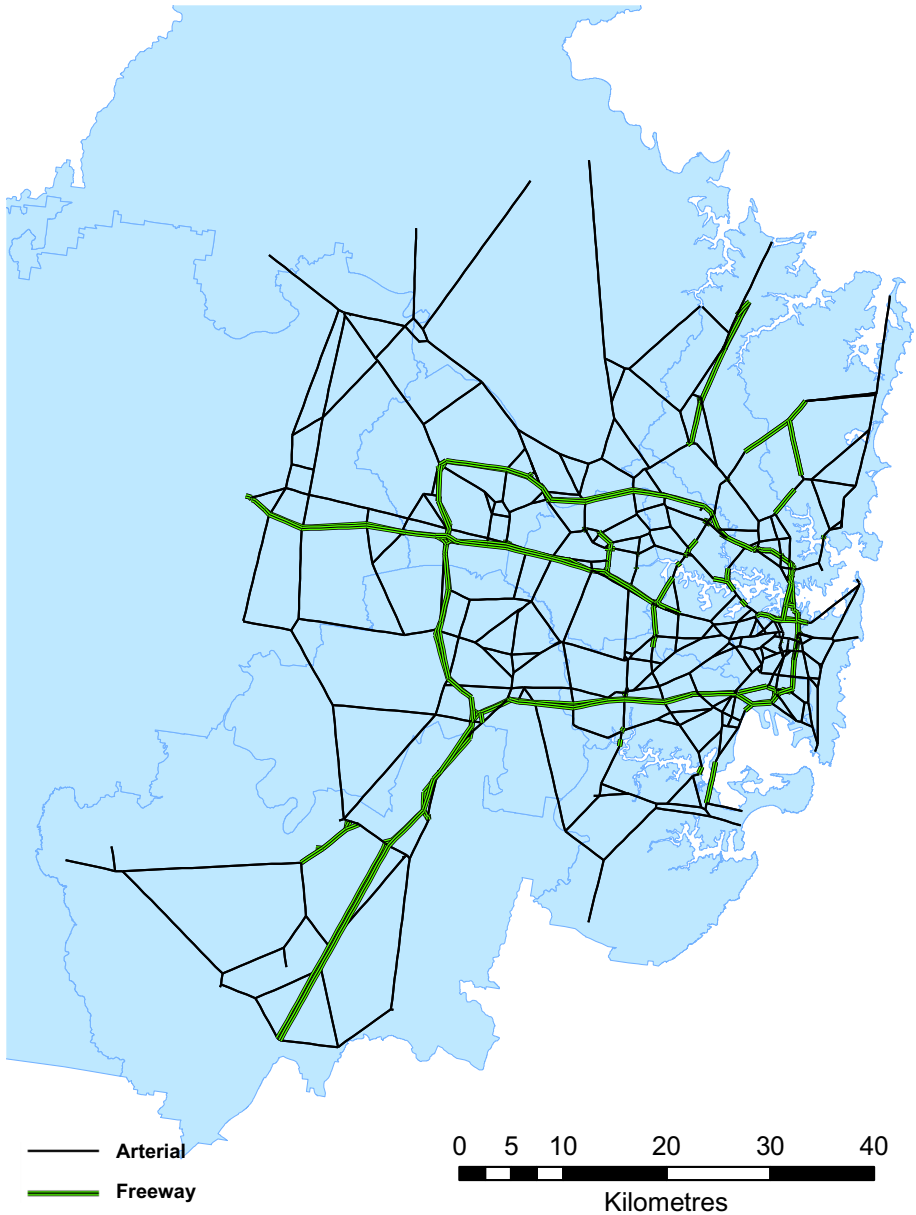


Fig. 6 Base road network for Sydney

- *Arterials* 50 km/h free-flow speed; 1000 veh/h capacity; BPR multiplier of 1, BPR power of 5.
- *Freeways* 75 km/h free-flow speed; 1500 veh/h capacity; BPR multiplier of 0.1, BPR power of 6.

CGE submodel calibration

Once the transport submodel calibration process is complete, the CGE model is calibrated to match travel demand “exactly”, which means that there is no need for the transport demand parameters to be estimated statistically. Calibration of a CGE model involves the specification of a benchmark economy that is assumed to be at equilibrium. The parameters of the CGE model are then back-calculated from the benchmark such that the model replicates the benchmark when run without changes. This is in contrast to the calibration of many transport models—it is an exact calibration, rather than a statistical one.

The calibration of the CGE submodel mirrors the calibration of the Robson and Dixit model (2017a). As in the Robson and Dixit model, the 14 Statistical Areas Level 4 (SA4) (Pink 1270) covering Sydney were chosen for the set of regions R , and the economy was aggregated to two industries: transport, and all others.

Prior to the calibration of the CGE submodel parameters, the multipliers $\xi_{H,t,r,r',n,n'}$, $\xi_{F,t,r,r',n,n'}$, $\eta_{H,t,r,r'}$, $\eta_{F,t,r,r'}$, $\kappa_{H,t,r,r'}$ and $\kappa_{F,t,r,r'}$ for linking trips and trip costs between the CGE and transport submodels were derived. Data from the 2011 Household Travel Survey (Bureau of Transport Statistics 2013) was first obtained to determine regional OD demand by time period and purpose. Next, a script iterated through each travel zone OD pair and allocated trips and trip costs to the corresponding regional OD pair. This generated the required multipliers and enabled the calculation of travel time prices and freight margins after running the transport submodel.

The development of the calibration data, including sources of IO data, is detailed in Robson and Dixit (2017b) and the calibration process is described in Robson and Dixit (2017a).

Application

Sydney is the capital city of New South Wales, Australia and its 2016 population of 5,030,000 is the largest in Australia (Australian Bureau of Statistics 2017). The Sydney economy is dominated by the professional and financial services sectors (SGS Economics & Planning 2017), with economic activity concentrated in the Central Business District (Region 3). Several secondary but significant hubs of activity are also spread throughout the urban area. WestConnex is the largest road project by distance and funding under construction in Sydney. It comprises a largely underground 33 km long motorway through inner Sydney, connecting the M4 Motorway from the west of the city to the Sydney Central Business District, before proceeding south to Sydney Airport, Port Botany and the M5 Motorway. Construction on the A\$16.8 billion project commenced in 2015 and is anticipated to be completed in 2023. The project is expected to deliver a benefit–cost ratio of 1.88 (NSW Government 2015).

Prior to WestConnex, the 22 km stretch of the M5 Motorway between Prestons and Beverly Hills was widened from two to three lanes in each direction. WestConnex itself comprises four stages:

- Stage 1A M4 Widening: an additional lane in both directions on the existing 7.5 km stretch of M4 Motorway between Parramatta and Homebush.

- Stage 1B M4 East: a new 6.5 km, mostly tunnelled motorway between the current terminus of the M4 Motorway in Homebush and the intersection of Parramatta Road and Wattle Street in Haberfield.
- Stage 2 New M5: a new 9 km tunnelled motorway duplicating the existing M5 East Motorway from King Georges Road in Beverly Hills to a new interchange in St Peters.
- Stage 3 M4-M5 Link: a new 8 km tunnelled motorway between the terminus of the M4 East in Haberfield and the terminus of the New M5 in St Peters.

New links were added to the road network in Fig. 6 and existing links were modified to represent the M5 widening and each stage of WestConnex. These links are shown in Fig. 7. The model was then run for the following six scenarios simulating the progressive introduction of each stage:

- Scenario 1: 2011 base.
- Scenario 2: 2011 base plus M5 widening.
- Scenario 3: 2011 base plus M5 widening and WestConnex Stage 1A.
- Scenario 4: 2011 base plus M5 widening and WestConnex Stages 1A and 1B.
- Scenario 5: 2011 base plus M5 widening and WestConnex Stages 1A, 1B and 2.
- Scenario 6: 2011 base plus M5 widening and WestConnex Stages 1A, 1B, 2 and 3.

Results and discussion

Table 1 provides a summary of results for Scenarios 2 to 6 in relation to Scenario 1, including welfare as measured by equivalent variations and percentage changes in non-transport production, leisure hours, household travel costs and household travel demand. The results from Table 1 utilise the version of the model without residential location choice for household agents. Table 2 provides the same summary for the version of the model including location choice. It should be noted that the total welfare effect is indicated by EV, while double counting can occur through simple impact addition. It is also important to note that the simplistic nature of the residential location choice mechanism used for the model leads to economic results that are highly skewed and do not represent the true impacts of the WestConnex project. Results from the model that are relevant to travel times and travel demand, however, can be useful.

Validation of transport appraisals that handle WEIs can benefit from comparison of model implied value of time and real derived value of time. The value of time reported in the Transport for NSW report is 16.26\$ per hour per person for a private car (TFNSW 2018). The developed CGE model provides a range of value of time for different people based on their residence and employment region, as well as the industry in which they work. The average value of time value from the model is equal to 17.62\$ per hour per person for a private car which indicates realistic implied value of time.

In Figs. 8 and 9, spatial pattern of equivalent variations (EV) and change in non-transport production output are provided respectively to present the spatial pattern of economic impacts.

