A Review of Computable General Equilibrium Modelling for Transport Appraisal

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Keywords: CGE modelling, transport economics, transport policy

ABSTRACT

The traditional cost-benefit analysis (CBA) for transport appraisal has two key weaknesses. Firstly, by assuming static prices in markets external to transport, externalities cannot be considered other than in an ad-hoc, case-by-case manner. This approach is only valid under restrictive assumptions regarding perfect competition and the reflection of marginal costs in prices, which may not be appropriate for large projects with wider economic impacts. The second key weakness is that a CBA does not describe the distribution of impacts. When setting policies, it can be important to know which households or industries are the recipients of economic impacts, particularly if regional equality is an intended policy outcome. Computable general equilibrium (CGE) models simulate agents in an economy reacting to price and quantity signals. By measuring welfare at the household level, CGE models are able to account for all the market linkages that affect income. We review existing CGE models applied to transport projects and policies, broadly separated into regional or urban models. Regional models incorporate transport as a mark-up industry to production or as a reduction in the value of goods in proportion to the transport cost. Urban models extend the regional concept by using discrete choice models for residence, work and shopping decisions. However, due to the large number of equations, CGE models are data hungry and computationally intensive. The CBA retains an advantage in modelling detail as the use of a generalised cost function can incorporate all the characteristics of transport that a consumer might consider relevant.

1. INTRODUCTION

With only scarce resources, communities face challenging decisions about which projects and policies to pursue to improve their transport networks. Planning authorities conventionally use a cost benefit analysis (CBA) as an aid in the decision making process, to quantify the impacts of a proposal to society, the economy and the environment. When applied consistently, the CBA allows planners to make comparisons and choose projects that suit budget and time constraints, provided that benefits outweigh costs. However, CBAs for transport projects typically assume that benefits accrue in user travel time savings; externalities may be measured to a limited, ad-hoc extent. The existing models which feed travel time savings calculations can be inconsistent in their application of economic theory and tend to be limited to the transport sector only. As changes in income and land use are taken as
exogenous, the CBA is only a partial equilibrium analysis, and is unable to detail the distribution of impacts.

Computable general equilibrium (CGE) models simulate entire economies through functions to describe the behaviour of economic agents (e.g. producers, consumers, governments and external markets) operating in markets at equilibrium. These equations are solved simultaneously to obtain economic flows due to an exogenous change in parameters. Transport networks are incorporated as time and financial costs of transport between regions. Unlike a CBA, a CGE model traces relationships throughout an economy both directly and indirectly, and hence is a more natural framework to assess externalities. Depending on the model formulation, it is possible to derive a range of impacts that may interest the planner, e.g. GDP, employment levels and wages. CGE models for transport are most often used in standalone analyses of major projects, in a complementary role to CBAs, although outputs can be used in a CBA context. Most models apply at a national or regional level with only a coarse representation of the transport network. Few CGE models explicitly link to a transport model at an urban scale, and fewer still incorporate a land use model as well.

This paper reviews CGE models as applied to transport appraisal, to understand how they are presently used and how they may be extended in future research.

2. OVERVIEW OF TRANSPORT APPRAISAL METHODS

Transport demand derives from the activities that transport can facilitate; the transport activity itself confers no benefits. To a passenger, transport consumes time, money (e.g. fares or fuel) and human energy (in terms of comfort, stress etc.). A service operator faces operation and maintenance costs, as well as capital expenditure for new infrastructure. For small projects, community impacts may not be difficult to manage. However, externalities incurred by large projects cannot be easily ignored, ranging from the environmental (e.g. noise, air and water pollution) to the economic (e.g. agglomeration, gains from trade). Any complete appraisal must consider all noteworthy impacts to assess the worthiness of a project.

