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To: Milla Hamunen, Department for Transport

From: Adolf Stroombergen and James Laird

Subject: Spatial general equilibrium models and their application to transport

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1. Report Brief

1.1 Background from DfT

Supplementary Economic Models (SEM) are commonly used to model outcomes of transformational schemes. However, due to the complexity of these models, various challenges exist in the development, validation, and the interpretation of the models' results.

Therefore, to better understand what distinct types of SEMs can offer for transport appraisal, the Department would like reviews on the state-of-the-art of supplementary models. These individual reviews will focus on different aspects of SEM modelling, including theoretical underpinnings, availability of data, usefulness for appraisal, applicability to inform transport questions, and any significant limitations. This particular review will consider Spatial Computable General Equilibrium (SCGE) models specifically.

1.2 Modelling the wider economy impacts of transport projects

SCGE models are one model type that can be utilised to capture the wider economy impacts of a transport project. Relative to other model types that can be utilised their particular strength is:

- Understanding displacement and crowding out effects;
- Understanding aggregate regional and national impacts;
- For situations where prices, wages and productivity are expected to alter; and
- Where relative changes in prices are expected to deliver gains in allocative efficiency.

The latter point refers to the situation where the economy adjusts to re-organise itself to maximise the opportunities presented by the transport project. This can include not only changes in spatial location of economic activity, but also in structural changes in the economy.

Given that transport investment has been seen to change national level productivity,[1] industry and city level productivity,[2] the spatial location of economic activity either clustering around the improved transport links[3] or expanding the size of cities, but potentially favouring differing ones,[4] or structurally changing industrial composition,[5] we can see that SCGE models are potentially suitable for exploring some of the most interesting economic impacts that transport projects have been found to generate ex post.

Whilst there are a number of common facets between SCGE models, the very different applications to which they can be applied plus data limitations and model complexity result in many different forms of SCGE model. This will be evident on reading our review. Understanding the question to be answered is

[1] Melo et al. (2013), Deng (2013), Holmgren and Merkel (2017).
[2] Duranton & Turner (2012), Duranton et al. (2014), Holl (2016), Lin (2017), Gibbons et al. (2019), Gibbons & Wu (2020).
[3] Chandra & Thompson (2000), Ahlfeldt & Feddersen (2017), Qin (2017).
[4] Rephann & Isserman (1994), Duranton & Turner (2012), Baum-Snow et al. (2020).
[5] Percoco (2010), Duranton et al (2014), Sheard (2014), Lin (2017), Dong (2018).

important to the specification of any model, but even more so with SCGE models. It is not sufficient to just have an interesting transport-economy problem, and then just apply any SCGE model to that problem. The model needs to have a specification tailored to the problem at hand, which could be pure economic growth, interaction between cities or regions, or structural change. Additionally, and as will also be seen when reading this report, the specification of the model needs to be cognisant of the policy scenario being tested. Is it likely to impact on freight flows mainly? Or, business traffic mainly? Or commuting and household behaviour? Is it an infrastructure project or a pricing project? How big an area are the effects expected to spread over? Are construction and financing impacts of interest? Is the intention to use the model outputs in a cost benefit analysis?

1.3 Approach

This report identifies aspects of SCGE modelling relevant to transport appraisal, particularly those features most likely to influence the results of the modelling. To be clear though, it is not the case that transport SCGE models are vastly different from SCGE models in general. The review is as much about the features of SCGE models that affect their application to transport questions, as it as about determining what extra features of a an SCGE model are required to make it suitable for studying transport questions.

In that context, our approach is to answer the specific questions raised by DfT; encompassing various seminal papers, more recently developed models and interviews with selected SCGE practitioners (listed in Appendix B) to gain a view of the state-of-the-art in the field.

We do not cover all of the technical details of SCGE modelling, nor do we provide a wide-ranging review of SCGE models applied to transport appraisal. Examples of such reviews are discussed below. In particular a sizeable amount of literature was covered in a review by HS2 earlier in 2023 to which readers are referred and which is included as an annex for convenience. We build on that work as appropriate, placing less emphasis on reviewing additional papers for marginal benefit, but placing more emphasis on discussion and interpretation.

Our report is structured around the questions posed by DfT. Section 2 addresses these questions: firstly looking at the theoretical underpinnings of S-CGE models and their applicability to transport, then mechanics, followed by a discussion on data and input parameters, then validation and output and finally SCGE applications. Some of the questions raised by DfT contain overlapping issues, but we have endeavoured to avoid repetition in the responses. Section 3 adds some additional points. A brief conclusion is presented in Section 4.

2. DfT Questions

2.1 Theoretical underpinnings and applicability to transport

What is the economic theory that underpins SCGE models?

SCGE models are CGE models applied to more than one region or zone. That is they include a spatial dimension. Modern (S)CGE models are the culmination of models that arose from the use of national accounting systems, in particular input-output tables[6] (Johansen, 1960 and Shoven & Whalley, 1992) and those that developed from what were known as AGE (applied general equilibrium) models, with the emphasis on 'applied' to distinguish them from the theoretical models based on Arrow and Debreu (1954) which had no link to national accounting systems. Mitre-Kahn (2008) provides a thorough review of the history and progression of CGE models.

A typical modern CGE model has the following features:

- Many industries in an input-output table and at least one household sector
- A role for government
- International trade
- Equations that describe the behaviour of agents in the model, such as industry production functions.
- Endogenous prices
- Consistency with national accounting frameworks such as the UN System of National Accounts.

The equations that describe the behaviour of agents in the model provide the consistency with economic theory. Households consume goods, and split time between work and leisure. They maximise welfare subject to money budget and time budget constraints. Firms produce goods requiring inputs of labour and materials. They are profit maximising and will invest in capital if expected returns are sufficient. There are monetary flows between households and firms, and between both of them and government. Beyond these basic specifications SCGE models can differ substantially in exactly what household activities can occur (commuting, migration, leisure time consumption), how firms behave in different market environments (is there monopolistic competition, are there benefits from agglomeration, etc?.) as well as the model dynamics. The macroeconomic closure rules (such as whether the fiscal balance is fixed or free to vary between scenarios) also play a very important part in the modelling, with some models permitting a variety of different closures, and others not. Closure rules are further discussed in Section 3.

A useful summary of SCGE models is presented in World Bank (2014). It notes that although SCGE models have a sound theoretical basis, their main problems are obtaining empirical data (such as for consumers' and producers' substitution elasticities) and the required computational effort. We return to these points below.

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[6] An Input-output (IO) table presents the transactions between industries and consumers, and between industries themselves in tabular form with rows representing sales and columns representing purchases. The standard macroeconomic accounting identities apply.

In contrast to LUTI models SCGE models are able to model economies of scale and the external economies of agglomeration (data permitting), and can therefore be used to estimate the non-transport benefits of new infrastructure that manifest in markets.[7]

As will be discussed below, potentially important aspects of (S)CGE models are:

- Choice of functional forms for behavioural equations (and parameter values)
- Representation of time (static or dynamic – recursive or perfect foresight)
- Model closure (especially macroeconomic)
- For SCGE transport models: representation of space and how transport costs are specified
- Imperfect competition and product variety.

Although SCGE models share many features with CGE models, the addition of a spatial dimension is not independent of other model features. The two main types of SCGE models for transport appraisal are urban SCGE models and regional SCGE models. Urban models typically relate to cities and zones within cities while regional models relate to essentially everything else, from local government regions within a country (such as the PWC model used to analyse HS2, in PWC, 2022) to a groups of countries within a wider bloc such as the European Union.

Urban SCGE models tend to be used more for issues that relate to the movement and location choices of people – commuting on intra-city rail for example – rather than the movement of goods. Regional SCGE models generally include goods trade and migration, but exclude commuting unless it is within the Marchetti wall,[8] such as between Copenhagen and Malmo.

In an SCGE model although the solution algorithm may solve for all regions simultaneously, each region or zone is in itself a smaller CGE system with connections between them. There are also partial SCGE models in which modelling occurs at the aggregate (say national) level and the results are distributed to individual regions, such as by converting changes in industry output into changes in regional output using an industry by region matrix. Similarly for changes in occupational demand, exports and so on. The latter may seem an inferior approach, but is fine if there is little feedback from the regional to the national level.

The other aspects of SCGE models listed above are discussed in various sections below.

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[7] Some LUTI models have add-on modules, that include for example agglomeration and thus variations in GVA/worker. A separate review of LUTI models is being undertaken by David Simmonds.

[8] Marchetti (1994) observed that in many countries, over different historical periods and irrespective of mode, travel time (especially for commuting) tends to be confined to a maximum of about one hour per day. Thus cities are roughly 'one hour wide'. This concept is sometimes described as the 'Marchetti wall'.

How applicable are these models to transport economics and appraisal?

What are latest developments in applying SCGE models to transport – and what are their limitations?

What kind of transport-related questions have SCGE models been used to answer?

What kind of transport schemes have SCGE models been used to investigate?

Tavasszy et al (2011) and Brocker & Mercenier (2011) provide good introductions to the use of (S)CGE models in transport appraisal. A key point is that in contrast to standard CBA, CGE models do not require perfect competition with fully flexible prices.

The strength of (S)CGE models is in their ability to capture welfare gains beyond direct transport user benefits. It is well known that under perfect competition and no distortions the transmission of transport user benefits to secondary markets (eg from travel time savings to lower product prices) does not alter the quantum of those benefits. However, this is not true in the presence of distortions such as taxes, market power and economies of scale. That is precisely where SCGE models can assist in transport appraisal. Indeed, one would struggle to incorporate these issues in any systematic way in anything other than an SCGE model.

Shahraki and Bachmann (2018) provide a comprehensive review of CGE models applied to transport issues. It covers 103 journal articles, 11 conference papers, 21 book chapters and technical reports. It looks at the advantages and disadvantages of various approaches. A summary is presented in their Table 1, reproduced in Appendix A for convenience.

There are many examples of applications to changes in transport costs (including road pricing) and to investment in transport infrastructure; rather fewer applications to trade and land use impacts. Most have transport costs explicitly identified as opposed to adopting the iceberg model – discussed below under Mechanics. A few studies used accessibility indices, but the only ones that identified transport capital are those that address infrastructure investment.

Although wide-ranging and interesting the review is occasionally too sweeping and lacking in subtlety. For example, the authors state that in recursive dynamic models (discussed further below) rates of return in future periods are assumed to be the same as the current period. This is simply not true. In another example with respect to model closure (also discussed below) it is claimed that fixed factor prices create a limitless pool of factors. Again, this is not true.

Robson et al (2018) also review the use of SCGE models in transport appraisal, with separate discussions of urban and regional models. However, there is little insight into how CGE modelling for transport appraisal is actually done. For example, what is exogenous in models, how accident costs are handled, what is done with non-market benefits such as leisure travel time etc.

Slides 25-32 of HS2 (2023), presented in Appendix C, have many examples of SCGE models applied to transport outside the United Kingdom, including numerous applications in Australia. A leading Australian example that illustrates the general approach is Hensher et al (2012) who combine a transport and land use model (LUTI) with an urban SCGE model to analyse Sydney's north-west rail link. Changes in travel time are exogenously set in the transport and land use model, which then produces changes in travel patterns. Changes in where people work generate changes in employment density in most zones, leading to agglomeration benefits and thus higher wage rates. Not all benefits are manifested in lower travel costs. Some workers may elect to spend more on travel because higher wages make them better off overall.

For the United Kingdom Overman et al (2009) used an SCGE model to estimate the effects on GDP of various scenarios with reductions in transport costs between Leeds and London, and Manchester and

London. The model has heterogeneous firms that select where they produce and workers who select where they live. Greater connectivity forces non-competitive firms out of business because of pressure from cheaper imports, while competitive firms grow by increasing exports. Thus, productivity is effectively partly endogenous. Wage growth moderates the impacts of differences in competitiveness.

More recent UK examples are well-known; PWC (2014, 2022) used SCGE modelling to examine options for airport expansion in London and high speed rail, namely HS2.

Charalampidis et al (2019) use the GEM-E3-R model (a regional economy-energy-transport model of the EU) to study decarbonization in transport. The model combines general equilibrium theory with location choice and new economic geography. The model does not have intertemporal optimisation, but still assumes some foresight. For example, suppliers of electric vehicles and charging stations anticipate both developments. The authors note that much regional data is not available so has to be estimated – an issue to which we return below.

Another SCGE model of the EU is RHOMOLO (Lecca et al, 2018) which appears to be based initially on CGEurope (Brocker et al, 2002), but has more in common with RAEM (discussed next). These models have been used to study transport projects and the allocation of cohesion funds, including for transport, across Europe.

The RAEM model in the Netherlands was developed specifically for transport appraisal and includes detail about modelling agglomeration economies (such as the need to consider input constraints and sunk costs that could limit a firm's ability to change location) and macroeconomic behaviour (Tavasszy et al, 2011). It has various descendants such as TIGER (Heyndrickx et al, 2011) and the new version of the Norwegian PINGO model (Hansen, 2019) for studying the wider economic impacts of transport projects, stressing the need for models to incorporate regional factor (labour and capital) mobility and increasing returns to scale – market power and product differentiation, but cautioning that there is a trade-off between model sophistication and data availability.

RELU-TRAN (Anas and Liu, 2007) is a well-known example of an urban SCGE model with an adjoining transport module. It has been applied to the urban areas of Chicago, Paris (Anas & Chang, 2023) and Los Angeles to analyse issues such as rail investment and road tolls. The RELU-TRAN model forms the basis of the LUISA model (Jin et al, 2013) which was used by the UK2070 Futures Study (2019) to analyse the spatial rebalancing of economic growth encompassing the location of jobs, the supply and demand for housing and the provision of transport services.