Scenario 1 was run to ensure the calibration data was replicated properly. Scenarios 2 to 6 were run for 20 iterations each, although the results largely converged to a band around 5% to 10% above and below the mean results within three iterations. These fluctuations were likely due to convergence criteria in the submodels being set too loosely,

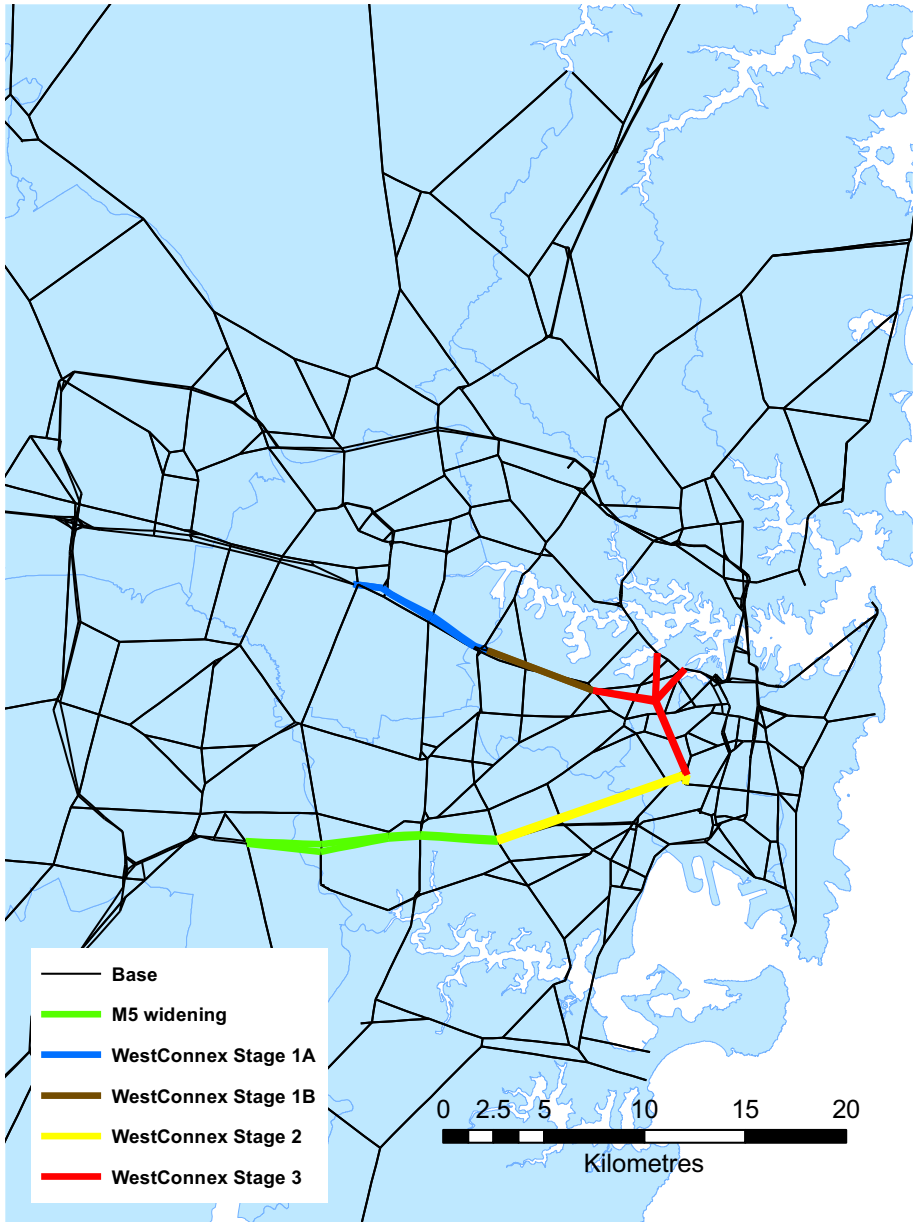


Fig. 7 Road network for model application

which is a subject for future investigation. Each model iteration took around 2 h to solve, almost entirely due to the transport submodel requiring around 30 min to converge for each time period. The transport submodel can be sped up in future models by implementing more efficient assignment algorithms and using multiple cores for processing.

For the model that did not include residential migration (i.e. for results presented in Table 1), in Scenario 2, the widening of the M5 Motorway resulted in a total increase in welfare of \$A259.10 million per year. The largest beneficiaries per capita were residents in Region 9, largely due to the M5's role as the primary road connection between Region 9 and the Sydney Central Business District. Correspondingly, non-transport production in Region 9 increased, but Region 13 had the largest increase due to its higher concentration of industrial activity. Residents in Regions 3, 5, 13 and 14 near the route of the M5 also experienced significant gains in welfare. On the other hand, residents in Region 8 experienced a slight disbenefit due to poorer traffic conditions from induced demand. The addition of lanes on the M4 Motorway in Scenario 3 led to more evenly spread gains in welfare across the metropolitan area, totalling A\$300.17 million per year. Regions 1, 8 and 10 experienced the fewest benefits, being some of the furthest regions from the improvements. In general, the M4 widening in Scenario 3 only resulted in marginal welfare improvements from Scenario 2, with leisure time, travel time and household travel demand similar to the M5 widening alone.

The introduction of new WestConnex links between the M4 and M5 via the Sydney Central Business District in Scenarios 4, 5 and 6 led to significant welfare gains of A\$593.14 million, A\$881.83 million and A\$1,602.84 million per year respectively, with every region experiencing improvements. In these three scenarios, Region 3 covering the Sydney Central Business District enjoyed the largest per capita increase in welfare, reflecting its position around the centre of WestConnex. In Scenario 4, the benefits were relatively spread across the metropolitan area, but over the progressive introduction of WestConnex, the benefits shifted towards the inner regions served by the new motorway. By Scenario 6, the inner city regions of 4, 5 and 6 in addition to Region 3 were the largest beneficiaries, with outlying regions in particular Regions 8 and 10 again experiencing the fewest benefits. In terms of non-transport production, Regions 3 to 6 correspondingly experienced the largest proportional increases in output due to their proximity to WestConnex. Production reduced in some outlying regions due to competition from the inner regions. In all scenarios and for all regions, the output of the transport industry shrunk in line with the reduction in freight requirements from improved travel times.

For results presented for the model including migration (i.e. for Table 2), it is important to note the large EV values presented in Table 2 should not be taken at face value. The mechanism of residential migration presented in this model is simplistic, and is intended to have higher flexibility in place of accuracy. It is likely that the lack of migration costs and the assumption that regions can contain an infinite number of household agents heavily skews the results. As such, the EV values presented in Table 2 should not be directly compared with those presented in Table 1.

Instead, the sign of the EV values obtained is noted to be mostly negative, which suggests that the WestConnex project may provide negative EV in the very long run once agents are able to move to their location of choice. It is also possible that the changes in utilities household agents experience as a result of their relocation is very large compared to the travel time changes the WestConnex project provides. It is more likely that the latter case is true, as the assumptions in the model of no relocation costs and regions having infinite housing capacity would incentivise heavy congregation in city CBD regions (region 13). Better modelling of residential location choice in future studies would improve the analytic capabilities of the model.

In both iterations of the model, however, the comparison of different scenarios' outcomes can be used as a decision-making criterion, policy recommendation, and economic implication. For Table 1, scenarios 4, 5, and 6 can be considered if total welfare gains are

Table 1 Summary of Scenario 2 to 6 results in relation to Scenario 1—no migration