2.1 Conventional methods

The CBA has been the predominant method of transport project appraisal in Australia for the past 40 years (Douglas & Brooker, 2013). User benefits are measured from the consumer surplus of reductions in generalised price – a cost index of transport which includes fares, the value of travel time savings and other variables. Transport supplier costs vary case-by-case. Typical outputs include the net present value, a sum of economic flows occurring over time, and the benefit–cost ratio. The CBA methodology is often standardised within jurisdictions to enable a rigorous comparison between proposals. The most recent Transport for NSW guidelines, *Principles and Guidelines for Economic Appraisal of Transport Investment and Initiatives* (2013), provides suggestions for quantifying some environmental externalities in addition to user and supplier costs.

Bröcker et al. (2010) explain that CBAs are appropriate on two conditions: (1) that all benefits can be measured in the transport system, and (2) that the distribution of benefits is not a concern. The first condition is true if prices represent marginal costs, and there are no technological externalities. For example, a transport user may trade away their travel time savings by changing their work or residential locations to maintain a daily ‘travel budget’ – see Marchetti (1994). According to Sue Wing et al. (2008), the resultant changes in land values would then be counted within the consumer
surplus measurement as they would be reflected in the valuation of travel time savings. The second condition is political in nature, as a CBA generally aggregates benefits across households and regions into a single measure. Projects which target particular households or regions would be difficult to assess in a standard CBA.

By diminishing the role of externalities and assuming all benefits accrue in the transport system, a CBA can only provide an incomplete picture of economic effects. Lakshmanan (2011) describes four mechanisms of broader economic consequences of transport: gains from trade, technology diffusion, coordination failure and agglomeration. Agglomeration explains how improved transport promotes the clustering of industries, influencing their growth rate through economies of scale, and is perhaps the most well known. From Venables (2007), additional employment itself improves productivity, but it has the additional effect of improving the productivity of existing workers. This externality partly explains the existence of cities, and is a significant source of benefits that cannot be captured with a traditional CBA. Large projects have already used wider economic benefits as a key justification – the £14.8bn Crossrail project in London is estimated to provide between £6bn and £18bn of benefit in welfare terms (Crossrail, 2010).

Looking beyond the transport market, some economic evaluation models incorporate production functions as well as measurements of accessibility to estimate impacts to firms. Oosterhaven and Knaap (2003) state that land-use/transport interaction (LUTI) and CGE models are the only options with suitable spatial detail to consider changes in transport demand. LUTI models involve equilibration between transport networks and land use patterns, using a strong empirical foundation and detailed sub-models to predict effects to a high degree of disaggregation. However, without an economic foundation, welfare cannot be derived directly from these models and it is difficult to incorporate market imperfections. In contrast, CGE models have a strong economic foundation, using microeconomic theory to model behaviours, with benefits measured at the household level. They are generally applied at a macro level and do not easily replicate the dynamics of an economy.

### 2.2 Overview of CGE modelling

CGE models are descended from the macroeconomic input-output models of Leontief (1936). These were the first applied models to encompass entire economies by specifying the input requirements for each industry. In an input-output model, the economy operates as a unit to match final demands, enabling the effects of an economic change to be traced to other sectors. As the inherent deficiencies of a linear structure and a lack of price signals became too significant, they fell out of favour. Johansen (1960) introduced the first true CGE model by incorporating production and demand functions for firms and households, keeping investment and exports fixed, and enforcing equilibrium with macroeconomic accounting equations. Most CGE models developed since have retained this core.

Mitra-Kahn (2008) argues that there is an important distinction between CGE models and applied general equilibrium (AGE) models, despite their synonymous use in literature. In the 1960s, Scarf was the first to propose an applied model of modern general equilibrium theory, based on the Arrow–Debreu model (Kehoe, Srinivasan, & Whalley, 2005). AGE models were further developed in the intervening years but proved difficult to construct and solve. Mitra-Kahn states that by the 1980s, AGE models merged with CGE models in terms of language and concepts, so that CGE models now claim to be fundamentally microeconomic but are still governed by macroeconomic balance and hence are not a pure representation of general equilibrium theory.
CGE models are complete mathematical representations of an economy, comprising the actions of producers (or industries/firms), households (or consumers), government, investors and exporters. Each of these agents participates in markets for supplying and demanding commodities and factors, and has an underlying behaviour that determines their decisions. For example:

- Producers wish to optimise their choice of intermediate inputs and primary factors to minimise costs, given a certain output.
- Households wish to maximise utility by choosing the optimal quantities of primary factors to supply, and with the income, choose what to consume.
- Governments, investors and exporters wish to maximise utility with respect to income etc.