Using SCGE models to analyse decarbonisation polices (as in Charalampidis et al op cit) may be a tad outside the usual understanding of transport schemes or transport appraisal, but such applications are becoming more common. For example, Figus and Swales (2018) analyse vehicle efficiency and fuel efficiency by using a multi-layered CES (constant elasticity of substitution) demand function for households that allows for input-biased technological change. Changes in aggregate fuel efficiency stem from changes in the vehicle mix and from actual changes in fuel efficiency for each vehicle type. The model can also capture lower operating costs from less maintenance due to newer vehicles or better roads, plus the effect on fuel use from better roads.

Of course there are criticisms of SCGE models, both in general and with regard to their application to the appraisal of transport projects. The most commonly cited ones include choice of functional form, data requirements and the validity of parameter values. We return to these points below. Although not without substance, just as if not more important is the modelling methodology – which transport costs and related input variables are shocked, what is the structure of the spatial zones in relation to the size of the project, what closure assumptions are used and so on.

What functional forms for utility and behavioural relationships are typically used, and what evidence are they based on?

The choice of functional form needs to consider issues such as theoretical consistency and ease of computation. Hence early models had mostly Cobb-Douglas production and utility functions, reflecting limitations in computing power at the time. In recent decades CES functions have become much more common, and these are frequently nested so as maintain tractability, but still allow different degrees of substitution between different types of inputs into production and consumption. For example, there might be a CES production function with labour and capital inputs in one tier, and a second CES tier for different labour skill groups.

However, more less restrictive functional forms are also being used, such as normalised quadratic and translog production functions,[9] and the Linear Expenditure System or Almost Ideal Demand System for consumer demand. Although these functions are desirable, a well-considered system of nested CES functions can work almost equally well and be more amenable to testing alternative elasticity values than say a translog specification. Flexible functional forms are preferred, but ultimately the choice tends to be dictated by available data and to some extent by the versatility of the model solution algorithm. Elasticity values are generally derived from econometrically estimated models, but rarely are such models linked directly to an SCGE model. Thus, most SCGE modellers use elasticities estimated in other studies or adapted from databases such as the Global Trade Analysis Project (GTAP, Corong et al, 2017). The chosen functions are then calibrated to satisfy the known base year prices and quantities for inputs and outputs. For example in the case of a Cobb-Douglas function, the quantities of inputs are known, as are the input shares (which are the exponents on the inputs). Thus the constant term is calibrated to ensure that the result of the function is the known quantity of output.

Some typical equations:

Cobb-Douglas production function with output (X), inputs of labour (L) and capital (K), with respective shares α and (1-α), and constant term λ.

$$X = \lambda L^{\alpha} K^{1-\alpha}$$

Constant Elasticity of Substitution production function, variables and parameters as above, with additional parameter ρ, which is related to the elasticity of substitution between the inputs (σ).

$$X = \lambda[\alpha L^{\rho} + (1-\alpha)K^{\rho}]^{\frac{1}{\rho}}$$

where $\rho = \frac{\sigma - 1}{\sigma}$

The translog function (second order) with inputs F.

$$X = \lambda + \sum_{i} \alpha_i LnF_i + \frac{1}{2}\sum_{i}\sum_{j} \beta_{ij} Ln(F_i)(LnF_j)$$

The Almost Ideal Demand System, used for household demand functions: w is the share of a commodity in total consumption (X), p is its price and P is the overall price index.

$$w_i = \alpha_i + \sum_{j} \gamma_{ij} Ln(p_j) + \beta_i Ln\left(\frac{X}{\mathrm{P}}\right)$$

[9] A translog (transcendental logarithmic) function is an n[th] order approximation to any arbitrary function.

2.2 Mechanics

How can transport networks and transport investments be integrated into SCGE models? What options exist for this? What are their pros and cons?

Is it necessary to model the impact of transport investment as a 'productivity shock', or can the role of the transport sector be more thoroughly integrated into the analysis?

Transport services feature in an economy in multiple ways including the transportation of physical goods as an input into the production process or as a final output. And, importantly, particularly in service sector dominated economies like the UK's, the transportation of people. Employers' business travel would involve workers travelling between office or factory locations within the firm, or to meet clients (a district nurse or estate agent visiting a household, or an investment banker meeting a client). Reductions in employers' business travel times increase firm level productivity.

Commuting has a very important economic function, and commuting costs can influence the work/leisure decision. Other types of non-work personal travel, whilst not having a direct impact on the production of goods, can influence production by affecting the spatial location of economic activity.

Different modes cater towards different types of trips. Roads in the main serve all types of trips. Rail is typically focused around person travel (although in the USA freight movement on rail is significant), with short distance services carrying household commuting and other trips, and longer distance services employers' business and leisure trips. Ports are focused around freight, whilst airports can vary in terms of the types of trips they serve. Some airports are focused around leisure, others business and leisure, and others still have a freight angle.

With such a variation in how transport services feature in an economy, the mechanics of incorporating them into an SCGE model have to vary. One option to model impacts is to convert the transport user benefits into a productivity shock, as has been done for UK applications to date. However, in doing so this can lose some sensitivity and insights the model can offer on the supply side of the transport sector, such as the car fleet or the rail sector, or on household or business behaviour. If models are geared around particular types of projects or policy, the mechanics will also likely vary with intended model applications. For example, it would be highly unusual to model the impacts of pricing policies using productivity shocks, but also the mechanics adopted may vary significantly depending on whether the project is expected to benefit only traded goods (freight traffic), or business travellers, or commuters and affect household location, or a mixture of all. The complication is that each of these 'transport project impacts' requires different 'mechanics' for inclusion in the model.

Looking at freight in the first instance, in early trade models transport was simulated using the iceberg approach whereby less of a good is received by the buyer than is sent by the seller – the goods 'melt' while being transported. The longer the distance the greater the melting. That might have been sufficient in single industry macro models, but in a CGE model that has distinct transport industries it is highly unsatisfactory for the following reasons:

- Transport industries have a different cost structure than goods producing industries. For example, a trucking firm requires inputs of fuel, vehicles, logistic services and drivers, which would have quite a different cost structure than the input mix required by a manufacturer of home appliances.
- The transport cost of moving a tonne of furniture would be different than the transport cost of moving a tonne of canned food even if in reality they used the same truck over the same distance. Under the iceberg approach the cost of transporting furniture would be linked to the cost of inputs such as timber, adhesives and joiners, but the cost of transporting canned food

would be a function of the cost of metal, preservatives, farm labour and so on, Neither are likely to bear much resemblance to the cost structure of a transport business.

- Lower transport costs imply, for a given level of demand, that less output needs to be produced, as less of the product would melt en route from supplier to consumer. Thus, a transport-intensive manufacturing industry is in a relatively disadvantageous competitive position when transport costs fall, as demand for its products would decline – a bizarre result.

Especially in a multi-industry model in which transport is a separate industry (or industries), the iceberg approach makes no sense. The cost of the good, which may include a transport margin, needs to be distinguished from the quantity of the good, which does not change when transport costs change. Freight transport costs should be modelled as margins, as in the Monash models (Dixon et al, 2013). In trade models such as GTAP trade and transport margins are automatically captured as the difference between fob (free on board) and cif (cost, insurance and freight) prices, although the pooled margin approach is adopted as which countries supply specific margins is unknown. More generally, most SCGE model have one or more transport supplying industries so changes in their cost structure and thus output prices can be simulated directly. In some applied applications, such as in Norway, a national freight model is linked to the SCGE model (PINGO) to ensure that freight cost changes are passed directly through into the SCGE model.

When looking at directly incorporating impacts on passenger trips into a SCGE model, the inputs could be the Generalised Travel Cost (GTC) or its components such as travel time, disaggregated by journey type. Business time savings would feed directly into business decisions regarding hours available for work, whilst non-work time savings feed into household decisions (specifically the work/leisure decision) and household location in urban models).

As in Hensher et al (2012, discussed above), Shahriari et al (2022) and the RELU-TRAN model system (Anas & Liu, 2007) there may be a series of linked sub-models including an SCGE model, a land use model and a transport (or LUTI) model, usually requiring feedback loops between them to ensure consistency. In RELU-TRAN the SCGE model of the economy is RELU. It has four agents: consumers, producers, landlords and developers. Its output includes two-way person trips by origin and destination. These are used in the TRAN model to determine a mode split and a route split. The model solution algorithms are linked to ensure that travel times and travel monetary costs are internally consistent and that corner solutions do not materialise. An interesting feature of the model system is that travel routes have flow rates and capacity rates so congestion can be modelled at a broad level.[10]

In an SCGE analysis of highway improvements (such as extra lanes and a divided carriageway) the main benefits might be greater fuel efficiency, fewer accidents and travel time savings for freight delivery and passenger travel. Greater fuel efficiency may be simulated in an SCGE model by changing the physical fuel consumption coefficients, which would capture both own-account fuel use and out-sourced transport services. Lower medical care costs (from fewer accidents) may be simulated as a change in the composition of government expenditure if most medical costs are paid by government.

Faster travel time could mean an improvement in labour productivity as less time is required to complete a given number of deliveries or journeys. It could also improve capital productivity as a truck could cover a greater distance and manage more deliveries for a given number of labour hours, so reducing the number of trucks required per tonne-kilometre.

Clearly not all of the benefits of a transport investment need be modelled as productivity shocks. However, the modelling itself may not be the main issue. There is also data to consider, especially regarding the time involved in business travel. For transport services purchased from transport

[10] Detailed congestion modelling requires very fine spatial data such as for specific road junctions and city blocks, with fine time intervals. SCGE models are not suited to such problems.

supplying industries it is reasonable to assume that most of the labour hours in those industries are involved directly in transport. Transport on own-account is not straightforward. The cost of petrol and diesel can be secured from input-output tables and energy tables, but what proportion of an industry's total labour input is related to own-account transport? Think of tradespeople collecting building materials or district health nurses travelling between appointments. In such cases other sources of data will be required – surveys perhaps or timesheet records. Once such information is known (or estimated) it is a simple matter to split industry labour input into transport and non-transport hours and then simulate productivity changes or to distribute total business travel time savings (such as from a transport model) by industry.

Household travel for commuting and leisure (shopping, visiting friends and holidaying) is discussed below under the land use and scale questions.

Conceptually any transport intervention that potentially has economy-wide economic impacts can be simulated in SCGE models. Practically there may be limitations imposed by the structure of the model and the adequacy of data. However, in many case it will be possible to mitigate, albeit not entirely resolve these limitations.

How do SCGE models take into account the interaction between land use and transport?

How has this been achieved in practice?

How do SCGEs take into account the movement of workers between regions, whether this is migration or commuting?

Land is a classic input to production. However, in transport economics the meaning of land use change is broader than that. A change in the number of people living or working in an area constitutes land use change; in fact changes in trip numbers to and from a zone constitute land use change. In this context changes in labour supply, commuting patterns, migration of workers/business between model zones and changes in residential density (and numbers) all constitute forms of land use change.

Looking first at land as an input to production, with the exception of production functions in agricultural industries most CGE models do not include land as a factor of production. This has generally carried through to SCGE models. Thus, excluding agriculture, changes in land use are implicit. For example, if a transport improvement encourages more professional service firms to cluster in a region, land use change may see more office buildings and fewer factories, but most SCGE models lack that degree of land use disaggregation, meaning that that land use must implicitly accommodate the changes in the industrial composition of economic activity.

The main reason that land use as a factor input is not (usually) explicitly modelled is the limitation on spatial disaggregation in SCGE models. Data on inter-zonal trade and standard economic measures such as GDP and gross fixed capital formation are generally not available at a level of granularity that has consequences for changes in land use as an input to production. The very fine spatial disaggregation that is often used in transport models does not makes sense in SCGE models because economic data is not collected at very fine spatial (and temporal) levels. Thus, congestion can usually be only crudely captured in SCGE models – as in RELU-TRAN above.

Consider the SCGE modelling of HS2 for example. In reality it might generate considerable change in land use (shifts towards retail and office functions) around the Birmingham Interchange, and some offsetting changes in Birmingham itself (and some elsewhere too), but the spatial disaggregation of the model was far too coarse to capture that sort of land use change. The relevant economic data was either not available or would have taken too long to assemble or estimate. What the model does capture though is an increase in economic activity in business services and other sectors which benefit from passenger rail travel in the model zone in which the Birmingham Interchange is located. This is land use change in the broader sense used in transport economics. The HS2 model, however, does not include a migration model therefore it does not capture all forms of land use change.

The question is though, does it matter? From the perspective of 'levelling up' the focus is on securing more economic activity in northern regions – in a broad sense. How that is distributed across particular counties or towns is a second order issue with likely negligible feedback to the wider region or nationally. If it is of interest it is best addressed by more granular transport or LUTI models.

Depending on the issue, different models choose to address these forms of land use change or not. They may also do it in different ways.

A comprehensive urban SCGE model would include household decisions on where to live and where to work, based on residential property rents/prices, wages on offer in various locations and commuting costs. In what is still an enduring example of an SCGE model of a city, Horridge (1999) developed an SCGE model of Melbourne (Australia) with nine zones, that was used to study a tax on transport as well as other polices. Households select in which zone to work, in which zone to live, and at what degree of housing density. Land costs, which tend to be inversely related to distance from the CBD, are traded off against travel (essentially commuting) costs. The model has two types of good, transport and other, but consumption of the former provides no utility (as a first order approximation). It is merely a cost that reduces the amount of income that can be spent on other goods and land for housing, which do enter the utility function. Thus, any reduction in travel costs (such as in fuel prices, fuel efficiency, or public transport fares) simulated as above, may affect job choice and residential choice.