| Result | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 |
|--------------------------------------------------|------------|------------|------------|------------|------------|
| Equivalent variations (EV) per capita (2011 A\$) | | | | | |
| Region 1 | 15.96 | 18.88 | 72.50 | 76.96 | 123.62 |
| Region 2 | 30.07 | 47.01 | 119.96 | 143.33 | 217.64 |
| Region 3 | 88.36 | 107.32 | 255.41 | 369.05 | 808.70 |
| Region 4 | 37.09 | 52.76 | 129.38 | 218.00 | 435.96 |
| Region 5 | 86.18 | 95.30 | 127.21 | 261.36 | 502.79 |
| Region 6 | 61.33 | 68.14 | 220.44 | 325.66 | 656.47 |
| Region 7 | 48.92 | 58.00 | 143.59 | 209.80 | 404.20 |
| Region 8 | − 3.52 | − 2.97 | 16.15 | 30.16 | 69.29 |
| Region 9 | 136.37 | 132.54 | 139.86 | 211.88 | 267.42 |
| Region 10 | 16.22 | 24.69 | 80.91 | 71.69 | 82.85 |
| Region 11 | 47.48 | 64.01 | 164.76 | 216.14 | 372.45 |
| Region 12 | 38.08 | 51.52 | 158.45 | 221.14 | 373.55 |
| Region 13 | 100.73 | 111.54 | 161.63 | 231.04 | 362.73 |
| Region 14 | 117.62 | 117.91 | 115.87 | 199.40 | 357.89 |
| Total equivalent variations (2011 A\$ million) | 259.10 | 300.17 | 593.14 | 881.83 | 1602.84 |
| Change in non-transport production output | | | | | |
| Region 1 | − 0.1015% | − 0.0981% | − 0.1648% | − 0.3075% | − 0.5449% |
| Region 2 | − 0.0432% | − 0.0112% | 0.0418% | − 0.0514% | − 0.2174% |
| Region 3 | − 0.0439% | − 0.0681% | − 0.0495% | 0.0830% | 0.2973% |
| Region 4 | − 0.0128% | − 0.0227% | 0.0495% | 0.1974% | 0.3023% |
| Region 5 | 0.1056% | 0.1186% | 0.0411% | 0.1550% | 0.3862% |
| Region 6 | 0.0094% | 0.0153% | 0.2081% | 0.2499% | 0.5810% |
| Region 7 | − 0.0502% | − 0.0821% | − 0.0750% | − 0.1158% | − 0.0440% |
| Region 8 | − 0.0808% | − 0.0983% | − 0.1471% | − 0.2019% | − 0.3555% |
| Region 9 | 0.1734% | 0.1752% | 0.0811% | 0.1111% | 0.0402% |
| Region 10 | − 0.0480% | − 0.0334% | − 0.0337% | − 0.1640% | − 0.4031% |
| Region 11 | − 0.0585% | 0.0065% | 0.2227% | 0.1048% | 0.0883% |
| Region 12 | − 0.0513% | − 0.1055% | − 0.0691% | − 0.1428% | − 0.2025% |
| Region 13 | 0.2021% | 0.2213% | 0.1409% | 0.1520% | 0.0957% |
| Region 14 | 0.1205% | 0.1087% | − 0.1356% | − 0.0219% | − 0.2617% |
| Change in labour time | − 0.0448% | − 0.0537% | − 0.0693% | − 0.1012% | − 0.1429% |
| Change in leisure time | 0.0281% | 0.0314% | 0.0616% | 0.0931% | 0.1724% |
| Change in household travel time | − 0.3968% | − 0.4272% | − 1.0060% | − 1.5363% | − 3.0510% |
| Change in household travel demand | 0.0232% | 0.0258% | 0.0615% | 0.0829% | 0.1737% |

a priority, as these scenarios resulted in significant total welfare gains. In the same vein, the negative welfare impact of scenarios 2 and 3 in region 8 should be considered when making decisions on these two scenarios. If equal benefit distribution across regions is a key decision-making criterion, scenarios 3 and 4 can be chosen because they have the most evenly distributed welfare impact with the lowest normalised standard deviation of all scenarios in terms of welfare effect. If a particular region has received additional attention,

Table 2 Summary of Scenario 2 to 6 results in relation to Scenario 1—migration inclusive

| Result | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 |
|--------------------------------------------------|--------------|--------------|--------------|--------------|--------------|
| Equivalent variations (EV) per capita (2011 A\$) | | | | | |
| Region 1 | - 71,135.58 | - 73,510.04 | - 79,456.6 | - 102,062.63 | - 131,190.98 |
| Region 2 | - 14,536.62 | - 14,393.32 | - 15,556.34 | - 19,483.54 | - 24,381.49 |
| Region 3 | - 61,382.89 | - 34,709.19 | - 29,559.01 | - 20,783.43 | 42,725.83 |
| Region 4 | - 58,641.88 | - 58,820.56 | - 63,951.49 | - 78,485.19 | - 106,547.92 |
| Region 5 | - 980.4 | - 401.24 | - 421.39 | 2475.26 | 2342 |
| Region 6 | - 35,444.52 | - 32,875.59 | - 32,536.42 | - 35,976.26 | - 40,549.64 |
| Region 7 | - 124,116.27 | - 124,939.86 | - 135,828.14 | - 183,662.71 | - 240,764.07 |
| Region 8 | - 51,899.15 | - 53,428.64 | - 58,286 | - 82,928.61 | - 107,758.39 |
| Region 9 | 21,411.86 | 23,244.36 | 26,218.24 | 28,119.53 | 32,815.64 |
| Region 10 | - 15,221.86 | - 15,386.03 | - 16,248.27 | - 19,879.03 | - 25,269.27 |
| Region 11 | - 6318.18 | - 5757.63 | - 5735.15 | - 6841.9 | - 8930.39 |
| Region 12 | - 52,045.19 | - 52,256.19 | - 56,018.97 | - 73,343.38 | - 93,284.39 |
| Region 13 | 91.78 | 421.28 | 479 | 746.88 | 722.84 |
| Region 14 | - 29,300.35 | - 23,901.35 | - 18,576.83 | - 7837.74 | - 44,490.31 |
| Total equivalent variations (2011 \$A million) | - 499,519.25 | - 466,714.00 | - 485,477.37 | - 599,942.75 | - 744,560.54 |
| Change in non-transport production output | | | | | |
| Region 1 | 1.5701% | 1.5102% | 1.2793% | 0.9742% | 0.5753% |
| Region 2 | 3.1661% | 2.7856% | 2.3093% | 2.3499% | 1.7878% |
| Region 3 | - 13.2033% | - 13.3456% | - 13.9114% | - 17.4837% | - 20.146% |
| Region 4 | - 3.8224% | - 3.7608% | - 3.1146% | - 3.1503% | - 1.3164% |
| Region 5 | 3.5872% | 3.7702% | 3.5906% | 4.7905% | 5.0808% |
| Region 6 | - 1.2148% | - 1.1314% | - 1.0381% | - 0.7874% | - 0.766% |
| Region 7 | - 5.6518% | - 5.4677% | - 5.1977% | - 5.7433% | - 5.6186% |
| Region 8 | 0.4993% | 0.4822% | 0.5604% | - 0.2629% | 0.0558% |
| Region 9 | 9.2881% | 8.56% | 9.9497% | 9.8643% | 11.8254% |
| Region 10 | - 1.8392% | - 1.894% | - 1.9278% | - 2.6429% | - 3.2034% |

Table 2 (continued)

| Result | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 |
|-----------------------------------|------------|------------|------------|------------|------------|
| Region 11 | - 2.0295% | - 2.1443% | - 2.5723% | - 3.1329% | - 3.5734% |
| Region 12 | - 6.6162% | - 6.5398% | - 6.6265% | - 7.593% | - 8.568% |
| Region 13 | 4.0914% | 4.2978% | 4.0611% | 4.424% | 5.1859% |
| Region 14 | 1.1979% | 1.1625% | 1.0934% | 6.2949% | 6.5702% |
| Change in household travel time | 2.1985% | - 0.2587% | - 0.1174% | - 3.3790% | - 3.6900% |
| Change in household travel demand | - 0.7514% | - 0.6254% | - 0.5774% | - 0.5239% | - 0.4854% |
| Total household population | | | | | |
| Region 1 | 36,944.23 | 36,849.52 | 36,970.72 | 36,558.25 | 36,459.24 |
| Region 2 | 167,597.2 | 167,149.1 | 167,367.3 | 165,987.6 | 165,778.8 |
| Region 3 | 4275.281 | 4260.124 | 4259.618 | 4224.259 | 4253.503 |
| Region 4 | 32,454.73 | 32,330.24 | 32,323.52 | 31,992.66 | 31,940.87 |
| Region 5 | 999,372.5 | 999,826.3 | 996,000.8 | 1,018,510 | 1,020,394 |
| Region 6 | 31,548.41 | 31,449.32 | 31,516.92 | 31,201.88 | 31,261.19 |
| Region 7 | 21,128.81 | 21,039.08 | 21,030.11 | 20,823.06 | 20,822.23 |
| Region 8 | 84,622.17 | 83,610.05 | 82,771.07 | 75,544.02 | 75,590.88 |
| Region 9 | 105,666.4 | 105,798 | 106,322.5 | 105,591.6 | 105,435.9 |
| Region 10 | 163,417.9 | 163,039.1 | 163,667.2 | 162,184.6 | 161,996.2 |
| Region 11 | 279,383 | 278,150.7 | 278,713.2 | 275,745 | 276,275.9 |
| Region 12 | 27,285.57 | 27,194.26 | 27,233.25 | 26,971.66 | 26,971.33 |
| Region 13 | 2,306,030 | 2,309,067 | 2,311,589 | 2,304,355 | 2,302,692 |
| Region 14 | 26,565.79 | 26,529.64 | 26,527.29 | 26,602.46 | 26,419.86 |
| Change in household population | | | | | |
| Region 1 | - 1.43% | - 1.68% | - 1.35% | - 2.46% | - 2.72% |
| Region 2 | - 1.15% | - 1.41% | - 1.28% | - 2.1% | - 2.22% |
| Region 3 | 1.72% | 1.36% | 1.35% | 0.51% | 1.21% |

Table 2 (continued)

| Result | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 |
|-----------|------------|------------|------------|------------|------------|
| Region 4 | 0.66% | 0.27% | 0.25% | - 0.78% | - 0.94% |
| Region 5 | - 7.51% | - 7.47% | - 7.82% | - 5.74% | - 5.57% |
| Region 6 | - 0.11% | - 0.42% | - 0.21% | - 1.21% | - 1.02% |
| Region 7 | 1.51% | 1.08% | 1.04% | 0.04% | 0.04% |
| Region 8 | 10.37% | 9.05% | 7.95% | - 1.47% | - 1.41% |
| Region 9 | - 4.16% | - 4.04% | - 3.57% | - 4.23% | - 4.37% |
| Region 10 | - 1.47% | - 1.7% | - 1.32% | - 2.22% | - 2.33% |
| Region 11 | 3.47% | 3.01% | 3.22% | 2.12% | 2.32% |
| Region 12 | 0.68% | 0.34% | 0.49% | - 0.48% | - 0.48% |
| Region 13 | 3.25% | 3.39% | 3.5% | 3.18% | 3.1% |
| Region 14 | - 0.1% | - 0.23% | - 0.24% | 0.04% | - 0.64% |