These behaviour sub-problems are solved analytically to find representative mathematical functions that respond to price, quantity and other signals. Substitution, e.g. between commodity bundles or inputs, is usually modelled with a form of constant elasticity of substitution (CES) function, including Cobb-Douglas (CD) and Leontief specifications. Additional behaviours can be modelled with the introduction of appropriate functions, e.g. to govern a household’s labour supply decision. There is no upper bound to complexity – modellers may attempt to model the real world as closely as the available data allows.

Together, the model is a set of non-linear equations, to be solved for a set of variables that represent market signals. Typically, more variables are specified than equations, and so a number of variables are designated as exogenous (i.e. determined outside the model), known as the model’s ‘closure’, in order to achieve a unique solution. This solution is the equilibrium, in that no agents have an incentive to deviate from their positions. Due to the large number of equations, CGE models are data hungry and computationally intensive. Calibration data is usually sourced from a social accounting matrix (SAM) – a matrix containing all the economic flows between agents in an economy, representing national accounts. If the model allows, a more limited input-output matrix could be used instead.

### 2.3 CGE model variants

Static CGE models are the basic form of model, used for comparative static analysis. An adjustment, or ‘shock’, to exogenous variables in a static model results in a change in endogenous prices and quantities compared to the base year. The ORANI (Dixon et al., 1982) literature describes the example of a drought which can be modelled as a reduction in total factor productivity (an exogenous variable) in the agricultural sector, leading to lower real consumption. It is assumed that the time period analysed is long enough for the economy to reach the new equilibrium. Closure in models like ORANI can be modified to simulate short run or long run equilibria. In contrast, a dynamic CGE model incorporates additional models to simulate the movement of stock variables through time. For example, capital may be accumulated based on depreciation and investment in the previous period.

Spatial CGE (SCGE) models are composed of multiple regions, acting in either a top-down or bottom-up approach depending on the level of interaction between regions. Commodities are traded between regions, incurring a transport cost as a margin industry or a reduction in the commodity value. Transport projects tend to have localised impacts and hence spatial CGE models are a natural fit for their assessment. While single region CGE models exist, they are limited to assessing the general impacts of policies.

Further realism is added by relaxing assumptions regarding returns to scale. Bröcker and Mercenier (2011) outline a method to simulate increasing returns to scale by separating factor inputs into...
variable and fixed quantities. Markets are also commonly assumed to operate under monopolistic competition using the Dixit–Stiglitz model (1977).

A final key differentiator of models is the solution method. Horridge et al. (2013) outlines two main strategies – (1) calculate the solution directly from the model equations, known as the ‘levels’ strategy, or (2) use a linear approximation of the equations, known as the ‘change’ strategy. The former is often implemented in GAMS, a general mathematical programming solution software, whilst the latter is implemented in GEMPACK, a specialised general equilibrium solution software with similarities to GAMS in syntax. Other software such as AMPL, Matlab and Excel are also commonly used, but some of these may perform poorly with larger models.

CGE models are formulated worldwide to answer questions ranging from tax and labour policy, to environment and energy modelling. Notable models include those developed by the Centre of Policy Studies in Melbourne (2014) and the GTAP model of global trade. Many countries around the world maintain their own national or regional level CGE models. Commercial institutions also maintain models for consultation purposes, e.g. the Deloitte DAE-RGEM model. All of these models require significant data input from government accounting bodies, and many are not publically accessible.