In a much newer paper Lennox (2023) provides an example of the importance of commuting and migration in an urban SCGE model, while also illustrating the difficulty (if not impossibility) of constructing an ideal SCGE model. The model is applied to a hypothetical enhancement of a proposed new metropolitan rail line in Brisbane (Australia), simulated by a change in transport (GTC) costs. It has considerable spatial detail; 354 zones in the relevant region and 100 covering the rest of Australia, but only five industries and three occupational groups. It also assumes Cobb-Douglas production functions and uses the iceberg approach to model the costs of trade.

However, these latter simplifications are of minor concern in this instance as the emphasis is firmly on modelling consumers'/workers' choices of where to live and where to work – as usual, although the disutlility of commuting features explicitly in the utility function. The utility function is forward looking and is maximised (with discounting) over time by choosing the optimal combination of where to live and where to work, and thereby determining commuting and migration patterns. Perfect foresight and Intertemporal optimisation mean that the wage rates, residential costs and commuting costs that enter into the decision making process evolve over time as expected.
The following model closure settings were adopted:

- The project is financed by an inflow of funds from overseas. The real exchange rate adjusts endogenously to prevent a change in the external current account (relative to a no project scenario).
- Total national employment is fixed at the Baseline level, but is free to vary by zone and region.
- The fiscal account is closed simply by treating all government services and public goods as taxes or subsidies to households. This still leaves scope for changing tax incidence by zone/region.

Model closure is further discussed in Section 3.

Interesting findings from the modelling are:

- In some zones that attract more workers the positive effect on labour productivity from agglomeration is offset by a constrained land supply, putting upward pressure on land prices and living costs, thereby deterring some inward migration.
- Direct accessibility benefits are more important in zones closest to stations, but general equilibrium effects that alter the price of housing and wage rates are stronger than accessibility benefits in other zones.
- With the migrations equations switched off (akin to very limited labour mobility) incumbent residents in attracting zones do not experience upward pressure on living costs and downward pressure on wages caused by immigration into those zones, but correspondingly, would-be migrants are worse off.
- Echoing a common problem in granular SCGE models, Lennox notes that nothing is known about the ownership of capital assets and financial flows across zones/regions. Thus, the distribution of land rents and therefore potential capital gains could offset or reinforce the effects of the incidence of taxation used to finance a project, albeit that this has little effect on benefits at the national scale.

What is the most robust spatial and sectoral scale for SCGE models? What level of spatial granularity would be possible and most appropriate, given data availability and the theoretical basis for SCGE models?

What impact does the choice of scale have on the overall results?

The preceding discussion points to two considerations:

- Are feedback effects from (say) the regional level to the national level significant?
- What scale – urban or regional – is relevant to the issue at hand?

Data issues are separately discussed below in Section 2.3.

As in the Horridge example, if the issue of interest is how an intervention affects land use and commuting between broad zones within in a city, a national SCGE model would provide few if any insights. Would Horridge's Melbourne model have been better with more zones? Perhaps, but the zones were selected on the basis of broad types of land use, available data and the scope of the project – appropriate to the issues of interest.

As discussed in Laird and Venables (2016), transport appraisal needs to be proportionate and context specific. They cite the narrative for Crossrail as being about facilitating employment growth and productivity in Central London, so city employment zones need to be distinguished. In contrast inter-city connectivity such as HS2 is about promoting economic growth and business efficiency, so a regional disaggregation is appropriate for the SCGE modelling (although the core analysis for HS2 used much more detailed spatial disaggregation).

A model like Horridge's or Lennox's could presumably be developed for large cities in the UK such as London (for Crossrail 2 for example), Birmingham or Manchester, perhaps linked to an HS2 model.

Berg (2007) develops an SCGE model focussed on household transport demand, ideally wishing to express household transport demand as a function of income, car ownership, trip purpose, population density, family type, distance travelled and the value of time. However, the absence of data precluded including family type and car ownership. Nevertheless Berg's SCGE model has an unusually detailed household sector with nine groups (three spatial location types that differ by density, each with three income groups) and transport demand split into work journeys (a complement to labour supply), short leisure journeys and long leisure journeys (< or > 100km), and by transport mode – car, bus or train, plus walking and cycling for work trips, and air travel for long leisure trips. Each mode has explicit costs and time arguments.

The spatial scale and transport disaggregation were appropriate to the question of interest – in this case the effects of a tax on carbon dioxide emissions. The results revealed different welfare effects, in aggregate and distributionally by household type, depending on whether revenue from the tax is recycled as a change in labour taxation of as lump sum grants to households. (This also raises the issue of fiscal closure which we discuss further in Section 3).

One aspect of spatial movement that is rarely explicit in SCGE models is business migration. However, most models do simulate investment by region and assume capital mobility (and labour mobility), which in effect determines changes in industry location.

In some situations it may be possible to simulate a spatial effect by expanding the number of industries. For example, distinguishing industry A in region X from industry A in region Y, with substitutability in demand reflecting their degree of heterogeneity and their distances from customers.

Do the existing models allow sequencing of investments?

The sequencing of investment (as in gross fixed capital formation, not financial investment) is only partly related to model structure. It is more related to model use. In SCGE models investment is typically endogenous, responding to the relative cost of capital as a factor of production, rates of depreciation, technological progress and industry demand – or expectations of demand. Whether the modelling is a sequence of comparative static snapshots or dynamic (see also next question) does not compromise its ability to simulate investment.

For example, a new highway that replaces an old rural road might change the capital-output ratio (such as within a nested CES production function) of the industry that supplies road services, simulated by an exogenous adjustment of a parameter for capital-augmenting technological progress. That would automatically translate into demand for investment, whether in the same period or prior periods through the usual intertemporal linkage between investment and capital stock.

A related issue, however, is whether construction prior to any operational phase should even be assessed with a CGE model. The consensus amongst modellers is that the construction phase of a project does not usually constitute a net addition to economic activity. The resources would otherwise be used in some other construction project. Even if the economy is in recession and there are unemployed resources (notably labour), some other construction project might have much the same economic effects during the construction phase. Expansions in construction activity that make use of otherwise idle resources do not usually generate the types of flow-on effects (changes in productivity, allocative efficiency etc) that are suited to SCGE analysis.

We therefore caution against claiming additionality of investment in a national sense, but this is not to proscribe additionality at the regional level with consequential effects on other regions, provided the relevant resource are regionally mobile – otherwise the above argument applies.

In that instance our advice would be to separately model the construction phase of a project. It might be simulated as an exogenous increase in government gross fixed capital formation in a region, directed to relevant industries and matched with a corresponding influx of labour – whether through commuting or migration. Of course, there may be a decrease in construction activity in other regions.

Slides 40-45 of HS2 (2023) present more detail on pre-opening effects.

How do state-of-the-art SCGE models consider issues of myopic vs. perfect foresight?

What are the relevant distinctions between dynamic recursive, intertemporal optimised and comparative static SCGE analyses, and how does this affect transport appraisal using SCGE models?

There is no consensus on this issue as neither the perfect foresight, also known as the intertemporal equilibrium (IE) approach, nor the recursive dynamic / sequential equilibrium (SE) approach is an accurate representation of investment decision making. Real world investment decisions vary along the spectrum from 'animal spirits' (Keynes, 1936) to complex scenario analysis and real options theory (Bowman & Moskowitz, 2001).

As more than one practitioner noted, policy uncertainty is high and expectations (especially about future technologies) are frequently wrong, so acting too hastily is extremely risky. Thus, perfect foresight does not exist, except perhaps by chance. By contrast, in IE models the assumption of perfect foresight means that the assumed prices that drive all decisions by economic agents (such as firms' decisions about investment and households' decisions about where to live) all evolve as expected. There is never any regret nor is it possible to raise welfare by making different decisions. Unsurprisingly, therefore, another commonly cited issue is the high programming and computational burden of IE models.

Hence IE models produce overly optimistic results, although they align nicely with welfare theory – if only it were that straightforward. As discussed by Stroombergen and Laird (2022) with regard to the HS2 modelling, the effect is more subtle as the perfect foresight assumption tends to bring other anticipatory investment too far forward. In the HS2 modelling, development along the proposed transport route and near stations begins well before the real benefits occur, but the actual benefit stream will inevitably be delayed so the mix and timeline of economic effects become very distorted and can lead to artificial additionality. As noted by one of the modellers we consulted, IE models tend to generate too much adjustment in the early years followed by almost straight lines over the rest of model's time span. In that particular case the IE approach was dropped for most model applications, in favour of the SE approach.

Recursive dynamic or SE models are at the other extreme. Here economic agents know nothing about future developments so there is no additional anticipatory investment. The models move forward period by period and solve each period separately, but using resources and technologies brought over from the previous period.

There are a number of ways to address the IE-SE dilemma:

- Some models such as the MIT's EPPA model can be set to run in either mode (Chen et al, 2017), but the IE version necessitated a considerable reduction in model complexity and breadth. One option is to use a small IE dynamic model to set the time path for variables such as investment, coupled with a larger SE model.

- Some IE models have the ability to constrain the degree of intertemporal optimisation such as by changing the intertemporal elasticities of substitution and the terminal year. Altering investors' desired rate of return to reflect risk is another option, but as shown in the HS2 modelling review the results can be difficult to explain, undermining the credibility of the analysis.

- Careful application of macroeconomic closure assumptions: Lecca et al (2013) find only small differences between IE and SE models with regard to both the long run states and the time paths when model closure assumptions relating to saving and investment are comparable. Time paths are affected by two types of adjustment parameters: the speed of adjustment in the SE model (which can be altered by changing the lag length on investment decisions) and the intertemporal elasticity of substitution in the IE model.

And going further as noted by Venables et al (2022) in their review of CGE trade modelling:

> "… typically, the fundamental mechanics and structure of (comparative) static and dynamic CGE models are largely the same … meaning that starkly different long-run results should not be expected compared to the static framework."

Considering that SE models essentially just endogenise the links between periods in successive snapshots of comparative static models, altering closure assumptions can also be applied to comparative static SCGE analyses to investigate the effect of bringing forward economic impacts in advance of project opening. For example, in a region that might be expected to see some anticipatory investment an exogenous adjustment to the demand curve for capital – perhaps in specific industries as informed by an accompanying narrative – would simulate investment. At a national level the constraint imposed by the current account balance and saving-investment accounting identity would naturally continue to apply, but that is largely irrelevant at the regional level.

Practitioners with whom we spoke tended to stress the greater importance of the IE approach in the context of migration as such decisions are based on expected future incomes, commuting costs and land prices. However, there was less enthusiasm for applying the IE approach to peripheral investment by businesses in the context of possible economic benefits from future transport projects. As we summarised in our review of the HS2 modelling by PWC, determining what is a realistic level of investment pre-project opening is context-dependent with an unavoidable degree of subjectivity and expert judgement. Evidence supports private sector actions in advance of the project, probably aligned to when construction begins and continuing for several years after opening of a project. See for example Stroomberegn and Laird (2022). This is rather at variance with IE modelling in which almost all investment is brought forward.

The above notwithstanding, the choice between dynamic and static modelling should be determined (as always) by the topic and scope of the analysis. How important are expected future changes in relative prices? Is the time path important? Perhaps less so in longer run modelling in which the time path may become quite spurious.

2.3 Data and input parameters

What are considered the most influential parameters in SCGE models in terms of model results?

Parameters in SCGE models are of two types:

1. Observable or theoretically measurable elasticities (even if the supporting evidence is at times thin) usually based on econometric estimation, such as labour supply elasticities and fuel substitution elasticities – elasticities that govern how readily consumers can switch between different fuel, such as gas versus electricity for home heating. The list below summarises the elasticities that are typically found in SCGE models. On a technical point, elasticities generally do not enter models as specific values. Rather they are implied by the parameters of production functions, household demand functions and so on.

2. Parameters that are essentially artefacts of the model's specification, such in the PWC modelling of HS2 which has a parameter that is described as changing businesses' propensity to return capital to owners, which is used to adjust the amount of anticipatory investment.

Another example is the use of a proxy for institutional factors or place-based attributes in migration equations. Such parameters provide a degree of stickiness that prevent migration adjusting fully to regional (or country) differences in wage rates. There is no typical list of these sorts of parameters.

Typical SCGE elasticities

- Industry production functions: elasticities of substitution between inputs, including factor inputs such as labour, capital and land, and intermediate inputs such as energy and raw materials.
- Industry production functions: elasticities of substitution in between goods in the same category, but produced in different regions – at least between imported and domestic sources, but in SCGE models also between multiple domestic regions.
- Similarly for final demand; elasticities of substitution between goods and services, and from different sources, at least for household consumption, and preferably also for gross fixed capital formation.
- Transport mode: elasticities of substitution in industry and household demand for transport (although really a subset of the above).
- Location: spatial choice elasticities for households and businesses.
- Labour supply elasticity, or elasticities if more than one type of labour or household.
- Export demand (or supply) elasticities.
- Land supply elasticity

The nature of the issue being modelled is paramount to deciding which parameters are most influential. Initial application of many CGE and SCGE models was to trade liberalisation, in which case elasticities of substitution between imported and domestic products were crucial parameters. Equally important though were structural features of the model such as whether imperfect competition and product variety were incorporated. See for example Harris (1984).

This also applies to SCGE models used for appraising transport projects. The structural features of the model are as important as the elasticities, but different ones. Given the S in SCGE models, agglomeration elasticities can be important, although this is not necessarily the case. As mentioned above, in a model of Sydney's north-west rail link, Hensher et al (2012) combine a transport land use model with an SCGE model and ascertain that the pure general equilibrium (GE) effects of workers having access to higher paying jobs account for 86% of the increase in the total wage bill. The other 14% is attributable to agglomeration benefits from greater productivity leading to higher wages. There are some sign differences at the zonal level as some have negative agglomeration effects, but positive GE effects.