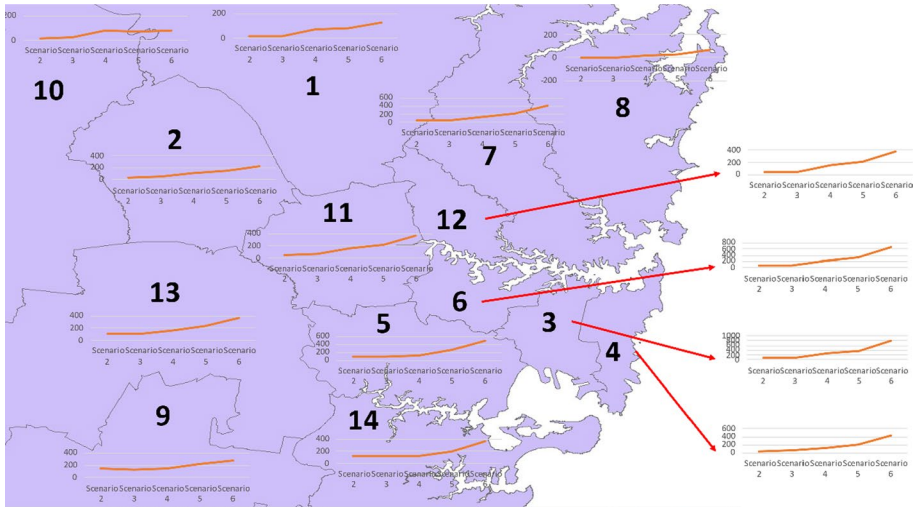


Fig. 8 Spatial pattern of equivalent variations (EV) per capita (2011 A\$)

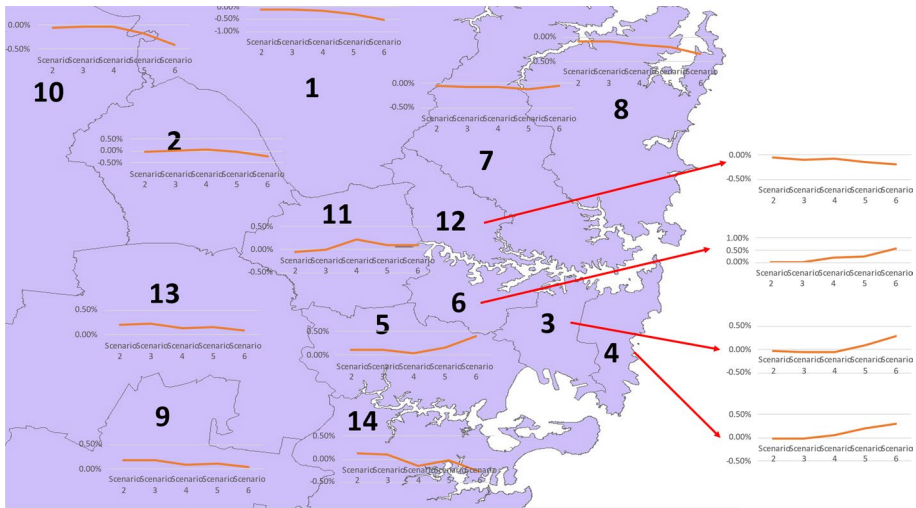


Fig. 9 Spatial pattern of change in non-transport production output

scenarios can be chosen based on their impact on that region. As illustrated in Fig. 10, scenarios 4,5,6 benefit regions 3 and 6, respectively, whereas scenarios 2 and 3 benefit regions 9 and 14, respectively. Non-transport production output, labour time, leisure time, household travel time, and household travel demand are some of the other criteria provided by the model for multi-criteria decision making.

For Table 2 results, decisions should be made in line with the process outlined immediately above, but instead of considering EVs (which are likely highly inaccurate and reflect the results of the migration process rather than the infrastructure project), consideration

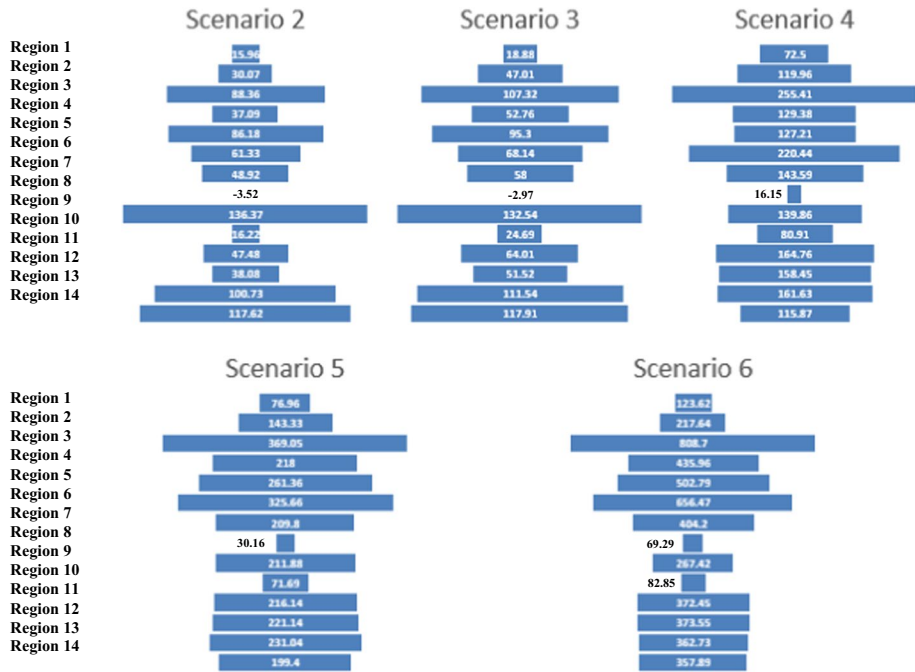


Fig. 10 Regions equivalent variations (EV) per capita (2011 A\$)

should instead be made for the total travel time that agents experience, with emphasis placed on minimising travel times.

Figure 11 shows changes in link volumes from Scenario 1 to Scenario 6. From Fig. 11, traffic was diverted from parallel arterial routes onto WestConnex and the widened M5. On the other hand, many links feeding the motorway network experienced increases in demand. Overall, there was a 0.1737% increase in household travel demand (induced demand) across the whole metropolitan area. The network improvements led to a reduction in household travel time of 3.051%, even after accounting for induced demand. The travel time saved was retained by households as leisure time, and the relative reduction in the cost of leisure travel compared to commuting travel led to further substitution towards leisure time from labour time.

To provide more detailed information about the transport related indicators, Tables 3 and 4 present the percentage change in travel time for different activity types. Table 3 provides the information for the model without residential location choice while Table 4 includes residential location choice. For Table 3, in all scenarios, leisure travel times reduce by the greatest proportion, followed by commuting and shopping. In each subsequent scenario (representing the progressive introduction of WestConnex), travel times for all three purposes continue to decrease, which is completely matching the intuition about the explanation of the network. Nonetheless, the essential point here would be the significance of such improvement in the level of service provided by the network expansion compared to the cost of the project and other economic benefits discussed under Tables 1 and 2.

The results in Table 4 are slightly less intuitive. The greatest reduction in travel time is commute time in this model iteration instead of leisure travel time. There are instead increases in travel time in scenario 2, but this returns to being decreases in travel time