In New South Wales, CGE modelling for transportation is an emerging methodology to be used in combination with traditional appraisals (Legaspi, 2013). The economic evaluation of the recent State Infrastructure Strategy Update 2014 was based on the Deloitte DAE-RGEM model (Deloitte Access Economics, 2014). However, a key concern remains that CGE models are not as transparent as CBAs, especially to the non-technical observer.

3. **CGE MODELLING IN TRANSPORT**

3.1 **Regional modelling**

Beginning at international scale modelling, CGEurope is a static SCGE model to assess proposals in the dense transport network of Europe. Bröcker (1998) developed the prototype to demonstrate that SCGE models are feasible and an improvement on multiregional input-output analysis. Bröcker’s model is parsimoniously designed with only three activities (production, transport and final demand) performed by three agents (firms, transport agents and households respectively). Firms in each region use local factors and inputs, outputting directly into their own regions. Transport agents transform outputs from other regions into a pool of each commodity in their own region (known as the ‘pooling’ assumption). Households sell factors locally and purchase pooled commodities. Behaviour is entirely specified with cost functions and input-output coefficients are determined with CES functions. Bröcker provides a solution algorithm, along with general discussion on the existence of a solution, and tests the model with a hypothetical dataset. The overall model is highly simplified with no factor mobility, few industries, no investment and little specialisation of functional forms, but provides a suitable core for future developments.

Bröcker et al. (2001) modifies the CGEurope model and offers it as part of a unified transport assessment framework for Europe. Six sectors are specified – five tradeable between regions, and one non-tradeable. Rather than a separate transport agent, one of the production sectors provides the transport service, based on the costs of transport in the existing network. Tradeable production sectors are characterised by increasing returns to scale to improve realism, and household utility now includes a component of passenger travel time. Bröcker (2002) continues to develop the passenger demand...
aspect by including business trips in production CES functions. However, these models are notably limited in their representation of the transport system as commuting trips are not included and there is no mechanism to simulate congestion.

Bröcker et al. (2004) signals a shift in the approach to transport. Instead of a production sector, the model follows the Samuelson (1954) ‘iceberg’ method by assuming that goods lose value, i.e. ‘melt’, in transit between regions in proportion to the transport costs. Two formulations of the model are provided – one with a single tradeable sector, with goods still differentiated by region, and one with multiple tradeable sectors. Results from the two models proved to be similar. Later, in Bröcker et al. (2010), the ‘iceberg’ approach is clearly favoured. In that model it is applied to the composite good, and in line with earlier results there is only one tradeable sector to reduce computational requirements. Additionally, there is a more explicit attempt to measure passenger benefits using consumer surplus. Factors are still immobile – in some ways a necessary assumption in order to assign benefits to regions.

Bröcker and Korzhenevych (2013) propose a dynamic extension that allows factors to adjust. Rather than iterating a series of static models, Bröcker and Korzhenevych’s model is forward looking and formulated in continuous time. Households and firms have perfect insight, maximising a discounted CIES utility function over an infinite time horizon. Labour supply still only changes exogenously, but the existence of a steady state, where endogenous variables grow constantly, is proven. Throughout all of the CGEurope models, the common style is to use a very limited number of agents (generally only one local producer, one tradeable producer, and one household for all final demand in each region) and a limited number of functional forms (CES, or in some cases, CD). There is never any explicit representation of transport or an attempt to replicate observed flows, but the emphasis is always to produce a workable model with only limited data, to which it succeeds.