Agglomeration effects are essentially (labour and capital) productivity effects and so generate higher wage rates, whereas GE effects improve allocative efficiency by altering the distribution of workers between industries and/or zones, thereby raising average incomes. Thus, a transport project can lead to structural changes in a city's economy. Industry level wage rates do not necessarily change, but could do if labour demand changes relative to supply.

Zonal or regional effects can be sensitive to the spatial mobility of labour for estimating the distribution of benefits, but this is much less important at the macro level. The overall elasticity of labour supply is important in that regard, although the vast heterogeneity in labour supply elasticities (affected by age, household type, macroeconomic conditions etc) points strongly to running at least one scenario with a fixed total labour supply – as discussed below under closure.

Other influential parameters in the transport context are mode substitution elasticities and fuel substitution elasticities (in a world where carbon emissions are priced).

How well are model parameters normally aligned with each other in SCGE models? Is parameter mismatch considered an issue in general (i.e., parameters sourced from different studies and/or applied at a different spatial scale than the scale of estimation)?

The first question is difficult to answer as most modellers do not release information on parameter values in research reports, but usually will do if asked. As full econometric estimation of (S)CGE models is extremely rare and usually impossible, parameter values are gleaned from other studies such as the GTAP database, albeit with adjustment for the spatial coverage of the model – between countries versus between regions within a country for example.

In our experience though, parameter mismatch is simultaneously not a major issue while also being extremely tricky to verify. That may seem an illogical statement. Verification could be achieved if models have identical structures, the same industries, the same regions and so on, but that is never the case. One model might have a 3-tier nested CES production function and another might have a translog production function, perhaps with different inputs. The elasticities are therefore not directly comparable. One could run a number of scenarios and compare model outputs, but if the results are different the reason could be the elasticity values or the structure of the production functions. Similar results might enhance their perceived reliability, but again reveal little about the significance of mismatched elasticities.

There are no perfect, universally agreed parameter values. All one can do, indeed must do, is test the sensitivity of results to different values used in the literature, but here again is the question of relative significance. Model results tend to be much more sensitive to how a scenario is specified, which parameters and exogenous variable are adjusted and in what way, and what model closure assumptions are adopted. We return to this issue below.

What data for SCGE models would be needed for a UK model? What are the limitations of the data?

A 'UK model' may be interpreted in three ways; a model of a city in the UK, a model of a region in the UK, or a model of the UK, in each case with some appropriate degree of spatial disaggregation related to the questions of interest. For example, the SCGE modelling of HS2 covers the entire UK, disaggregated into ten regions.

At the risk of being repetitive, everything including the data requirements hinge on the topic to be studied. Given that caveat, Table 2 below lists what is likely to be essential and what is likely to be desirable, cross-classified by whether the model is urban SCGE or regional (within a single country) SCGE. The categorisation is not absolute. For example, in a model of the use of high speed rail by households a mode split would be essential, not just desirable.

Some key data sources of which we are aware are as follows:

- Census: data on commuting, household characteristics etc at fine spatial levels.

Table 2: SCGE data requirements

	Urban SCGE (household focus)	Regional SCGE (industry or household focus)
Prerequisite	A thorough description of the context and objectives of the proposed modelling. Is a transport SCGE model necessary?	
Essential	• City input-output tables if modelling industry type and location, or more likely a national or regional table adjusted by more detailed data on employment, spending etc. • Main fiscal flows such as revenue from income tax, VAT, and excise duties, plus expenditure on government consumption and welfare benefits. • Elasticity values for commodity-labour-leisure substitution. • Households disaggregated by zone, eg intra-city. • Household transport demand split into commuting and other. • Values of travel time. • Data on business travel • Migration, primarily between zones, but also net migration into or out of the aggregated area.	• National and regional input-output tables linked via trade flows. • Main fiscal flows such as revenue from income tax, VAT, and excise duties, plus expenditure on government consumption and welfare benefits. • Elasticity values for trade, industrial production and household consumption. • At least one transport supplying industry. • Explicit transport margins. • Data on business travel including the number of extra hours that a time saving would release for extra work. • Migration.
Desirable	• Disaggregated fiscal data: Fuel excise duties, public transport fares, vehicle registration fees etc • Households split by demographic or socioeconomic group. • Household transport demand by mode and reason for travel. • Values of travel time by mode.	• Disaggregated fiscal data: Fuel excise duties, distance charges, vehicle registration fees etc • Transport supplying industries by mode. • Own-account transport labour requirements (for industries that do not out-source their transport requirements).

- National travel survey: data on business travel by industry, but sample size would limit spatial disaggregation (local authority level perhaps) and mode split.
- The DfT's National Trip End Model has trip origin and destination numbers by zone.
- National and Scotland input-output tables. Underlying data should have information on fuel excise duties, distance charges, vehicle registration fees etc. Similarly for transport margins as IO tables are expressed in basic prices. However, there is no spatial disaggregation.
- Household expenditure surveys: available by government office region. Cost items are quite coarse; whilst fares by mode are separated out, the running costs of a car are all aggregated together. The Living Cost and Food Survey does not give many datapoints at an even moderate level of spatial accuracy. The lowest level of disaggregation is the nine regions of England plus Scotland and Wales.

However, we note that not all data will be available from official sources. Regional IO tables are typically estimated by using region-specific row and/or column totals of gross output (or employment as a proxy) by industry, and using the national IO table as a starting point for a technique such as iterative proportional fitting. This was done for the HS2 SCGE evaluation, albeit with a minimum entropy algorithm instead of iterative fitting. Inter-regional trade flows are often estimated using a combination of survey data and modelling – commonly with the gravity model. If a project is expected to impact on inter-regional trade and that is a key outcome of the project, then consideration would need to be given to some primary data surveys to get some observations on these inter-regional transactional flows.

For intra-city trade the situation is conceptually the same, but is immediately more complex. Theoretically each zone could have an input-output table with inter-zonal trade flows, commuting and migration. Actually developing such a database would involve a substantial amount of estimation and probably guesswork. Employment data is usually known at fine spatial levels by location of production, but the data has limitations – builders and relief/supply teachers are likely work in many different places over the course of a year. Census data provides a snapshot of a day or a week which inevitably is assumed to provide a reasonable distribution for travel of that type. Bus drivers' place of work is probably the bus depot. Thus at the city level the output from the estimation techniques becomes progressively less reliable – the exogenous data input is often not available at fine spatial scales and any given firm is less likely to have the cost structure of its associated industry.

The spatial attribution of transport (and trade) margins is even more tenuous. A particular product could be purchased by a person who works in area A, lives in area B, buys the product in area C, that is made in area D and transported by a company based in area E. Obtaining this data for inter-regional trade is already challenging, but at least areas A, B and C will frequently coincide, and area E is quite often in either area C or area D. For areas within cities such overlaps are much less common.

For within-country regional input-output tables, GDP is attributed to either the place where production takes place or the place of residence of workers, although the latter option usually has to make some rough assumptions about the allocation of non-wage income. Out of zone spending by households is treated as an import from the relevant production zone, in which it is treated as an export.

For questions related to transport infrastructure (such as HS2) the spatial dimension is important, especially in the context of the 'levelling up' agenda, but the size and scale of a project matters too. Small projects such those that are typical of components of the Road Investment Strategy 2 (RIS2) - with a total programme budget that is perhaps a quarter of the HS2 budget - are not amenable to SCGE modelling – the required data do not exist, and even if they existed or could be reliably estimated, the modelled benefits would likely not extend much beyond the direct user benefits.

However, an overall strategy (i.e. the whole of RIS2) or combination of projects within a region could be amenable to SCGE modelling.

Other SCGE applications are less reliant on detailed IO tables and inter-zonal trade. For example, Lennox's (op cit) SCGE model, which assesses the spatial distribution of costs and benefits of a hypothetical new passenger rail line in a city, predicts that the line would improve accessibility to the CBD and lead to a more efficient residential configuration. The model has five industries with identical production technologies in each area (although of course the size of each industry varies across areas), but industry configuration is not the focus of the analysis. Commuting and migration are of prime interest so data relating to those aspect of the model is on a more solid basis.

Nevertheless, even this highly spatially disaggregated model cannot simulate all changes in land use. Lennox notes that an increase in residential density in a zone might typically be accompanied by more retail activity, but it is impossible to say whether this would entice a whole new suburban shopping centre or an expansion of existing stores.

Data for policy questions associated with transport prices and taxes will also place different demands on the data. For example, the question of charging electric vehicles for the use of roads (given that they do not pay fuel tax). Indeed, disaggregation of the household sector by socio-economic group might be of more interest than a spatial disaggregation as place-based averages may not necessarily deliver much insight into this question. It also raises the topic of fiscal flows as itemised in Table 2. Different ways of financing road construction will have different implications for the fiscal budget, implying different deadweight costs. Hence the importance of an SCGE model incorporating the main types of government expenditure and revenue – for this sort of issue. Fiscal effects are further discussed in Section 3.

With regard to elasticities, as discussed in Section 2.1 elasticity values in SCGE models are usually adapted from econometrically estimated values in other studies, as econometric estimation of all elasticities tailored to a specific SCGE model is an immense task that is usually beyond the resources available to an SCGE modelling assignment.

As mentioned previously data requirements can increase exponentially as models expand to include more industries, more regions/zones, and more types of households. Trade-offs are inevitable, with any decisions needing to take full account of the issue at hand. Data and parameters can frequently be estimated, but as the degree of empirical grounding slides the need for sensitivity testing escalates. Or the scope of one's modelling objective may need to be less ambitious.

At this point in time within the UK the spatial detail of IO data is limited, which places bounds on the level of disaggregation possible and the scale/size of the infrastructure policies that can be tested.

If thinking about infrastructure and Transport Business Cases a key restriction on spatial granularity is likely to be the household expenditure surveys, which do not seem to deliver many data points at geographic levels below government office region. Thus working at that level one would be looking only at assessing transport projects that are impacting at a wide regional level such as HS2, the Road Investment Strategy programme (RIS3 being the latest) and the new proposed rail Network North programme. It is likely that not the whole programme would need assessing, and subsets of each programme would be appropriate for an SCGE application, but the impact needs to sufficiently large to make a difference in regional level economic performance. Looking beyond infrastructure, SCGE models are well suited to understand the structural impacts of transport policies which impact nationally, but will also lead to some regional differentials. For example, studying decarbonisation of the transport sector, and the different pathways for achieving that. Most of the recent applications of SCGE to the transport sector are to this topic.

SCGE models would also be very informative for the study of regulation of the rail sector, particularly fare regulation and the subsidy of the infrastructure operation and the operation of the train services. For such an application the model would need to be constructed to have a detailed representation of the cost side of the rail industry, data for which should be available. Finally, whilst not in the DfT sphere of responsibility, how road transport is taxed via fuel duty or some road charge is a policy that will have large structural and welfare implications; something that would lend itself very well to the application of SCGE. For such an application the cost structure of the road sector would need a detailed representation on the model, and again the data on this should be available.

These spatial data aggregation issues are of course not unique to SCGE models, as in the absence of any observed inter-regional trade data all wider economy modelling methods (LUTI, econometric, etc.) would suffer the same challenge. Over time observed regional IO data could be built up and more disaggregated SCGE models could be developed. The Norwegian PINGO (Hansen, 2019) model is an example of such a phased development.

The data challenge is also not unique to transport applications of S-CGE. For example an SCGE analysis of a major reform of the tax-benefit system would require detailed data on household demographics, expenditure patterns, income and hours worked. An analysis of subsidies for home insulation as part of an emissions reduction policy package would need data on the current profile of insulation across the housing stock, and also how the cost of a subsidy compared with other economy-wide mitigation policies such as a carbon price. The SCGE approach would be especially important if a country needed to purchase emission units on the international market to meet its nationally determined contributions under the Paris Agreement, as the relativity between the domestic carbon price and international carbon price is crucial to reducing emissions at least national cost.

Augmenting the data with surveys and information on freight flows would enable finer spatial disaggregation, but as one moves away from real data and towards more estimation and synthesis, the greater the potential inaccuracy which at some point will undermine the modelling.

2.4 Validation and output

How are SCGE models validated? What are suitable approaches to validation?

How well have SCGE models predicted real-world outcomes?

The lack of validation has always been a disadvantage of CGE models. They are not like econometric models, albeit that their parameter values may often be derived from econometric analysis. Hence projections outside the sample period cannot be evaluated with statistical tests of time series performance (such as Theil's U-statistic).

Validation in the sense of replicating an economy in some year other than the base year of the model (for which replication is perfect by construction) is ambitious. All of the exogenous variables in a CGE model would need to be set to their actual observable values where possible, such as for population, world prices and government spending, with extrapolation of historical data where observable values are not readily available. Examples here include total factor productivity by industry, shifts in numerous export demand curves, and shifts in consumer preferences (household demand curves) to reflect the influence of factors outside the model's consumption function such as population aging. The task is demanding and few modellers with the exception of Boratyński (2012) and Dixon & Rimmer (2010). have (or had) the required time and resources.

As well as providing a historical simulation the model can then also be used to decompose historical changes into effects from different 'shocks' such as changes in population. That enhances confidence in the model's ability to analyse future scenarios, particularly if previous shocks are comparable to current policy interests.

However, to our knowledge and based on discussions with other practitioners, no such detailed process has been attempted for SCGE models as the data requirements become overwhelming, although one practitioner has replicated historical regional growth differences.