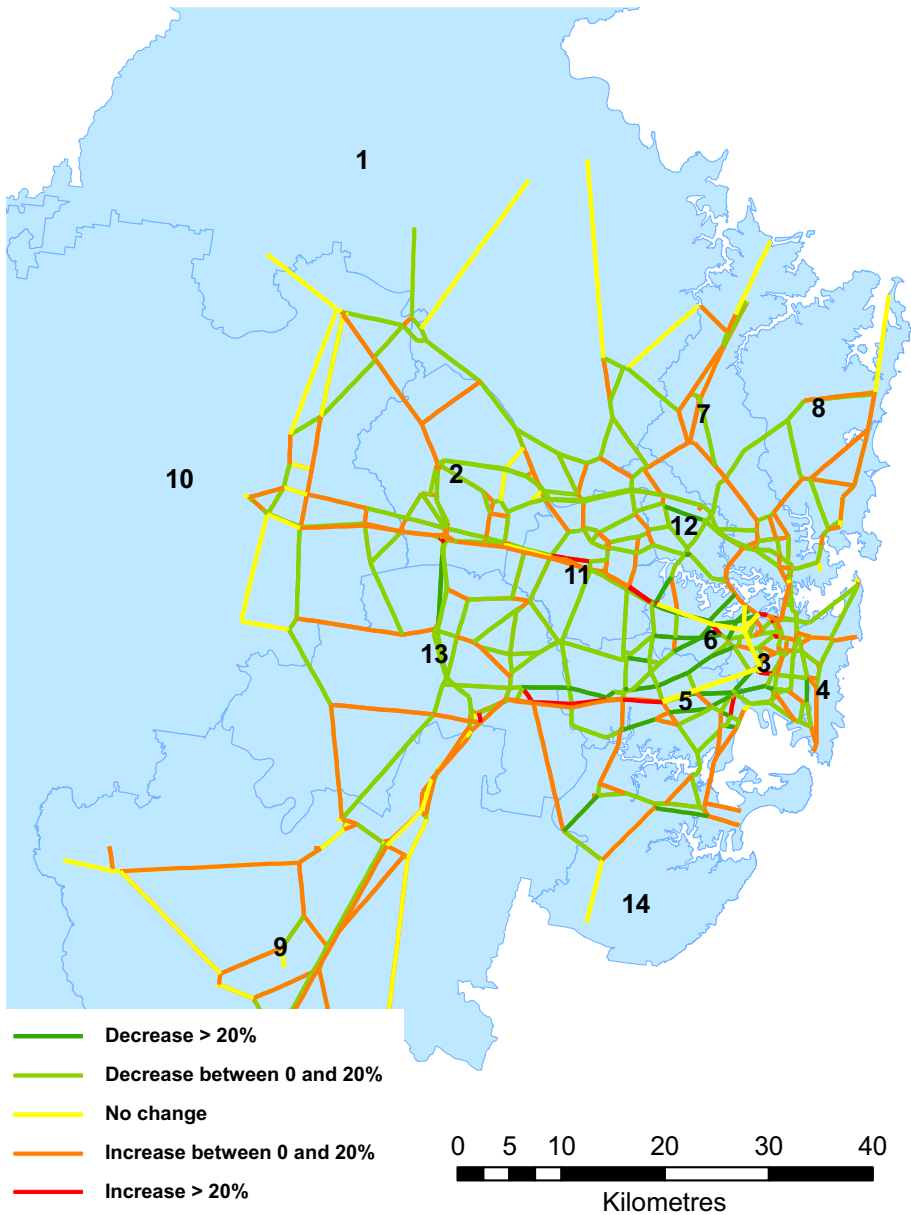


Fig. 11 Change in link volumes from Scenario 1 to Scenario 6

in scenarios 3–6. There is still a decreasing trend in travel times as the project continues (with a slightly smaller decrease in scenario 4 compared to 3). The increases in scenario 2 is likely a result of the changes in the network due to migration causing overcrowding in certain regions. As the project has the smallest impacts at this stage, it is expected that changes in travel time caused by this overcrowding would be significant when compared to the reductions the project would provide. As the project progresses however, the reductions

Table 3 Total travel times (percentage change from Scenario 1)—no migration

| | Scenario 2 (%) | Scenario 3 (%) | Scenario 4 (%) | Scenario 5 (%) | Scenario 6 (%) |
|-----------------------|----------------|----------------|----------------|----------------|----------------|
| Shopping travel time | − 0.19 | − 0.19 | − 0.48 | − 0.74 | − 1.45 |
| Commuting travel time | − 0.39 | − 0.43 | − 1.00 | − 1.56 | − 3.14 |
| Leisure travel time | − 0.45 | − 0.49 | − 1.12 | − 1.74 | − 3.40 |
| Total | − 0.40 | − 0.43 | − 1.00 | − 1.56 | − 3.06 |

Table 4 Total travel times (percentage change from Scenario 1)—migration inclusive

| | Scenario 2 (%) | Scenario 3 (%) | Scenario 4 (%) | Scenario 5 (%) | Scenario 6 (%) |
|-----------------------|----------------|----------------|----------------|----------------|----------------|
| Shopping travel time | 0.64 | 0.06 | 0.14 | − 0.59 | − 0.53 |
| Commuting travel time | 1.51 | − 0.57 | − 0.7 | − 3.71 | − 4.49 |
| Leisure travel time | 2.45 | − 0.31 | − 0.08 | − 3.7 | − 3.98 |
| Total | 2.2 | − 0.26 | − 0.12 | − 3.38 | − 3.69 |

are now significant enough to offset the initial increases. It is worth noting that the large reductions in commuting travel time is likely partially due to the migration; household agents are likely to migrate to locations closer to their place of employment, and in so doing contributes to a reduction in commute travel time.

Another advantage of the proposed transport-based CGE model is that accessibility indicators derived from the true transport (the relatively close to the real world transport network of this paper) network can be extracted in interaction with economic indicators. Table 5 and 6 presents labour and retail accessibility based on accessibility for each region being estimated according to the inverse of exponential of travel time multiplied by labour and retail opportunities for each firm shown in Eqs. 36 and 37 (Goodwin 2019) with provided graphical presentation in Fig. 12.

$$\text{Labour accessibility} = \sum_{i=1}^{i=14} \frac{\text{Labour demand}(i)}{\exp(\text{weight} \times \text{traveltime}(i))} \quad (36)$$

$$\text{Retail accessibility} = \sum_{i=1}^{i=14} \frac{\text{Good production}(i)}{\exp(\text{weight} \times \text{traveltime}(i))} \quad (37)$$

Table 5 shows changes in labour accessibility for residents in each region, in the migration inclusive model. Table 6 shows the same for the model with migration included. Labour accessibility is calculated as the sum of hours demanded by each firm, weighted by an exponential function of the travel time to each firm. The changes in accessibility generally align with changes in production as reported in Table 1 in the manuscript. This table also shows changes in retail accessibility for residents in each region. Similarly, retail accessibility is calculated as the sum of non-transport output from each firm, weighted by an exponential function of the travel time to each firm.

Table 6 shows generally negative changes in both labour and retail accessibility. As these metrics measure retail and labour opportunities, they are likely to be highly skewed

Table 5 Accessibility values for labour and retail opportunities—migration inclusive

| Region | Scenario 2 | | Scenario 3 | | Scenario 4 | | Scenario 5 | | Scenario 6 | |
|--------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|
| | Labour access- sibility (%) | Retail access- sibility (%) | Labour access- sibility (%) | Retail access- sibility (%) | Labour access- sibility (%) | Retail access- sibility (%) | Labour access- sibility (%) | Retail access- sibility (%) | Labour access- sibility (%) | Retail access- sibility (%) |
| 1 | 0.391 | 0.178 | 0.357 | 0.167 | 1.377 | 0.604 | 1.863 | 0.756 | 3.181 | 1.380 |
| 2 | 0.674 | 0.341 | 1.003 | 0.521 | 2.588 | 1.412 | 3.736 | 1.771 | 5.931 | 2.833 |
| 3 | 0.296 | 0.446 | 0.329 | 0.468 | 1.412 | 1.528 | 1.519 | 2.018 | 3.437 | 3.639 |
| 4 | 0.265 | 0.396 | 0.236 | 0.381 | 1.532 | 1.503 | 1.605 | 1.992 | 4.368 | 3.878 |
| 5 | 0.539 | 0.549 | 0.673 | 0.602 | 1.030 | 0.844 | 3.219 | 1.697 | 6.525 | 3.489 |
| 6 | 0.307 | 0.339 | 0.349 | 0.417 | 1.126 | 1.273 | 1.959 | 1.754 | 4.417 | 3.552 |
| 7 | 0.201 | 0.172 | 0.206 | 0.185 | 0.685 | 0.737 | 0.967 | 1.082 | 1.889 | 2.160 |
| 8 | 0.232 | 0.235 | 0.052 | 0.127 | 1.080 | 0.948 | 1.305 | 1.236 | 2.319 | 2.390 |
| 9 | 2.436 | 1.543 | 2.000 | 1.271 | 3.477 | 1.889 | 6.651 | 3.160 | 9.787 | 4.575 |
| 10 | 0.943 | 0.487 | 1.181 | 0.588 | 2.900 | 1.661 | 4.218 | 2.016 | 6.735 | 3.136 |
| 11 | 0.484 | 0.300 | 0.589 | 0.340 | 2.718 | 1.490 | 3.784 | 1.835 | 6.568 | 3.205 |
| 12 | 0.222 | 0.177 | 0.398 | 0.243 | 1.381 | 0.907 | 2.009 | 1.249 | 3.198 | 2.364 |
| 13 | 2.136 | 1.262 | 2.210 | 1.344 | 3.502 | 1.923 | 6.142 | 2.875 | 8.448 | 3.923 |
| 14 | 0.187 | 0.424 | 0.893 | 0.608 | 1.353 | 0.748 | 2.413 | 1.427 | 6.313 | 3.126 |