RAEM is a static SCGE model of the Netherlands based on Venables (1996) specifications in New Economic Geography, similar to CGEurope and Venables and Gasiorek (1999). While much of the model development occurred in the early 2000s, we refer to the published journal article of Knaap and Oosterhaven (2011). RAEM is less aggregated than CGEurope, consisting of fourteen sectors and two modes of transport. Production is described with a CD function combining labour and commodities (no capital), and household utility is a CES function combining consumption from each region for a particular sector. Producers and consumers share the same elasticity of substitution, and both production and consumption exhibit monopolistic competition. Labour migration is exogenously modelled, but firms can enter and leave depending on profitability. Similar to CGEurope, there is a distinction between local and tradeable goods, represented instead by a sector specific parameter of tradeability to measure the share of output that can only be produced on location. Transport is modelled with a modified iceberg assumption – prices for freight are marked up in proportion to distance travelled, and prices for passenger transport are marked up according to the average travel time by public transport and travel time.

The original study suffered from poor data and a number of methodological issues discussed by Tavasszy et al. (2011). Firstly, the iceberg assumption, while elegant for one sector models, leads to a fundamental flaw for multi-sectoral models as it assumes that transport is produced in the same manner as the transported commodity, despite different sectors using different production functions. Furthermore, a reduction in transport costs of a particular commodity means that less production is necessary to satisfy demand of that commodity, as compared to commodities that don’t require transportation (Oosterhaven & Knaap, 2003). As a result, changes in demand between these commodities cannot be properly compared. Additional problems identified with the original
formulation included the calibration and interpretation of the varieties of products, and improper modelling of agglomeration when land use constraints are neglected. A suggestion to overcome this problem was to introduce a cost to reduce or increase production in a region.

Thissen (2005) extends the original RAEM model, introducing additional detail to deal with the identified methodological issues. Search theory is applied to the labour market, where the unemployed search for jobs and firms set vacancies. Each region incorporates housing and environmental factors such that overall household utility is identical between regions. Transport is now modelled explicitly using its own production function – a contrasting path of development to CGEurope – applying to commodities as a price mark-up. However, transport costs (for commuting, freight and shopping) remain exogenous as it is argued in Tavasszy et al. (2011) that a separate transport model is better able to deal with transport alternatives. The model also adds a government sector, purely to redistribute taxes covering unemployment benefits.

For a study of proposed highways across Korea, Kim et al. (2004) use the concept of spatial accessibility explored in Vickerman et al. (1999) to model the effects of transport. Instead of facilitating trade, as in RAEM and CGEurope, Kim et al.’s model assumes that improved transport links provide a direct input to the production capabilities of a region, through a measure of accessibility. The dynamic CGE setup largely borrows from Kim and Kim (2002) with a greater disaggregation of economic agents compared to RAEM and CGEurope. In each of the four macro regions of Korea, four industries produce a single representative good under constant returns to scale and perfect competition. Labour, but not capital, is mobile, and a government exists to collect taxes, invest and subsidise others. The dynamic model consists of a within-period static CGE model combined with an intertemporal model to update exogenous variables including capital stock, determined by investment, as well as population and government expenditure. Thus, the model is recursive, and unlike Bröcker and Korzhenevych (2013), decisions are optimised for each static time period only.

The key difference in Kim et al.’s (2004) model is that the production function is a CD combination of labour, capital and accessibility, with accessibility measured by a gravity model index from Vickerman et al. (1999). The accessibility index is calculated using the minimum distance from each region to other regions weighted by population; minimum distances are calculated by a transport model implemented in EMME/2. It is claimed that the two models together form an integrated transport–CGE model, although the nature of the connection between the two models is not clearly explained. Furthermore, Vickerman et al. also discuss the difficulty of devising an appropriate index of accessibility, not being a desirable good by itself, and may require further theoretical validation.

### 3.2 Urban modelling

All of the models discussed so far vary significantly in setup, spatial and industry aggregation, and particularly in the representation of transport. In most cases, transport costs are calculated using an external transport model with one, or perhaps two modes of transport considered. At a regional level, simplified transport network structures may be an acceptable approximation, but at an urban scale, congestion, route choice and modal split become significant.