In general validation of CGE/SCGE models is achieved by the following means:

- Use of accepted functional forms with plausible parameter values.
- Considered application of the model (as mentioned above); how a scenario is specified, which parameters and exogenous variables are adjusted and in what way, and what model closure assumptions are adopted.
- Judicious sensitivity analysis. More general, but time-consuming (unconditional) sensitivity analysis would be to run Monte Carlo simulations with all parameter values varied according to their underlying error margins – from whatever source they were obtained or even by assuming a statistical distribution. Berg (2007) assumes uniform distributions for unconditional sensitivity analysis and runs 500 simulations. The results are very robust with the main welfare measure (equivalent variation) having a 90% confidence interval of ±10%.
- An accompanying narrative, perhaps accompanied by a Back of the Envelop (BOTE) model, as discussed in Dixon et al (2013).
- In some cases a model is checked for errors in coding and data, but this is a time-consuming process that requires considerable expertise with the model software. It is more like an audit of the model than validation of the model.

Ex post assessments of the performance of (S)CGE models are rare. Probably the two most well-known examples are Kehoe et al (1995) and Kehoe (2003). The former found that the model performed well in estimating the effects of Spanish fiscal reform, but the latter found the opposite – poor performance estimating the effects of NAFTA. Kehoe conjectured that the largest effect of the liberalisation of trade and capital flows is on firm productivity – something that more recent SCGE models incorporate.

If the opportunity arises after a project is operational, the model could be re-run with the known final project input assumptions (ignoring all other external changes) and the results compared with an econometric study (such as a 'difference in differences' approach across both space and time) of the effects of the project. Target variables might be regional GDP, the number and concentration of businesses, commuting propensity and so on.

A simpler approach, recommended by one of the applied CGE modellers with whom we consulted is to apply the model to analyse major shocks with known effects (ex post) that are measurable above the usual economic variability. The COVID19 shock would be an example.

Do SCGE models produce results that are aligned with relevant economic theories, such as New Economic Geography for example?

This depends entirely on how the models are specified. Early models were mostly based on neoclassical economics with constant returns to scale and perfect competition. In SCGE models a fundamental objective is to determine the distribution of economic outcomes over space, so that means capturing agglomeration effects. Hence current SCGE models incorporate many features of NEG such as imperfect competition, increasing returns to scale and product variety. Oosterhaven & Knaap (2017) claim that modelling inter-regional trade of the same good (such as a country importing and exporting motor vehicles) requires the model to incorporate product differentiation and monopolistic competition. However, this is not true. Imperfect substitution between such goods is all that is required. The Dixit & Stiglitz (1977) monopolistic competition approach is commonly used, such as by Tavasszy et al (2011) in the RAEM model. This allows for heterogeneous goods with mark-ups over marginal cost.

Like most model parameter values, agglomeration elasticities such as the elasticity of labour productivity with respect to employment density, tend to come from other studies. The elasticities differ in how they have been estimated and are usually industry-specific and location-specific. Thus, sensitivity testing of these parameters is recommended.

Albeit with regard to trade modelling rather than transport modelling, Takeda (2010) investigates the effect of different model structures on welfare effects. The structures vary in terms of the presence of economies of scale (fixed costs) and product variety, and whether or not firms set their output taking others' output into account. The results show that the scale effect implies lower costs with more output, leading to greater welfare gains; essentially a simple efficiency effect. Products variety also delivers a welfare gain, as do lower markups in which price is closer to marginal cost. However, some gains could go offshore in the form of lower prices for exports.

Overall the variety effect is more important than the scale and markup effects. Under trade liberalisation some industries contract so the presence of scale effects exerts a negative effect on welfare. Also notable is that the welfare effects in the perfectly competitive model are not always smaller than those in models with imperfect competition.

In a study of proposed high speed rail options in the Netherlands Elhorst & Oosterhaven (2008) find that the additional economic benefits from incorporating market imperfections (relative to allowing for only direct transport benefits) vary from –1% to +38%, and depend on regions concerned, especially on their labour markets.

There has been some concern that models with NEG characteristics and intertemporal optimisation could be subject to multiple equilibria, but we are not aware of any such instances in applied situations – a point also made by Lennox (2023). It is likely that initial (base year) conditions and closure assumptions mitigate or eliminate such risks.

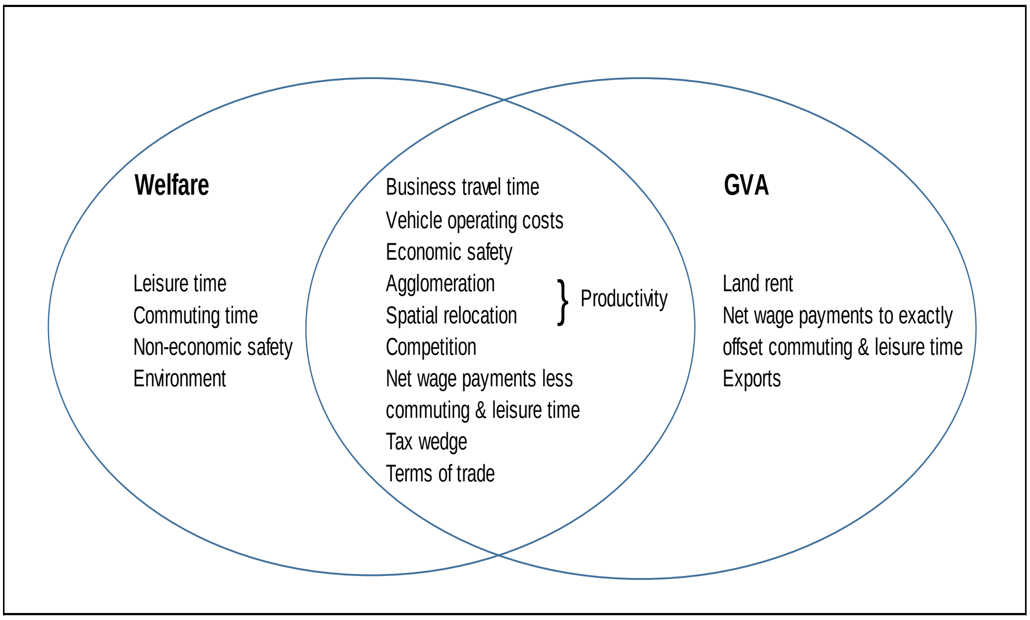
How do SCGE models regard GDP vs. Welfare impacts? How can welfare estimates be derived from SCGEs?

There is an overlap between the coverage of CGE models and economic welfare, as shown in Figure 1 below. With regard to transport the main omissions from CGE models are impacts without markets, such as reductions in fatal and serious injuries. Leisure time may or may not be monetised.

More generally, models contain consumer utility functions from which demand functions are derived. The utility function may contain non-market benefits such as leisure time or indeed the opposite; services such as commuting which may generate no utility yet still appear in consumer demand functions. Utility changes can be monetised, given a value for the marginal utility of income.

As discussed above the SCGE model in Berg (2007) has a detailed household sector and disaggregation of household transport demand. The specification ensures that the marginal rate of substitution between leisure and general consumption depends on the wage rate and the price, including time, of commuting. This enables a fairly comprehensive measure of changes in welfare to be derived from the model, expressed as the change in equivalent income variation (EV) – the change in income that would produce the same new level of utility as generated by the change in prices associated with the transport project.

Figure 1: potential transport effects



Source: Venables et al. (2014)

Invariably, not all impacts of a transport project will be contained within the SCGE model. The welfare estimate, if being used in a CBA, will likely need to be augmented with additional impacts depending on the model structure (e.g. non-work user benefits, environmental impacts such as noise, accident benefits, etc.). When doing so care will obviously be needed to ensure there is no double counting, This will particularly be the case where some elements of an impact such as non-user benefits are included in the SCGE, but others are not (e.g. commuting time is included, but other forms of non-work trips such as leisure trips are not), Additionally, the model may only have a 'rough' representation of some elements of welfare impact (due to e.g. zonal size), and more precise estimates might be preferred in the CBA.

With regard to the additionality of wider economic impacts to the user benefits and their treatment in an SCGE, this is discussed in detail in our review of the HS2 modelling (Stroombergen & Laird, 2022). A section is quoted below:

> "The SCGE model includes multiple market failures associated with the government sector as well as a model of imperfect competition. Surpluses associated with these, as would be calculated within a Level 2 appraisal consistent with DfT's Transport Analysis Guidance (TAG), are therefore embodied in the household function in the model. When putting together a full Level 3 appraisal HS2 Ltd/DfT therefore should not add Level 2 wider economic impacts to these values. We illustrate why by briefly discussing labour supply and the move to more productive jobs tax wedge.
>
> If there was no tax on labour earnings, any increase in labour income brought about by greater participation would produce no change in aggregate welfare as the value of the extra income would be exactly offset by the value of lost leisure. GDP would, however, increase. The existence of a tax wedge changes the equation as some of the benefit of people working more hours accrues to the government. Thus the tax paid is an additional benefit that should be included in a welfare metric. The same effect applies if, as result of a transport intervention, a

worker moves to a higher paying job in a different industry or different region. What happens to the tax wedge in a CGE model? In PWC's model any surplus tax revenue is recycled back to households as a lump sum. Hence the tax wedge is captured in GDP as more consumer spending (or as investment via savings). So, both the change in hours worked and the tax wedge are captured by the model" as they should be.

Alternatively, as is the case with the PWC applications to HS2 and Lower Thames Crossing, the welfare impact can be built up from the GDP estimate. Here the accounting exercise requires careful consideration as to how GDP and welfare are measured. In the HS2 example investment is removed, and the additional value of increased leisure is added in (workers work fewer hours with HS2, than without it). Leisure time can be monetised, but its valuation is not trivial. One option is to use the net wage rate as the marginal value of leisure. Another is to use the marginal value of travel time savings for non-work travel. The former could incorporate an adjustment for the extra utility or disutility of work – social status for example. The value of travel time savings may need adjustment for productive time while travelling (dealing with work emails) or the disutility of uncomfortable travel (relative to other non-work travel).

An aspect that has not been addressed to date in using GDP changes to create a welfare change, as far as we have seen, is the correct treatment of moving to more/less productive jobs. Here only the tax component of the GDP change can be included in the welfare analysis if commuter user benefits are to be added on. In that situation the SCGE model would give the full GDP impact, but the non-tax aspect of the GDP change needs to be eliminated to derive a welfare estimate from the GDP change. Alternatively all the relevant benefits in the SCGE model could be measured in the welfare function at household level, as without decomposition an SCGE model will not distinguish between high incomes that arise due to agglomeration and those that arise from moving to more productive jobs/locations. To an extent this problem was avoided in the HS2 application as the SCGE model did not include a migration model. Had it done, the accounting exercise would have needed to make that adjustment.

There are no definitive answers as to how to obtain welfare measures from an SCGE model. Ultimately, an SCGE model will only give a partial estimate of welfare change, and the approach adopted to obtain the welfare estimates from the model will be highly dependent on the model's structure. If a key requirement of the model is to output welfare metrics of transport projects, the specification at the outset of the model development should reflect that.

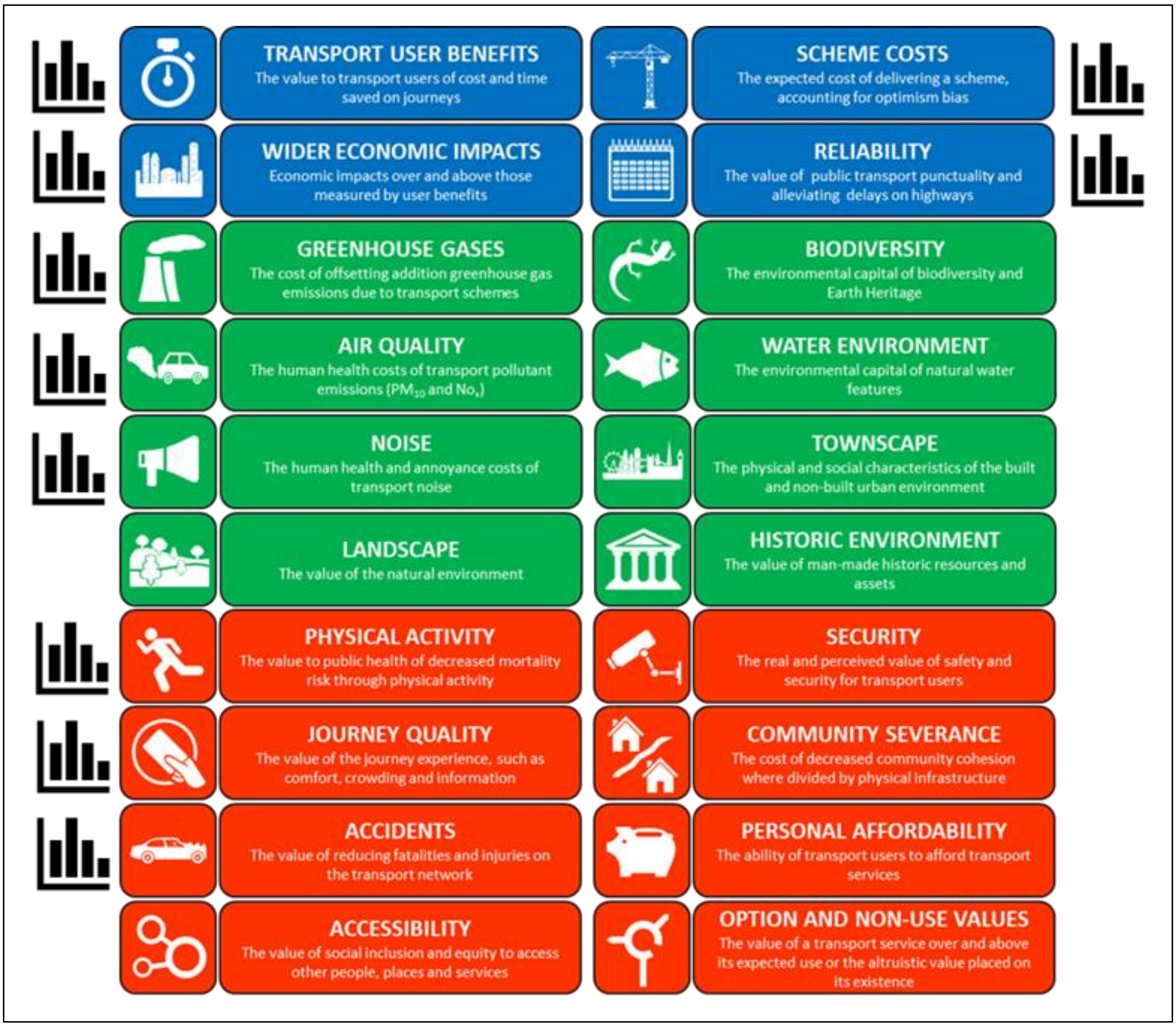
Of great significance in welfare analysis is the financing strategy associated with a transport investment. Alas this is frequently ignored. We discuss this further in Section 3. It also raises the wider issue of the role of government in household welfare. As pointed out to us by one model practitioner, household utility functions in CGE models rarely incorporate the welfare that consumers received from services that have a large component of government funding. Depending on the fiscal closure rule (Section 3) government spending on transport infrastructure may be offset by reductions in spending on other services that enhance household utility such as health and education. Both sides of the equation should be in the welfare function. Of course if a transport project is not expected to change health and education provision by government, public expenditure on them may be ignored in a welfare measure as they would net out.