Table 6 Accessibility values for labour and retail opportunities—no migration

| Region | Scenario 2 | | Scenario 3 | | Scenario 4 | | Scenario 5 | | Scenario 6 | |
|--------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| | Labour accessibility (%) | Retail accessibility (%) | Labour accessibility (%) | Retail accessibility (%) | Labour accessibility (%) | Retail accessibility (%) | Labour accessibility (%) | Retail accessibility (%) | Labour accessibility (%) | Retail accessibility (%) |
| 1 | -2.272 | -2.671 | -23.669 | -2.231 | -1.301 | -2.108 | -0.995 | -1.792 | -1.797 | -2.151 |
| 2 | -2.083 | -2.583 | -29.324 | -1.595 | -0.338 | -1.367 | 1.059 | -0.278 | -0.409 | -1.382 |
| 3 | -5.386 | -4.607 | -17.323 | -3.986 | -4.933 | -3.33 | -7.35 | -3.06 | -5.387 | -1.836 |
| 4 | -5.986 | -4.763 | -20.505 | -4.051 | -5.193 | -3.3 | -7.929 | -3.24 | -5.018 | -1.421 |
| 5 | 5.748 | -0.204 | -35.172 | 2.811 | 9.912 | 2.617 | 47.611 | 17.104 | 56.998 | 19.304 |
| 6 | -4.3 | -3.749 | -19.199 | -3.059 | -3.478 | -2.671 | -3.833 | -1.933 | -2.254 | -0.949 |
| 7 | -4.882 | -4.378 | -17.595 | -4.06 | -4.94 | -3.912 | -6.069 | -3.927 | -6.772 | -3.854 |
| 8 | -4.819 | -4.067 | -23.491 | -3.777 | -4.782 | -3.511 | -5.799 | -3.502 | -6.474 | -3.395 |
| 9 | -3.565 | -4.588 | -19.547 | -3.266 | -2.318 | -2.516 | -2.767 | -3.065 | -2.881 | -3.15 |
| 10 | -4.136 | -3.825 | -38.782 | -3.271 | -1.735 | -2.7 | 1.447 | -0.373 | 2.13 | -1.633 |
| 11 | -2.757 | -3.449 | -26.419 | -2.458 | 1.303 | -0.99 | 1.778 | -0.484 | 1.952 | -0.678 |
| 12 | -3.606 | -3.448 | -18.6 | -3.012 | -3.074 | -2.856 | -3.363 | -2.441 | -3.651 | -2.103 |
| 13 | -21.351 | -14.813 | -64.416 | -11.98 | -19.145 | -12.172 | -19.714 | -12.293 | -22.562 | -15.842 |
| 14 | 13.734 | 2.885 | -30.957 | 6.699 | 21.983 | 10.425 | 61.988 | 26.669 | 70.685 | 26.863 |

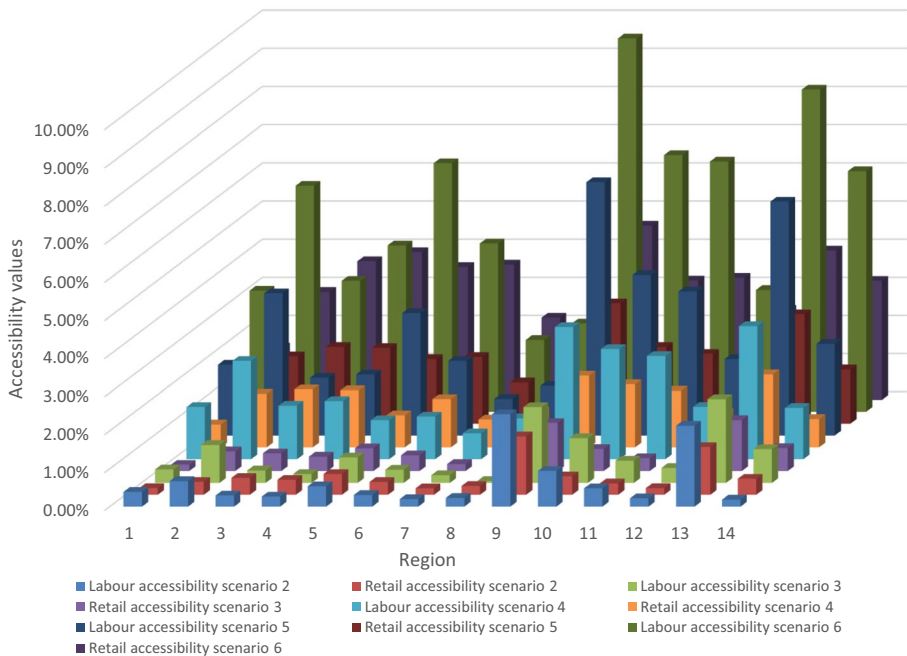


Fig. 12 Graphical presentation of accessibility values for labour and retail opportunities

due to migration (similar to Table 2’s results), and as such is likely not very useful for informing policy planning in the current state. With better modelled migration, these metrics would be more useful.

To further assess the accessibility formula used in estimation of the results of the previous table, Figs. 13 presents a sensitivity analysis of the weight factor in the accessibility function for labour accessibility values of Scenario 6 discussed in the previous table, and Fig. 14 shows a sensitivity analysis of the same for retail accessibility, varying from 0.5 to 3, while it was set to 1 in the result presented in Tables 5 and 6.

It can be seen from the figures above that the percentage change in the estimated accessibility values can be linearly proportional to the accessibility weight factor of travel time in the impedance function.

Sensitivity analysis

To determine the model’s empirical robustness, a sensitivity analysis is performed. This is accomplished by altering particular input variables one at a time to examine the degree of change in the model’s outputs; significant unintuitive changes in the model’s outputs from minor input changes would suggest potential model instability.

Testing is carried out on variables from both the CGE and the transport submodels of the integrated model. Endowment of capital (e_k) and endowment of time (e_t) from CGE submodel and link free flow costs (z_0) and link capacities (q_c) from transport submodel are the variables that have altered.

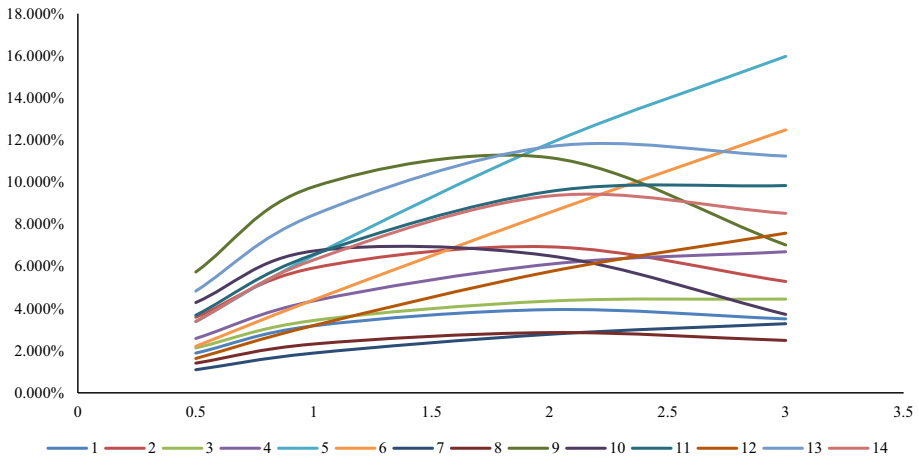


Fig. 13 Sensitivity analysis of weight factor in labour accessibility function

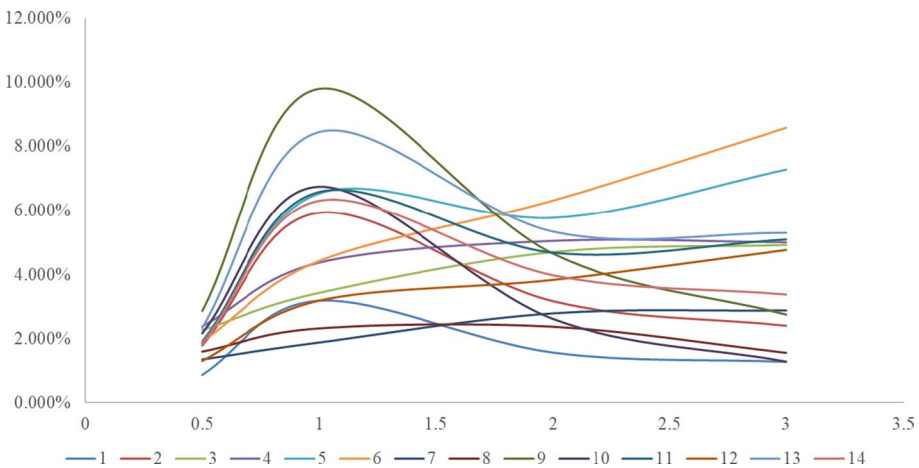


Fig. 14 Sensitivity analysis of weight factor in retail accessibility function

The two CGE submodel variables are selected as they are easy to understand motivators for household agent behaviour. Changes in the model outputs should be able to be reasonably intuitively understood based on changes in these variables. Abnormal changes are therefore evidence for model instability. The transport submodel variables were similarly selected as they are intuitive to understand. Additionally, typical hard infrastructure upgrades primarily affect these two aspects of transportation, and so ensuring they do not contribute to significant model instability is especially important for policy considerations.

For each variable outlined above, four tests are conducted with reducing and increasing the input variable by 5% and 10%. The stability of outputs was then assessed by comparing results to the base model. The equivalent variation (EV) of the network and the percentage change in income compared to total household income in the base scenario are calculated.