Urban CGE models incorporate discrete choice structures with random utility to explain variations in route choice and modes. Horridge (1994) is one of the earliest examples, proposing a prototype CGE model of urban transport demands for Melbourne. In the model, the urban area is divided into zones, workers/households are divided into groups based on income, there are two goods (transport and
other) and there are two factors (land and labour). Each individual faces a decision of where to work, where to live and their residential land size. Their utility function contains a systematic and idiosyncratic component, with the idiosyncratic component varying according to a Weibull distribution so that the logit model gives the proportion of individuals choosing a certain option. Systematic utility is composed of residential land and other goods consumed. Transport services for commuting do not provide utility – costs are instead deducted from the budget. Production is a CD combination of land and labour, transformed into transport services or other goods. The overall model is simplistic in using only a minimal number of goods and factors, but by representing congestion, develops an economic basis for a significant portion of observed traffic flows. Some of the proposed extensions include incorporating time costs and externalities, as well as modelling other traffic flows and land uses.

Anas and Kim (1996) develop a similar stochastic CGE model to study urban structures. Their CGE model allocates a fixed land supply to households, firms and roads depending on demand. Production uses land, labour and intermediate inputs with constant returns to scale, and products are differentiated by location. Consumers supply labour and travel to all locations to shop. Unlike previous CGE models, travel times are endogenous as measured with a volume delay function. Similar to Horridge (1994), consumers face a two-stage decision problem. At the lower level, given a particular set of work and home locations, each consumer must choose their land size, amount of leisure supply, amount of labour supply and shopping trips, all combined with a CD function subject to their budget constraint. At the upper level, each consumer chooses the work-home pair that gives them the highest utility, including an element of random utility. Firms choose land, labour and intermediate inputs according to a CD function. Finally, a representative transport planner levies a congestion toll to compensate land owners for road space.

The study is unlike other CGE models examined so far as the optimal amount of road space is endogenous to the model. As it is necessarily a closed model for theoretical study, it may be difficult or unsuited to empirical applications, especially since the city was assumed to be linear, travel time was valued at the wage rate and CD functions were used for production and utility. Anas and Xu (1999) modify the model by leaving jobs and residences unconstrained, and altering the linear city to a wedge-shaped city. They use the model to show that dispersed cities can improve welfare if there are no agglomeration externalities. Anas and Rhee (2006) demonstrate with the model that strict urban boundaries are a poor substitute for congestion pricing.

Anas and Liu (2007) introduce the RELU-TRAN model, a dynamic extension combined with a transport model to enable practical application. Consumers still face a two-level problem. At the lower level, consumers wish to maximise a utility function composed of the quantity of housing, labour and retail goods, subject to monetary and time budget constraints. Employment levels are endogenous, and time is again valued at the wage rate. At the upper level, consumers choose the combination of home location, work locations and housing type that will maximise their random utility, as given by the logit model. Producers use a CD technology combining labour, capital, buildings and intermediate inputs with constant returns to scale, aiming to minimise costs. To model land use, a representative landlord controls the supply of floor space depending on profitability, and developers construct and demolish buildings according to demand.

The CGE component (RELU) of the unified model generates travel demands from commuting and discretionary shopping trips. These are fed into the stochastic user equilibrium model of transport (TRAN), which performs modal split and assignment operations. To solve the model, RELU iterates until convergence, as measured by convergence of excess demands and economic profit, and then
TRAN iterates until convergence. Expected travel costs from the TRAN model are fed back into the RELU model, and the two then loop until equilibrium is reached. The full RELU-TRAN model is a significant step forward in integrating transport and land use in a CGE framework. While it does not yet represent the full range of transport demands, the detailed modelling of changes in building stocks and land use provide the planner with a rich set of predictions for project and policy evaluation. However, as with all models, greater complexity is more burdensome to calibrate and assumptions regarding landlord and developer behaviour may not always hold. It is also questionable whether using a traffic assignment algorithm with a real network is appropriate when the network is not loaded with the full set of travel demands.