2.5 Applications

What are the mechanisms used in SCGE models to calculate wider economic, and other wider social benefits as in the UK government's Transport Analysis Guidance?

Transport appraisal in the UK covers the categories shown in Figure 2. Those that are routinely monetised are shown with bar graphs beside them. The social benefits are specifically those in red, but can also touch on those in blue.

Figure 2: UK Transport Appraisal



Source: Cambery (2023).

We assume the term 'wider social benefits' refers to the TAG category of social benefits as the TAG does not refer explicitly to '<u>wider</u> social benefits', which might include a change in community severance for example. Such benefits are absent in SCGE models. However, we note there are other types of wider economic impacts such as increased employment for youths or increased income for low income households that are also not usually in SCGE models (due to insufficient household or labour market disaggregation).

The standard definition of wider economic impacts (in contrast to wider social impacts) are clear:

1. Increased output in imperfectly competitive markets. This will manifest as increased profit to businesses.
2. Agglomeration
3. Increased tax revenue from an increase in labour supply.

4. Changes in tax revenue from a relocation of economic activity between areas (and industries) with differing levels of productivity. This is called the move to more/less productive jobs (M2MLPJ).

5. Dependent developments where land value uplift is used instead of user benefits. This is typically for small projects that open up a site for development.

Assuming an SCGE model includes imperfect competition, it will capture (1). With income tax and other taxes, (3) and (4) are also captured. For example the RAEM set of models and Berg (2007) calculate welfare at the household level.[11] Agglomeration (2) could be either included endogenously in the model or could be calculated using a sub-model, given a suitable spatial scale. Capturing land value uplift is unlikely in regional SCGE models as it needs a link between land values and accessibility at a suitable spatial scale. Urban SCGE models in which the land market is likely to be explicitly modelled, are better placed in this regard.

In terms of the mapping between SCGE models and transport appraisal in the UK:

- SCGE models focus exclusively on market impacts (as discussed above). Non-market impacts are not captured. These include non-work time savings (unless they are in the utility function), willingness to pay for accident reduction, environmental improvements and so on.

- However, some aspects of 'non-market' impacts are market related. For example there may be productivity benefits of improved health from fewer injury accidents, more physical activity, less noise and better air quality. Labour productivity is picked up in SCGE models.

- Spatial matching is often difficult. Many of the impacts in a transport appraisal are very local to the project, not only user benefits, but particularly 'social' benefits such as noise, accidents, air pollution, severance, etc.

- Household type/disaggregation could also be important and most SCGE models cannot identify the impacts on particular marginal groups: specifically low income and ethnic minorities, or households with no car.

How have other countries used SCGE model results in business cases?

Business cases in the UK are a formal part of the reporting of a transport appraisal. Not all countries, however, have business cases. In fact not all countries, even amongst OECD nations, have cost benefit analysis guidelines (Smith and Braathen, 2015). Furthermore, guidelines where they exist might also be only at the national level, rather than specific to the transport sector, and may be advisory rather than compulsory.

The picture is similar for the incorporation of wider economic impacts. Wangness et al (2017) find that transport appraisal guidelines in only 15 of 23 OECD countries acknowledge Wider Economic Impacts (WEIs), of which only 7 permit their monetisation in the CBA. The UK DfT seems to be the trend-setter in WEIs guidance. In all jurisdictions standard transport CBA always takes priority – and rightly so, with WEIs often added using parameter values from other studies. New Zealand's use of agglomeration elasticities (NZTA, 2023) estimated by Mare & Graham (2009) is an example. Only the Netherlands has guidelines for using CGE models in WEI assessment, although Transport for NSW (2018) provides

[11] Care is required here. Including the full GDP impact of M2MLPJ in the welfare appraisal is incorrect as only the tax revenue should be included.

some guidance on using CGE models, specifically mentioning the CoPS/Monash-developed TERM model.

Business cases are of course a lot broader than just the CBA. There needs to be context and alignment with policy objectives. Countries and agencies (such as the EC and World Bank) for whom SCGE models have been developed utilise them to examine transport related policies. How influential the models are in the ultimate decision making process is not obvious. Through our personal knowledge and interviews with experts we are aware of SCGE transport applications by public agencies in the Netherlands (RAEM), Norway (PINGO), European Commission (RHOMOLO and GEM E3), Australia (TERM) and New Zealand. The TERM model also has American and European versions, the latter covering five countries and 27 regions. Overall, our understanding is that SCGE models play a peripheral role in the actual CBAs, but where they exist and have been applied to transport projects they are part of the narrative and context. They are not of much value for small projects; they need to be applied to large projects (such as HS2) or to wider strategies (many projects in a highway network for example). In such case the spatial scale of the model needs to be carefully specified.

What is the likely cost of developing an SCGE for the UK?

Subject to our point above about the three interpretations of 'a UK model', we offer some guidance.

More than one of our interviewees suggests a two-stage approach to developing an SCGE model; Essentially they are specification and data, always in the context of the issue of concern.

<u>Specification</u>

- Which industries and how many, especially transport-related.
- City zones or sub-country regions, land use types; how many.
- Household sector disaggregation – income group, family type, how many types of travel.
- Variables specific to transport modelling – fuel excise taxes, distance charges, travel times by mode and reason for travel.
- Freight margins and inter-regional trade.
- Employers' business travel time and money costs
- Imperfect competition and product variety.
- Comparative static or dynamic – IE or SE.
- Work/leisure decision (labour supply function)
- Migration and commuting (and influence on household and business location, households' work-leisure decisions).
- Selection of functional forms.
- Level form or logarithmic differential (Johansen) form and how will it be solved – a package such as GEMPACK or GAMS, or a purposely designed algorithm. In this regard note that models specified in logarithmic differential form (often using GEMPACK) are not easily amenable to discontinuities such as for new technologies. For example there may be no electric vehicles in the base year dataset, so a small amount of EV use needs to be added, coupled with a high price elasticity so that EVs are adopted as expected/desired in a future year or policy scenario.

Data

The model should first be run with fictitious but realistic data, including for elasticity values. As actual data becomes available the fictitious data is replaced. If some data requirements have no practical hope of being met, some elements of model specification may need to be revisited.

Practitioners stressed the inevitable need for data cleaning such as typically required with census data.

We cannot assess the financial cost of the above stages, but in terms of person years our discussions with other practitioners revealed a fairly wide range from half a person year to two person years, assuming skilled personnel and excluding any large-scale econometric estimation of parameter values. Much depends on the skills and experience of the people involved, and the starting point – is 'clean' data available from another project for example. Clearly a sound knowledge of SCGE modelling is essential although it is more than just knowing about the algebraic representation of producer and consumer behaviour and mathematical algorithms. Models with a user-friendly interface can be operated by most analysists, but people with a solid understanding of economic theory, particularly general equilibrium theory, are needed to design the scenarios and interpret the results.

Knowledge of national accounting systems (input-output tables, social accounting matrices, institutional sector accounts etc) is also a must, along with knowing what is available and what needs to be, and indeed could be estimated.

The task does not end with a 'completed' model. A model may be designed to answer quite a wide set of questions, but invariably issues will arise that require adapting the model in some way. Also, models need to be kept up to date especially with input-output tables and associated data such as for employment and consumer demand functions. In our experience the updating process probably requires 2-3 months every few years. Adapting and operating the model may be more irregular, but that means it is important that at least one suitably skilled person is always available. Otherwise there is a real risk that the modelling expertise vanishes.

Some practitioners suggested that good links to a university would have numerous benefits including access to academic expertise, lower costs by employing PhD students and an increase in the potential supply of people who might later work with SCGE models themselves or know enough about such models to promote their use in policy development. The Centre of Policy Studies in Melbourne is an example. It is currently based at Victoria University, but was previously at other universities.

Not developing an in-house SCGE model (and modelling team) means contracting out such services on an as-needs basis. That may be an efficient strategy if an SCGE model would be used infrequently, but the models that are available in the consultancy or academic market may not have the structure or features required to study the issues at hand. Of course that may also apply to an in-house model, so either way DfT would incur the cost of model alteration. Again then, frequency of use should be considered.

An additional point from our interviews is that if a model is readily or near-readily available, it is more likely to be used than if each potential application requires a new contract with outside providers. Perhaps that disincentive could be mitigated by designing contracts that cover multiple applications over a period of a few years.

In summary, if DfT envisages frequent use of SCGE models it is probably worthwhile to incur the up-front cost to develop and then maintain a modelling team in house. However, even if the decision is to retain the out-sourcing approach, some in-house SCGE expertise is still advisable to ensure that the right questions are asked and that the results are properly understood and interpreted.

3. Additional Matters

There are some issues in SCGE modelling of transport appraisal that we wish to discuss, in addition to those explicitly mentioned in our brief. These are:

1. Fiscal effects and financing
2. Model closure
3. Heterogeneity
4. New developments

3.1 Fiscal effects and financing

Shahraki & Bachmann (2018) note that how the financing strategy of investment in transport infrastructure is modelled can have a significant effect on its economic impact. They cite various references in support as well as some where the financing strategy has been disregarded. We agree that this aspect of transport investment appraisal is frequently ignored and that this can severely distort the results. Modelling of expansions in public transport and cycleways (Stroombergen and Barkle, 2022) demonstrates that explicit modelling of the financing strategy can reverse the gains in national income from lower GHG emissions and likely health benefits (insofar as health benefits are captured in traded markets). Similarly Parry and Bento (2001) find conflicting welfare results when revenue from a congestion charge is redistributed as transfer payments compared to reducing labour taxes. With regard to a tax on GHG emissions Berg (2007) finds that the welfare cost differs between recycling the tax as a lump sum to households and recycling it as a reduction in labour taxes.

The essence of the issue is that publicly financed transport projects (as many are) imply a need to rebalance government expenditure or to increase its revenue. That has the potential to create or change deadweight loss. This effect can be captured in a CGE model provided it includes a government sector that incorporates government consumption and the main transfer payments and taxation streams, along with suitable consumer demand and/or labour supply functions. Additional household disaggregation such as by income quintile adds further richness, as in Berg (2007).

More broadly it is not just government financing that is of interest. Anas & Rhee (2006) investigate tolls and changes in urban boundaries to investigate how urban sprawl can be controlled. The options lead to quite different effects.

We should note at this stage that SCGE modelling of transport appraisal has nothing to do with budget allocations between government departments. The fiscal closure assumption (see below) needs to specify how projects are financed and whether this involves a change in the overall size of government (so capturing the marginal cost of public funds). That is, which particular departmental budgets are affected is not a modelling issue, but the method of financing is.

In New Zealand and in the United Kingdom (and doubtlessly elsewhere) the reduction in revenue from fuel excise duties due to the increasing uptake of electric vehicles is forcing governments to consider other options such congestion charges and distance based charging (already applied to diesel vehicles in New Zealand). All options have implications for the marginal cost of public funds, as would subsidised public transport for the elderly or students, which could be financed by different funding methods such as property taxes levied by local authorities or labour taxes levied by central government. The mechanism is important in SCGE modelling, not the institutional arrangements.

3.2 Macroeconomic model closure

At various points above we have mentioned model closure. As Venables et al (2022) state :

> "In any CGE modelling simulation, the selection of 'closure' rules is paramount to scenario design."

We agree. There are four key areas of macroeconomic closure:

1. Labour market
2. External balance of payments
3. Investment
4. Government fiscal balance

Labour market

In models with labour supply functions, wage rates and total employment are endogenous to the model. In models without labour supply functions there are typically two options: wage rates adjust to keep total employment (not necessarily full employment) unchanged from the model's Baseline scenario, or the opposite. For longer run modelling it is generally assumed that wage rates are the equilibrating variable. This prevents the long run level of total employment being determined by say, transport policies, rather than by the forces of labour supply and demand, and the skills of the workforce. Demand side stimuli have no impact in the long run. Of course this result can also be secured in models with a labour supply function by setting the elasticity to zero – which is in any case a useful sensitivity test. Over time education and training programmes respond to a different set of market demands so that those entering the labour force acquire the necessary skills and occupations.