Tables 7 and 8 shows the sensitivity analysis on the impact of variables from the CGE submodel and transport submodel on EV and the percentage change in income compared to total household income in the base scenario.

Changes in the model outputs for income and utility are intuitively explained from the input variable changes, where any additional costs or reduction in endowments resulted in negative EVs and the reverse resulted in positive EVs with no significant fluctuations in the model outputs. Changes Other economic model outputs (the goods gap and labour gap) follow an intuitive trend. For example, reductions in agent capital endowments lead to a large labour gap in each region, as less labour is supplied at the same demand. In the same line, increasing in network links capacity and decreasing of the links free flow cost resulted in positive EVs and income change as expected without any substantial changes in the model outputs.

Conclusion

Existing models in the four-step transport planning framework can simulate travel demands and interactions in transport networks with a high degree of detail, but many rely on fixed economic parameters for markets other than transport and land. With recent interest in the wider economic impacts of transport, CGE models have been increasingly applied to analyse transport projects and policies. Since CGE models are simulators of entire economies, they are able to estimate the magnitude and distribution of impacts both spatially and through markets, while also providing a rich set of outputs including GDP and welfare.

This paper presented an integrated CGE and transport model and calibrated it for the Sydney road network and economy. The contributions of this model are both conceptual—in applying the CGE submodel as a trip generator and distributor in the four-step framework—and technical—in developing the linkages between the submodels that enable them to be calibrated as full CGE and transport models. Several existing models link CGE and transport network models, but very few incorporate detailed networks or generate a complete set of travel demands (including household and freight), both of which are necessary in the four-step framework. In the presented model, the CGE submodel simulates the behaviour of households and firms interacting in markets, where their behaviour takes trip costs into account. The model then generates trips as a derived demand from agent activities and assigns them to the road network according to user equilibrium, before feeding back trip costs to the CGE submodel. The model was tested by simulating the WestConnex motorway project under construction in Sydney. The results showed significant increases in welfare for regions close to the improvements.

Like any model, the presented model was built for a purpose—to provide a tool for the rapid strategic assessment of transport projects and policies when economic responses cannot be assumed to remain static. Compared with some activity-based models and discrete choice modelling frameworks, CGE models tend to represent the behaviours of travel markets in less detail, but do provide a comprehensive structure that allows for the incorporation of more complex models where required.

There are a multitude of avenues for expansion of the presented model. The most immediate feature required in the four-step framework is mode choice. From this, land markets can be incorporated as additional commodities in the CGE framework to replicate the behaviours of a LUTI model. The inclusion of a better and more accurate residential location choice mechanism within the model could also lead to more accurate economic

Table 7 Sensitivity analysis on impact of endowment of capital (e_k) and endowment of time (e_t) on EV and the percentage change in income compared to total household income in base scenario

| Region | Endowment of time, e_t | | | | | | | | | | | | |
|-------------------|-----------------------------|-------------------|-------------------|-------------------|-------------------|-------------------|--------------------------|--------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| | Endowment of capital, e_k | | | | | | Endowment of time, e_t | | | | | | |
| | Decrease by 10% | | Decrease by 5% | | Increase by 5% | | Increase by 10% | | Decrease by 10% | | Decrease by 5% | | |
| EV (% difference) | EV (% difference) | EV (% difference) | EV (% difference) | EV (% difference) | EV (% difference) | EV (% difference) | EV (% difference) | EV (% difference) | EV (% difference) | EV (% difference) | EV (% difference) | EV (% difference) | |
| 1 | -415.54 (-0.9635) | -210.83 (-0.4888) | 210.29 (0.4876) | 424.20 (0.9835) | 754.91 (1.7503) | 354.32 (0.8215) | -325.93 (-0.7557) | -618.07 (-1.4330) | -210.83 (-0.4888) | 210.29 (0.4876) | 424.20 (0.9835) | 754.91 (1.7503) | 354.32 (0.8215) |
| 2 | -414.45 (-0.6755) | -212.95 (-0.3471) | 217.01 (0.3537) | 438.41 (0.7146) | 770.20 (1.2554) | 363.25 (0.5921) | -330.4741 (-0.5387) | -631.45 (-1.0293) | -212.95 (-0.3471) | 217.01 (0.3537) | 438.41 (0.7146) | 770.20 (1.2554) | 363.25 (0.5921) |
| 3 | 403.67 (1.0525) | 184.45 (0.4809) | -153.29 (-0.3997) | -275.73 (-0.7189) | -136.15 (-0.3550) | -73.67 (-0.1921) | 76.57 (0.1997) | 148.39 (0.3869) | 403.67 (1.0525) | 184.45 (0.4809) | -153.29 (-0.3997) | -275.73 (-0.7189) | -136.15 (-0.3550) |
| 4 | -30.63 (-0.0677) | -22.32 (-0.0494) | 41.32 (0.0914) | 97.21 (0.2150) | 268.44 (0.5936) | 121.90 (0.2695) | -101.69 (-0.2248) | -196.37 (-0.4342) | -30.63 (-0.0677) | -22.32 (-0.0494) | 41.32 (0.0914) | 97.21 (0.2150) | 268.44 (0.5936) |
| 5 | -735.01 (-0.7602) | -372.21 (-0.3850) | 363.23 (0.3757) | 735.36 (0.7606) | 1379.39 (1.4267) | 664.18 (0.6870) | -635.66 (-0.6575) | -1250.65 (-1.2936) | -735.01 (-0.7602) | -372.21 (-0.3850) | 363.23 (0.3757) | 735.36 (0.7606) | 1379.39 (1.4267) |
| 6 | -37.47 (-0.0806) | -28.97 (-0.0623) | 46.14 (0.0992) | 111.51 (0.2398) | 302.44 (0.6504) | 135.21 (0.2908) | -116.62 (-0.2508) | -219.46 (-0.4719) | -37.47 (-0.0806) | -28.97 (-0.0623) | 46.14 (0.0992) | 111.51 (0.2398) | 302.44 (0.6504) |
| 7 | 188.57 (0.2934) | 70.94 (0.1104) | -35.07 (-0.0546) | -32.07 (-0.0499) | 192.12 (0.2989) | 71.32 (0.1110) | -44.39 (-0.0691) | -67.37 (-0.1048) | 188.57 (0.2934) | 70.94 (0.1104) | -35.07 (-0.0546) | -32.07 (-0.0499) | 192.12 (0.2989) |
| 8 | -398.52 (-0.8027) | -202.33 (-0.4075) | 206.51 (0.4159) | 416.94 (0.8398) | 706.78 (1.4235) | 329.87 (0.6644) | -296.38 (-0.5969) | -557.90 (-1.1237) | -398.52 (-0.8027) | -202.33 (-0.4075) | 206.51 (0.4159) | 416.94 (0.8398) | 706.78 (1.4235) |
| 9 | -580.41 (-1.153) | -288.59 (-0.5733) | 284.89 (0.5659) | 561.48 (1.1154) | 969.13 (1.9251) | 467.55 (0.9288) | -433.88 (-0.8619) | -843.68 (-1.6759) | -580.41 (-1.153) | -288.59 (-0.5733) | 284.89 (0.5659) | 561.48 (1.1154) | 969.13 (1.9251) |
| 10 | -677.10 (-1.098) | -339.03 (-0.5496) | 336.28 (0.5451) | 664.65 (1.0775) | 1068.91 (1.7328) | 505.34 (0.8192) | -458.38 (-0.7431) | -874.93 (-1.4184) | -677.10 (-1.098) | -339.03 (-0.5496) | 336.28 (0.5451) | 664.65 (1.0775) | 1068.91 (1.7328) |
| 11 | -250.61 (-0.3741) | -135.88 (-0.2029) | 149.47 (0.2232) | 312.89 (0.4671) | 614.14 (0.9168) | 283.24 (0.4228) | -253.56 (-0.3785) | -480.61 (-0.7175) | -250.61 (-0.3741) | -135.88 (-0.2029) | 149.47 (0.2232) | 312.89 (0.4671) | 614.14 (0.9168) |
| 12 | -33.76 (-0.1218) | -23.96 (-0.0865) | 34.27 (0.1237) | 79.26 (0.2860) | 195.40 (0.7050) | 87.09 (0.3143) | -72.08 (-0.2601) | -134.89 (-0.4867) | -33.76 (-0.1218) | -23.96 (-0.0865) | 34.27 (0.1237) | 79.26 (0.2860) | 195.40 (0.7050) |
| 13 | -346.59 (-0.4961) | -181.71 (-0.2601) | 189.48 (0.2712) | 389.64 (0.5578) | 732.43 (1.0484) | 343.57 (0.4918) | -309.03 (-0.4424) | -590.61 (-0.8454) | -346.59 (-0.4961) | -181.71 (-0.2601) | 189.48 (0.2712) | 389.64 (0.5578) | 732.43 (1.0484) |