Truong and Hensher (2012) provide theoretical justification for the link between discrete choice and continuous demand models. In their paper, they show that it is valid to follow the Anas and Liu (2007) approach of specifying an overall level of demand with a CGE model, and then use a discrete choice model to specify mode, employment and location choices. They argue that such decisions are better represented in discrete choice models than continuous demand models as the former is differentiated by quality attributes and the latter is concerned with aggregate behaviour. The presented example is the TRESIS-SGEM model, used in Hensher et al. (2012) to estimate wider economic impacts of a new rail line in Sydney.

Rutherford and Van Nieuwkoop (2011) introduce an urban CGE model with endogenous mode choice and travel times. The entire model is formulated as a mixed complementarity problem to solve the transport and economic sub problems simultaneously. Like other urban CGE models, households choose employment and residence locations based on prices, wages and commuting time. Utility is a nested CES function of housing, consumption and leisure, and households receive labour, capital and housing income. Production is a CD function of labour and capital. On the transport side, households choose their transport mode with a logit formulation, based on travel times. A delay function is defined for a private transport mode, and a capacity constraint for the public transport mode. The transport assignment sub-problem is solved with a mixed complementarity form of user equilibrium. Overall the paper provides a possible method for true integration between CGE and transport models, but in its current form relies on restrictive assumptions regarding urban commuting options.

### 3.3 Other CGE models

Many CGE models have been developed beyond the basic forms to assess policy issues relating to urban and regional externalities. Recent popular topics of study include congestion and sustainability.

Berg (2007) extended the CGE model of Sweden (EMEC) to analyse the effect of Swedish greenhouse gas policies. The primary innovation was to create a consumer demand module to account for all sources of transport demand. Consumer utility is a large CES nested structure of work trips and leisure trips, in addition to the more common components of leisure, housing and other goods and services. Additional CES nests perform modal split operations and describe energy inputs for household cars and heating. Consumers have budget and time constraints, and there is no modelling of congestion. Production similarly involves nested CES functions of energy, labour, capital and material inputs. The complete EMEC model is static and simulates the actual energy/environmental tax system, showing that the common assumption of ad valorem taxes may be replaced without great difficulty.

Berg (2007) acknowledges that a greater separation of households by sociodemographic characteristics would improve travel demand predictions, and the model as it stands does not account
for the movement of households. There is also little discussion about whether CES functions are the best method of modelling substitution between modes. However, the model contains so far the most complete representation of household travel demands of any CGE model. Tscharaktschiew and Hirte (2010) and Tscharaktschiew and Hirte (2012) use the Anas and Xu (1999) model to study CO₂ emissions, but with endogenous mode choice and travel times as predicted with a logit model.

Steininger et al. (2007) investigate the distribution of impacts of nationwide road pricing in Austria. Their CGE model distinguishes 35 sectors in production, with a nested CES structure of primary and intermediate inputs. Household demand is a nested CES structure of transport and non-transport goods, performing a modal split between public and private transport. The model provides another example of endogenous modal split, but is not spatially disaggregated and it is unclear how congestion is modelled. Vandyck and Rutherford (2014) provide a more complete model of congestion, using a volume-delay function and separating labour into hourly and salaried workers to disaggregate the effects of congestion pricing.

4. CONCLUSION

CGE models are an uncommon form of transport appraisal in Australia, only seen in a selection of major projects with regional impacts. The examples discussed above demonstrate their flexibility in application to a range of policy questions which would otherwise rely on less economically-sound methods of evaluation. We reviewed both regional and urban forms as applied to transport, finding significant variation in mechanics, data and assumptions. There is scope for standardisation and wider use, aided by research which will explore further integration between transport models and CGE models. Urban CGE models in particular have potential uses as foundations for integrated models combining land use, transport and other networks. In the future, we may find CGE modelling playing a greater role in transport project and policy development as the community pursues the best use of its scarce resources.

5. REFERENCES