In situations where real wages are set largely by centralised wage bargaining and government direction, or for short term model applications it may be better to reverse the closure rule and let total employment be the equilibrating variable.

Balance of payments

The current account balance or sometimes its accounting equivalent; investment less saving, is generally fixed at the baseline percentage of GDP. This means that pressure on the external deficit such as may be caused by a decline in the terms of trade cannot be met simply by borrowing more from overseas with indefinitely deferred repayment. However, a dynamic model presents the opportunity to examine different profiles of borrowing and repayment. In either case the equilibrating mechanism is the real exchange rate – that is in CGE models without an absolute price level, which is most of them.

Investment

Recognising that most countries are part of the international trading and financial system, in models that include taxes the post-tax rate of return to capital is fixed across scenarios. This ensures consistency with the preceding rule. Investment is the equilibrating mechanism.

Government fiscal balance

In long run modelling the fiscal balance should generally be fixed across scenarios. This means for example that if the government needs to finance a high speed rail project it must ensure that it has matching income or reduce other spending. The usual equilibrating mechanism would be income tax rates, but again this requires a model that includes at least a rudimentary taxation structure. Many modellers sidestep the issue by assuming implicit changes in lump sum taxes. Although such taxes do not change relative prices and so are non-distortionary in that sense (at least not directly) the income effects can still distort purchasing behaviour and labour market responses. Of course one could also look at a switch in government expenditure with no change in tax revenue, but ideally one would then compare both expenditure options with a counterfactual of lower taxation.

3.3 Heterogeneity

An issue that receives less, but growing attention in (S)CGE modelling is the role of the representative agent. This is especially related to household labour supply elasticities as different types of economic shocks can produce different labour supply responses. For example, a change in commuting costs could have rather different effects on a household's labour supply than a change in social welfare benefits, for the same change in disposable income, as only one partner might be employed.

A possible solution is to link microsimulation (or agent-based) models with SCGE models in a bi-directional relationship. Although SCGE models can incorporate behaviour that is not fully rational, such as by limiting elasticities of substitution between goods and services in household demand equations, microsimulation models can capture much richer heterogeneity in socio-demographic characteristics such as income, age, education, type of dwelling and so on. Such heterogeneity can lead to nonlinearities in consumer behaviour and adaptation to social pressures and dynamics. Model processes can be deterministic (such as for aging) or stochastic (such as for income transition).

Clauss & Schubert (2009) provide an example in which a microsimulation model provides the aggregate labour response to welfare reform policies, which becomes an exogenous input into the CGE model. Any GE-relevant effects, for example changes in wage rates, then go back into the microsimulation model, and so on until convergence. Niamir et al (2020) provide an example of linking such models in the area of climate change mitigation by simulating household decisions on energy use at a disaggregated level. Questions about transport choices could be similarly investigated.

This type of model interaction is probably beyond what DfT envisages, but if microsimulation models of tax and welfare exist in the UK it may be relatively straightforward to explore transport scenarios.

3.4 New developments

Our discussions with practitioners suggests that although academic SCGE modellers continue to slowly extend the frontier on issues such as capital vintages and its interaction with model dynamics, finding ways to combine the better aspects of SE and IE specifications, and testing alternative functional forms, there is little in the way of new technical or methodological advances that have immediate relevance to applied policy modelling.

Indeed most research activity is at the applied end. In essence that is about tailoring models to better address the questions at issue. For instance, one agency is developing an SCGE model focussed on health that has calorie coefficients attached to food consumption, analogous to GHG emission coefficients attach to fuel use in a transport SCGE model. Or research may be as mundane, but still important, as improving data quality and refining the degree of spatial disaggregation.

In the transport domain an example is specifying functions to endogenise variables that are usually exogenous, such as splitting labour use by industry into travel and non-travel hours, so as to endogenise the change in labour productivity in response to a change in travel costs, or to identify commuting impacts by household type to better model the work/leisure decision given that low income households have less mobility both to commute and to move house.

4. Conclusion

Similar to the view of Dixon et al (2013), there seem to be four features that customers of (S)CGE modelling desire:

1. Up-to-date data that underlies a Baseline (business as usual) projection or scenario.
2. Accurate representation of the policies and interventions in question.
3. Results disaggregated by industry, region or whatever dimensions are of interest.
4. A plausible narrative around the input shocks, the likely consequences and the model results.

As is hopefully clear from the preceding sections, (S)CGE modelling, including of transport issues, is very much a question of how the model is used, rather than of the model itself – within reason of course.

Summarising the main points:

1. Spatial CGE models are well-suited to transport appraisal, notably for capturing benefits that are additional to the direct user benefits. This is possible because SCGE models allow for departures from the standard assumptions in partial equilibrium (cost-benefit) analysis by including as endogenous effects, distortions caused by taxation, imperfect competition, agglomeration and more generally, changes in important prices such as those of labour and foreign exchange.
2. This is not to deny the crucial role of CBA, not only in its own right, but as input for SCGE modelling. Consistency and reconciliation (such as relating to welfare measures) between partial equilibrium (PE) and GE analysis is essential.
3. There is ongoing debate amongst CGE modellers about the specification of dynamics; the sequential equilibrium (SE) or intertemporal equilibrium (IE) approaches, as well as, though to a lesser extent about functional forms. Although IE models are theoretically more suited to deriving welfare measures, many practitioners find their dynamics too unrealistic and their practical application rather taxing. Nevertheless for modelling household location choices, some forward looking behaviour is recommended.
4. Receiving less attention in the literature, but just as important is the 'how' of SCGE modelling; notably what macroeconomic closure assumptions are adopted, whether project/policy financing is included, and what model levers are adjusted to simulate particular scenarios.
5. Another limitation is data, especially for SCGE as opposed to CGE models. Ideally inter-regional SCGE modelling has regional input-output tables plus data on inter-regional trade (including services) and migration. For urban models the emphasis is on commuting rather than trade, but location choice modelling requires data on where people live, work and spend. Data may need to be estimated (such as the estimation of regional IO tables in PWC, 2022). This is entirely reasonable, but interpretation of modelling results must be in the context of whatever data limitations apply. In some cases data limitations will preclude reliable SCGE modelling.

6. Data requirements can increase exponentially as models expand to include more industries, more regions/zones, and more types of households, as well as more sophistication (such as with translog production functions). Thus trade-offs are inevitable, with any decisions needing to take full account of the issue at hand. For example in the modelling of HS2 by PWC (2022) there is not a separate transport industry, let alone a rail industry. Arguably therefore the model is only able to address questions surrounding a productivity increase, and is not available to be used for other potential interesting policy questions (e.g. on the performance, pricing and subsidisation of the rail sector and the transport sector in general).

7. A prior matter is to decide on the questions that the SCGE model is intended to answer and what degree of industry, spatial, household and fiscal detail is desired. Whilst the basic building blocks of SCGE models are similar, myriad variants of SCGE models could be built. It is important to develop one that answers the policy questions being asked. Then the search for data can begin and options for missing data explored.

8. A model database may have an imperfect allocation of transport and travel across space, industries and households, but the strength of (S)CGE models is in analysing relative changes between a baseline scenario and scenarios with transport interventions or shocks – such as scenarios of 2050 with and without a major infrastructure project. Relative changes stemming from a transport shock are more robust than the absolute levels on which they are based.

9. Overall, SCGE models are powerful tools for analysing the benefits of transport projects, beyond the standard user benefits identified in partial equilibrium analyses. These models have solid theoretical underpinnings and sophisticated equations and functionality that can capture an immense variety of market characteristics and agent behaviour.

10. Models need to be thoughtfully applied to the issue at hand, coupled with well-designed and implemented sensitivity analysis.

11. We see no reason in principle why DfT should not either commission the development of an in-house SCGE model or utilise existing external SCGE models on a case by case basis. The latter option would require less SCGE expertise on the part of the DfT's personnel, but we would not push this argument too far. Effective use of external SCGE models is not assured if the DfT do not have a solid understanding of how SCGE models work, what they can do, and how to interpret and assess their output. Developing an in-house model would be costly at the start, but would likely be cheaper in the long run than continual out-sourcing. The payback period depends on the frequency of model use.

12. The basic data required for a UK SCGE model have been identified along with some limitations. However, it is beyond the ambit of this report to delve into the specifics – characteristics and limitations – of all the data sources that might be required to develop an SCGE model.

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Appendix A: Table from Shahraki & Bachmann

Table 1. Representation of transportation cost in CGE models.

Application/ Transport cost	Iceberg	Modified iceberg	Explicit transport cost	Accessibility index	Transport capital
Road pricing			Rutherford and van Nieuwkoop (2011), Mayeres and Proost (2004), Mayeres (2000)*, Steininger, Friedl, and Gebetsroither (2007)*, Van Dender (2003)*, Parry and Bento (2001)*, Van Steenbergen et al. (2011), Kalinowska and Steininger (2009a, 2009b), Mayeres et al. (2005), Munk (2006), Steininger, Schmid, and Tobin (2012), Arnott and MacKinnon (1977), Steininger (2002), Thissen, Limtanakool, and Hilbers (2011), Vandyck and Rutherford (2013), Larsen, Madsen, and Jensen-Butler (2005), Proost and Van Dender (1999)		
Disaster evaluation and management	Tatano and Tsuchiya (2008)		Ueda et al. (2001), Kato, Fujiwara, and Ieda (n.d.), Thissen (2004)		
Transportation network changes (expansion, removal, speed change)	Bröcker (2004), Oosterhaven et al. (2001), Knaap and Oosterhaven (2011), Oosterhaven and Knaap (2003), Caspersen et al. (2000), Sundberg (2010b)	Bröcker (1998a), Bröcker et al. (2010)	Robson and Dixit (2016), Elshahawany, Haddad, and Lahr (2016), Nitzsche and Tscharaktschiew (2013), Miyagi (2001), Tsuchiya, Tatano, and Okada (2007), Koike, Tavasszy, and Sato (2009), Tirasirichai and Enke (2007), Ueda, Koike, Yamaguchi, and Tsuchiya (2005)	Kim and Hewings (2003, 2009), Kim et al. (2004), Haddad et al. (2015)	
Infrastructure investment/financing	Bröcker (1998b)	Bröcker (1998b), Bröcker (2000)	Li (2015), Conrad and Heng (2002)*, Conrad (1997)*, Mayeres (2000)*, Mayeres and Proost (2001), Kim (1998), Hadj-Salem et al. (2016), Gallen and Winston (2016), Mayeres (2001)*, Steininger et al. (2007)*, Van Dender (2003)*, Parry and Bento (2001)*, Siegesmund et al. (2008), Tscharaktschiew and Hirte (2012), Rioja (1999)*, Imdad and Westin (1998), Nordman (1998), Chen et al. (2016), Chen and Haynes (2015)*, Berrittella (2010)*, Deloitte (2014), Roson and Dell'Agata	Bröcker, Kancs, Schürmann, Wegener, and Spiekermann (2001), Kim et al. (2011), Kim et al. (2017)	Conrad and Heng (2002)*, Conrad (1997)*, Seung and Kraybill (2001), Rioja (1999)*, Chen and Haynes (2015)*, Berrittella (2010)*, Kim and Kim (2002), Duffy-Deno and Eberts (1991), Chen and Haynes (2013)

(Continued)

Table 1. Continued.

Application/ Transport cost	Iceberg	Modified iceberg	Explicit transport cost	Accessibility index	Transport capital
			(1996), Hensher, Truong, Mulley, and Ellison (2012), Duffy-Deno and Eberts (1991)*		
Land-use impacts			Anas and Kim (1996), Anas and Rhee (2006), Anas and Xu (1999), Anas and Liu (2007), Horridge (1994), Venables (1996), Anas and Hiramatsu (2012), Doi, Itoh, Tiwari, and Doi (2006), Jin, Echenique, and Hargreaves (2013)	Lennox and Adams (2016), Lowty (1964)	
Cross-border trade			Shunsuke, Anderson, and Maureen (2015), Roberts et al. (2014), Nguyen and Wigle (2011), Haddad, Hewings, Perobelli, and dos Santos (2010), Doi et al. (2006), Avetisyan, Heatwole, Rose, and Roberts (2015)		
Transport cost change (ITS, cost change, fuel cost change)		Bröcker and Korzhenevych (2013), Sakamoto (2011)	Lahr et al. (2016), Kawakami, Tiwari, and Doi (2004), Buckley (1992), Lofgren and Robinson (1999), Haddad and Hewings (2001), Anas (2015), Verikios and Zhang (2015), Ishiguro and Inamura (2005), Aydın (2016), Konan and Kim (2003), Ando and Meng (2009), Karplus, Paltsev, Babiker, and Reilly (2013), Roson (1996), Lofgren and Robinson (1999), Chen, Rose, Prager, and Chatterjee (2017), Schaefer and Jacoby (2005), Johansen and Hansen (2016)	Mittal, Dai, Fujimori, Hanaoka, and Zhang (2016)	
Infrastructure interdependencies			Zhang and Peeta (2011, 2014)		
Trade Agreement		Bröcker (1998a)	Itakura and Lee (2015), Takeda (2010), Bröcker et al. (2001), Higgs et al. (1988), Bachmann (2017)		

*Studies that fall under two application categories.

Source: Shahraki & Bachmann (2018)

Appendix B: SCGE Practitioners Consulted

As part of our review we have liaised with five leading practitioners of SCGE modelling, covering a broad range of locations and model applications:

1. Prof. Peter Dixon and James Lennox at the Centre of Policy Studies at Victoria University in Melbourne, Australia. CoPS has been at the forefront of (S)CGE modelling since the 1970s and are leaders of the logarithmic differential equation (percentage change) approach to modelling, using the GEMPACK software package. Their SCGE model (TERM) has been applied to a wide range of issues. Prof Dixon was a member of the Trade Modelling Review expert panel, for the UK Department for International Trade.