Table 7 (continued)

| Region | Endowment of capital, ϵ_k | | | | | | Endowment of time, ϵ_t | | | | | | | | | |
|--------|------------------------------------|-------------------|-------------------|-------------------|-----------------|-------------------|---------------------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| | Decrease by 10% | | Decrease by 5% | | Increase by 5% | | Increase by 10% | | Decrease by 5% | | Decrease by 10% | | Increase by 5% | | Increase by 10% | |
| | EV (% difference) | | EV (% difference) | EV (% difference) | | EV (% difference) | EV (% difference) | EV (% difference) | EV (% difference) | EV (% difference) | EV (% difference) | EV (% difference) | EV (% difference) | EV (% difference) | EV (% difference) | EV (% difference) |
| 14 | -293.74 (-0.6072) | -156.71 (-0.3240) | 162.09 (0.3351) | 341.34 (0.7057) | 722.90 (1.4944) | 335.80 (0.6942) | 302.20 (-0.6247) | 573.60 (-1.1858) | 1920.15 (-0.2493) | 2052.67 (0.2665) | 8541.08 (1.1090) | 3989.03 (0.5180) | 3603.75 (-0.4679) | 6891.26 (-0.8948) | | |
| Total | | | | | | | | | | | | | | | | |

Table 8 Sensitivity analysis impact of link capacities (q_c) and link free flow costs (z_c) on EV and the percentage change in income compared to total household income in base scenario

| Region | Link capacities, q_c | | | | | | Link free flow costs, z_c | | | | | |
|--------|--------------------------------------|-------------------------------------|-------------------------------------|--------------------------------------|--------------------------------------|-------------------------------------|-------------------------------------|--------------------------------------|-------------------------------------|-------------------------------------|--------------------------------------|--|
| | Decrease by 10% EV (% difference) | Decrease by 5% EV (% difference) | Increase by 5% EV (% difference) | Increase by 10% EV (% difference) | Decrease by 10% EV (% difference) | Decrease by 5% EV (% difference) | Decrease by 5% EV (% difference) | Decrease by 10% EV (% difference) | Increase by 5% EV (% difference) | Increase by 5% EV (% difference) | Increase by 10% EV (% difference) | |
| 1 | -203.82 (-0.4726) | -87.88 (-0.2038) | 60.42 (0.1401) | 106.37 (0.2466) | 109.4405 (0.2537) | 52.16 (0.1209) | -58.80 (-0.1363) | -116.06 (-0.2691) | | | | |
| 2 | -230.98 (-0.3765) | -96.52 (-0.1573) | 69.87 (0.1139) | 121.00 (0.1972) | 134.70 (0.2196) | 66.78 (0.1089) | -71.81 (-0.1171) | -139.67 (-0.2277) | | | | |
| 3 | -485.85 (-1.2668) | -196.67 (-0.5128) | 161.83 (0.4220) | 276.09 (0.7199) | 241.77 (0.6304) | 123.31 (0.3215) | -118.44 (-0.3088) | -240.07 (-0.6260) | | | | |
| 4 | -267.69 (-0.5919) | -106.46 (-0.2354) | 87.09 (0.1926) | 145.06 (0.3208) | 120.20 (0.2658) | 61.66 (0.1364) | -60.15 (-0.1330) | -120.50 (-0.2664) | | | | |
| 5 | -559.51 (-0.5787) | -233.65 (-0.2417) | 175.03 (0.1810) | 289.90 (0.2998) | 227.86 (0.2357) | 112.35 (0.1162) | -119.60 (-0.1237) | -235.78 (-0.2439) | | | | |
| 6 | -295.74 (-0.6360) | -119.21 (-0.2564) | 95.14 (0.2046) | 156.48 (0.3365) | 137.41 (0.2955) | 70.38 (0.1513) | -68.45 (-0.1472) | -137.37 (-0.2954) | | | | |
| 7 | -516.41 (-0.8035) | -214.13 (-0.3332) | 165.72 (0.2578) | 279.82 (0.4354) | 232.08 (0.3611) | 118.75 (0.1848) | -114.54 (-0.1782) | -235.58 (-0.3665) | | | | |
| 8 | -156.95 (-0.3161) | -63.91 (-0.1287) | 46.16 (0.0930) | 81.27 (0.1637) | 74.91 (0.1509) | 38.96 (0.0785) | -37.08 (-0.0747) | -80.36 (-0.1619) | | | | |
| 9 | -185.26 (-0.3680) | -72.87 (-0.1448) | 61.84 (0.1228) | 109.16 (0.2168) | 131.03 (0.2603) | 69.31 (0.1377) | -63.85 (-0.1268) | -129.44 (-0.2571) | | | | |
| 10 | -107.13 (-0.1737) | -45.00 (-0.0730) | 29.60 (0.0480) | 52.96 (0.0859) | 126.84 (0.2056) | 63.33 (0.1027) | -67.99 (-0.1102) | -133.02 (-0.2157) | | | | |
| 11 | -326.00 (-0.4867) | -134.95 (-0.2015) | 102.06 (0.1524) | 173.71 (0.2593) | 177.08 (0.2644) | 87.93 (0.1313) | -92.38 (-0.1379) | -181.14 (-0.2704) | | | | |
| 12 | -169.57 (-0.6118) | -69.90 (-0.2522) | 53.78 (0.1941) | 90.00 (0.3247) | 77.73 (0.2805) | 40.02 (0.1444) | -39.33 (-0.1419) | -80.13 (-0.2891) | | | | |
| 13 | -296.02 (-0.4237) | -118.07 (-0.1690) | 91.94 (0.1316) | 160.81 (0.2302) | 168.70 (0.2415) | 83.25 (0.1192) | -85.97 (-0.1231) | -171.70 (-0.2458) | | | | |
| 14 | -354.71 (-0.7333) | -146.06 (-0.3019) | 106.26 (0.2197) | 180.47 (0.3731) | 130.00 (0.2688) | 67.26 (0.1391) | -67.39 (-0.1393) | -134.92 (-0.2789) | | | | |
| Total | -4155.71 (-0.5396) | -1705.32 (-0.2214) | 1306.81 (0.1697) | 2223.16 (0.2887) | 2089.80 (0.2714) | 1055.51 (0.1371) | -1065.82 (-0.1384) | -2135.82 (-0.2773) | | | | |

analysis. Incorporating monopolistic competition as per new economic geography models could also be investigated as it would enable the assessment of wider economic impacts stemming from agglomeration. This could lead to further improvements in productivity from increasing returns to scale, and correspondingly worse congestion. Further transport interactions could be added, for example business trips, which may have a significant impact on the productivity of service industries that dominate cities like Sydney.

While the developed model is investment-driven due to expenditures on capital stock and investment activities, other studies have focussed on models with saving driven closure. For instance, Cardenete and López-Cabaco (2021) provided saving account where the closure establishes the level of investment. In another study by Kim et al. (2004a), aggregate savings determine investments. There is only one capital market, and savings come from four main sources: household savings, regional production sector corporate savings, private borrowings from overseas, and government savings. Future work can be directed to providing a saving driven closure for the model. When defining macro closure, the impact on macroeconomic factors should also be considered. Closure rules have a greater impact on macroeconomic factors than on distributional ones, where the effect of the macro adjustment on the size of income distribution is generally minimal and indifferent to the closure rule (Adelman and Robinson 1988).

While the proposed model in this study is used to assist in capturing the wider economic benefits of implemented policies with a focus on detailed transport behaviour, various studies have assessed the impact of financing methods and expenditure patterns on the economy. Any infrastructure improvement, such as increased capability, must be funded. It should be noted that infrastructure funding may have a significant impact on welfare. The economic effects depend on the magnitude and source of funding (i.e., tax revenues, government funding, or private funding) (Kim et al. 2017). For instance, the effects of the transportation investment on the Korean economy is analysed by Kim (1998). According to results, financing alternatives for infrastructure projects impact elasticities of infrastructure investment such as GDP, exports, private utility, and inflation. The effect of transportation investment on inflation is found to be minimised if transportation investment expenditure is entirely funded by tax revenues. In the same line, Kim et al. (2011) investigated the effects of highway development using various financing methods, such as using the current tax system or imposing earmarked taxes. According to the findings, imposing regional earmarked taxes has a greater impact on income growth and the reduction of regional income inequality than the current tax system. In addition, Chen et al. (2017) investigated transportation infrastructure public–private partnership’s socioeconomic impacts using a dynamic computable general equilibrium (CGE) model. The simulation results show that public–private partnerships generate greater positive gross economic output and welfare impacts compared to traditional public financing models by reducing the regional economy’s collected tax burden. The effect of funding can be divided into two categories: short-term construction and long-term operation and maintenance (Kim et al. 2004b). While this study considers the yearly impact, the Financial Computable General Equilibrium (FCGE) model proposed by Kim et al. (2017) can be used to model the short- and long-term economic impacts of financing.

The focus of the current study is on detailed transport behaviour. Greater focus on including financing method (defining source of financing) and allocation of expenditure pattern could produce an overall impact assessment which could be explored in further research. In addition, future work could be directed to incorporate a saving account in the model to provide a complete impact assessment. The savings account can be used to determine whether transportation development costs will be paid for from government funds or

from private savings. The resulting model would provide a universal tool in which a modeller could input proposed changes to a transport network, and from the one model estimate link flows and induced demand, extract welfare metrics and forecast long-term changes to the urban economy.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11116-022-10276-x>.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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