2. Dr. Erwin Corong, Principal Research Economist, Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University, USA. Dr Coorong is an expert SCGE modeller specialising in GTAP. He is also familiar with and has run the CoPS suite of models. Dr Corong was also a guest panellist for the Trade Modelling Review expert panel.

3. Prof. Niven Winchester, Auckland University of Technology and previously principal research scientist working on the EPPA model, Massachusetts Institute of Technology, Joint Program on the Science and Policy of Global Change, Cambridge, USA. The EPPA model has been mainly applied to energy and GHG emissions, and associated policy analysis. Prof Winchester developed the model, based on EPPA, used by the New Zealand Climate Change Commission.

4. Dr. Gioele Figus, senior lecturer in economics, and Dr. Kevin Connolly, Chancellor's Fellow, both at the University of Strathclyde and experienced SCGE modellers especially in the areas of trade, tourism, energy and city modelling.

5. Dr. Olga Ivanova, senior researcher, Netherlands Environmental Assessment Agency (PBL): experienced SCGE transport modeller with RAEM and RHOMOLO. And Dr. Wiljar Hansen, Senior Research Economist, Institute of Transport Economics, Oslo, Norway: PINGO and NOREGE models.

Results of the interviews have been interspersed throughout the main text, but not individually identified.

Main topics discussed:

SCGE in general

- Examples of recent modelling work.
- Model dynamics: comparative static, recursive dynamic and intertemporal optimisation. Applications where the choice matters, computational issues, realism.
- Spatial approach: top-down v bottom-up.

- Funding, financial flows etc by region. Data on ownership of capital by region.
- Validation; what is best practice?
- New SCGE developments priorities, research directions or problems to be addressed.
- Cost of developing/building an SCGE model.

SCGE transport applications

- Modelling of transport shocks; productivity v price v K/X ratios etc.
- Migration and commuting, roles in urban and regional models, how modelled.

UK focus

- UK expertise
- Data for SCGE modelling:
    - Latest national IO table (& frequency),
    - Regional data – employment by industry, IO tables,
    - Inter-regional trade flows,
    - Surveys of household travel and business travel.

Appendix C: Selected Slides from HS2 Literature Review

The slides below are slides 25-32 of the presentation by HS2 of their literature review of general equilibrium modelling, June 2023.

3. Suitability of CGEMs for policy-making

Introduction

- This section has the aim of understanding the suitability of CGEMs for policy-making b means of researching whether successful applications of CGEMs exist in the field transport appraisal.
- The section will show whether or not:
  - Transport CGEMs have had any fortune in public institutions throughout the world;
  - There are any notable applications developed by the private sector, research institute and the academia;
  - CGEMs application has been accompanied by any critique;
  - Any critique can be addressed for the sake of procuring a CGEM for the appraisal of HS2

3. Suitability of CGEMs for policy-making

Influence of CGEMs in public institutions

- Public institutions throughout the world already make regular use of CGEMs for policy appraisal
- In Europe:
  - The Netherlands: the **official CBA guidance** explicitly cites spatial CGEMs as a tool to identify agglomeration benefits (the **RAEM**, used in transport appraisal – see Knaap (2000)); the CPB (part of the Dutch Ministry of Econ affairs) also owns the MIMIC, a GEM for the appraisal of the impact of policies on the labour market – see Romijn (2013). It should be noted that the guidance also states that CGEMs are rarely employed because of their complexities and costs.
  - Norway: The country has a long tradition of policy analysis using GEMs. The **Ministry of Transport** and Communications financed the development of the **PINGO** SCGE model in two stages (see Ivanova (2002) and Vold and Jean-Hansen (2007)). Shortcomings in PINGO, such as perfect competition and constant returns to scale posed the basis for the development of an enhanced model – see Hansen (2010). The **Norwegian National Transport Plan committee** commissioned the Transport Economics Institute (TØI) to analyse the wider economic impacts of the NTP 2018-2029 using the **new SCGEM** (applied to study 15 projects in total) – see Hansen (2016). More recently, following the development of the NOREG 1.0 GEM for the Ministry of Trade and Industry (Bruvoll (2015)), NOREG 2.0 has been developed integrating NOREG 1.0 with the latest Hansen's PINGO model, and a further regional model from Statistic Norway (SSB). NOREG 2.0 is meant to be updated in new sub-versions (2.1, 2.2, etc) to produce reports up to 2028 – see Rosnes (2020). It should be noted that Norwegian CBA guidance still does not allow for the inclusion of 'ripple effects' in the BCR due to the lack of a sufficient empirical basis.[1]

3. Suitability of CGEMs for policy-making

Influence of CGEMs in public institutions

- **EU institutions** have developed a suite of GEMs to appraise several types of policies. In the period 2019-2022, across the 40 European Commission's Impact Assessments that made use of modelling, GEMs have been used 10 times – see Di Benedetto (2023) and MIDAS.
- The latest available model that can be used for transport appraisal is **RHOMOLO** (Brandsma (2015)), although specific models have been developed for transport in the past. RHOMOLO treats transport costs via the iceberg assumption, it can relate public investment to cost changes by means of elasticities estimated by the EC, and **has been used for the assessment of EU Cohesion Policies (including transport policies)** – see for example Di Comite (2018). Land-Use and CGE model interactions have also been investigated with the LUISA-ROHMOLO approach – see Lavalle (2017). Past transport-specific CGEM developments included; CGEurope (I and II, see also the IASON project and report); the Limobel; TIGER/ISSEM; TRIMODE – procured in 2015, with first details published in 2018 and due to be published in 2019 but still under development.
- For a comparison between the RHOMOLO, RAEM 3.0, CGEurope II and LIMOBEL models see Hansen (2011).

3. Suitability of CGEMs for policy-making

Influence of CGEMs in public institutions

- Australia:
  - **Transport for New South Wales** (2016) presents three CGE models that can be used for freight investment appraisal for the largest of infrastructure projects
  - The **Infrastructure and Transport Ministers** (2021) listed over a dozen notable applications procured from the academia or the private sector, including two applications for very fast and high-speed rail policies and other four rail initiatives. Notably, the document reports that most national and regional CGE models applied in transport appraisal are dynamic due to the length of construction and the benefit ramp-up period associated with large transport projects best suited to CGE analysis. Example of private sector's publications in the Australian context can be found below:
    - EY (2008): The economic contribution of Sydney's toll roads to NSW and Australia
    - KPMG (2015): Economic Contribution of Australia's Toll Roads

Table 1 Application of CGE models to transport infrastructure investments in Australia

Year	Initiative	Model	Author
National CGE models (comparative static			
1990	Very Fast Train	ORANI	Centre for Regional Economic Analysis (1990)
1993	Road investments	ORANI	Allen Consulting (1993)
1997	Increased road construction expenditures	AE-CGE (ORANI)	Austroads (1997)
Multi-region CGE models (dynamic)			
1996	Melbourne City Link	Monash MR	Allen Consulting, Cox and CoPS (1996)
2002	Improvement in Melbourne port efficiency	MMRF-GREEN	CoPS (2002)
2010	Inland Rail	Tasman Global	Acil Tasman (2010)
2012	Toowoomba Second Range Crossing	MU-TERM	CoPS
2012	High speed rail	MMRF	AECOM (2012)
2015	Inland Rail	MMRF	PwC (2015)
2016	Melbourne Metro	VU-TERM	CoPS (2015)
2003	AusLink (program)	MMRF-GREEN	BITRE (2003)
2010	Road investment in Victoria (1996-2008) (program)	TERM	Ernst & Young (2010)
2014	State Infrastructure Strategy – Rebuilding NSW (program)	DAE-RGEM	Deloitte Access Economics (2014)
2015	Economic Contribution of Australia's Toll Roads (program)	MMRF	KPMG (2015)
Urban CGE models (linked to a transport model at an urban scale, comparative static)			
2012	Sydney North-West Rail Link	TRESIS–SGEM	D. A. Hensher, et al. (2012)
2016	Western Sydney Airport	SCGE	Ernst & Young (2016)

Note: The list of applications is not exhaustive. These are shown as examples

3. Suitability of CGEMs for policy-making

Notable applications for transport appraisal in the academia and research institutes

- Notwithstanding how some of the CGE developments on behalf of public institutions have been led by academics – e.g. see Bröcker (2010) for the CGEurope – other models have been maintained altogether by Universities and research institutes.
- One of the most notable early models in the Australian landscape is the **ORANI model by Dixon** (1982), defined as a 'top-down' (Ando 2009) or 'macro' model (Thissen 1998). According to the authors, the multi-region, multi-sector model displayed '*an **unusually detailed treatment of margins**. For example, to arrive at the aggregate demand for road transport, ORANI determines the demand for road transport to be used in facilitating each of the many thousands of commodity flows (intermediate and final) recognized in the model*. [... It] *has two other advantages: (i) it allows detailed modelling of **variations in the purchasers' prices** of any commodity across users and (ii) it allows **simulation of the effects of technical change involving particular uses of margins**. ORANI could, for example, be used to simulate the effects of containerization at Australian ports on the purchasers' prices of imported commodities and the consequent effects on the level of demand for imports and the levels of output and employment in domestic industries'* (idem, page 3, section 1.4).
- The first model displayed 113 sectors and 8 regions, later expanded to 56 (Fallon (1982)).

3. Suitability of CGEMs for policy-making

Notable applications for transport appraisal in the academia and research institutes

- The ORANI model was further developed into other models by CoPS known to belong to the so-called **'MONASH' family**, and despite its early origins it still has effects on modelling choices of more recent CGEMs for transport appraisal – see for example Haddad (2005), Robson (2017), Betarelli (2020).
- Dixon (2013) mentioned that MONASH models operate in numerous countries *'to provide insights on a variety of questions including the effects on: macro, industry, regional, labor market, distributional and environmental variables of changes in: taxes, public consumption, environmental policies, technologies, commodity prices, interest rates, wage-setting arrangements, **infrastructure and major-project expenditures**, and known levels and exploitability of mineral deposits'*.
- More recently, the CoPS has developed **TERM (The Enormous Regional Model)** – see Horridge (2012). Born as a static, bottom-up model where each region has its own CGE model, the TERM could handle 38 industries and 45 Australian regions – see Wittwer (2002) – the model now allows dynamic specifications and can treat 216 sectors in 334 regions, although to avoid slowing down computations, it is recommended to run the mode with a disaggregation of max 100 regions plus sectors. The dynamic model has been developed also for Indonesia, Brazil, Finland, New Zealand and USA. **The EuroTERM has recently appeared** in the literature, which **includes 41 UK regions and 74 sectors** – see Wittwer (2022). Examples of applications of the TERM to transport appraisal are mentioned in the slide about the Australian public sector CGE experience.

3. Suitability of CGEMs for policy-making

Notable applications for transport appraisal in the academia and research institutes

- To conclude, it is worth mentioning a separate family of CGEMs developed by **Anas at the regional/urban level** starting from the '90s named '**RELU**' (Regional Economy Land Use and Transportation) and including **multiple equilibria** and endogenous congestion – e.g. in Anas (1996) – which the authors used to analyse congestion tolls in a dynamic setting – see Anas (1999).
- In the 2000's, the model was further developed into the so-called 'RELU-TRAN' CGEM, solving for a *'4-building, 4-industry, 4-labor-type, 15-land-use-zone, 68-link-highway-network'* system, although the TRAN algorithm only allowed for single-equilibrium solutions. An interesting feature of such models is that the *'stock of buildings in each model zone as changing slowly while other markets clear instantaneously'* – see Anas (2007).
- By 2013, the RELU-TRAN had been *'calibrated and used for the **Chicago Metropolitan Statistical Area and the Greater Paris Region**'*, while it was being implemented for the Greater Los Angeles metropolitan area. While the application to the Chicago MSA mainly involved the analysis of road-related impacts, the application to the Paris region examined *'the effects of projected growth and of **planned rail investments on concentrating jobs in growth poles around the City of Paris**'*, *'meant to make easier the peripheral circulation around the City of Paris'*. It should be noted that although the infrastructure investment examined would involved just the Greater Paris area (approx. half of the GLA), the study analysed the **effects on the whole Ile-de-France area** (which in the UK would include a corridor running from Liverpool to York and down to Sheffield (which suggests the model could be as well classified as regional) – see Anas (2013).

3. Suitability of CGEMs for policy-making

Notable applications for transport appraisal in the academia and research institutes

- To conclude, other noteworthy applications have been presented in the following academic research

Topic	Paper Title (full ref. in the notes)
High-speed applications	The impact of high-speed rail investment on economic and environmental change in China: A dynamic CGE analysis
	Unequal regional impacts of high speed rail on the tourism industry: a simulation analysis of the effects of Kyushu Shinka
	Job and population location choices and economic scale as effects of high speed rail: Simulation analysis of Shinkansen, Japan
Integration of transport models and CGE models	An Application of an Integrated Transport Network – Multiregional CGE Model: a Framework for the Economic Analysis of Highway Projects
	Assessing the wider economy impacts of transport infrastructure investment with an illustrative application to the North West Rail Link project in Sydney, Australia
Disruption appraisal	A framework for economic loss estimation due to seismic transportation network disruption: a spatial computable general equilibrium approach (includes HSR disruption)
	Economic Loss Assessment due to Railroad and Highway Disruptions
Subsidies and project financing	Should subsidies to urban passenger transport be increased? A spatial CGE analysis for a German metropolitan area
	Financing road infrastructure by savings in congestion costs: A CGE analysis
Maritime infrastructure	Regional Effects of Port Infrastructure: A Spatial CGE Application to Brazil