Imperial College London

A new generation of transport policy appraisal: Developing a random utility spatial general equilibrium model

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Guidance

Transport analysis guidance

Transport analysis guidance (TAG) provides information on the role of transport modelling and appraisal.

From: Department for Transport
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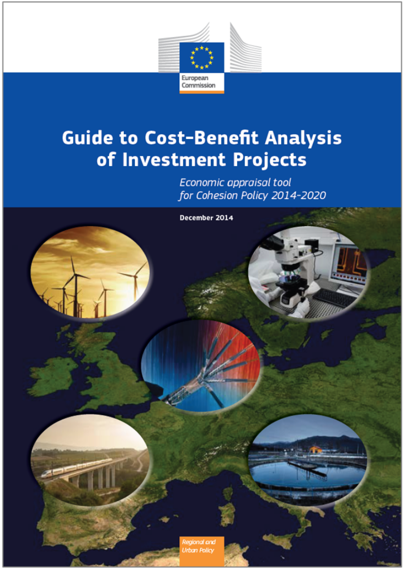
Contents

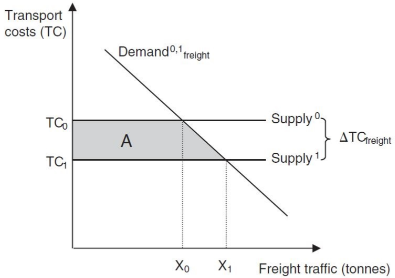


Partial equilibrium CBA

The majority of practical transport policy appraisal methods rely on partial equilibrium assumptions.

Net welfare effect is the sum of

- Net user benefit: **consumer surplus derived from an observed and an estimated point on an assumed demand function**
- Net financial cost of transport provision
- Externalities linked to transport volume



Partial equilibrium + ‘Wider Economic Impacts’

Transport affects activities in other markets, e.g. labour, housing, production markets.

When **market failures** are present in these markets, transport interventions may increase/decrease the deadweight loss associated with market failures.

Aim: Quantify the resulting *indirect* welfare effects and *add* them to the partial equilibrium results.

Example: Agglomeration economies

- Empirical evidence: causal link between accessibility and firm productivity
- Transport makes firms more productive
- This is an external benefit on top of the direct user benefit
- See Graham and Gibbons (2019)

Prone to criticism: we don’t know exactly what is under the demand curve – **some of the benefits may be double counted** (Eliasson and Fosgerau, 2019)

Graham, D. J., & Gibbons, S. (2019). Quantifying Wider Economic Impacts of agglomeration for transport appraisal: Existing evidence and future directions. Economics of Transportation, 19, 100121.

Eliasson, J., & Fosgerau, M. (2019). Cost-benefit analysis of transport improvements in the presence of spillovers, matching and an income tax. Economics of Transportation, 18, 1-9.

Growing scepticism around partial equilibrium CBA

One example: Do user benefits disappear when congestion rebuilds due to induced demand?

ELSEVIER

Transportation Research Part A: Policy and Practice

Volume 147, May 2021, Pages 312-319

Economic benefits of road widening: Discrepancy between outturn and forecast

David Metz

The forecast of faster traffic speeds was the input to the economic model used to compare investment benefits with costs, yielding a benefit-cost ratio of 2.9, which justified the investment. However, the absence of observed increase in traffic speed raises questions about the applicability of a long-established transport model and of travel time savings as the main economic benefit of road investment, as well as about the value of investment to increase the capacity of strategic roads where these are used extensively for local trips.

(Influential person harvests 300 likes on LinkedIn by resharing this article with appreciative comments.)

CBA in general equilibrium? An unrealised dream so far

Department for Transport (2005) discussion paper on "Transport, Wider Economic Benefits, and Impacts on GDP"

> " [The limitations of static models] suggest that **a more rigorous approach, such as general equilibrium (GE) modelling, could deliver more robust estimates**. (...) A GE approach requires a much more complex model and significantly more data. So far there are few GE models that can credibly model changes in transport costs, let alone provide estimates for particular schemes. Lack of data crucial in GE modelling provides a further barrier to applying such a framework in the UK. **Until there are further developments in GE modelling** for the UK, we advise that estimates of this wider benefit are based on the partial analysis. "

Early spatial models for transport

Land Use/Transport Interaction LUTI models

Lowry, I.S. (1964). A model of metropolis. Memorandum RM-4035-RC. Santa Monica: RAND Corpo-ration.

Hunt, J. D., & Simmonds, D. C. (1993). Theory and application of an integrated land-use and transport modelling framework. Environment and Planning B: Planning and Design, 20(2), 221-244.

Spatial Computable General Equilibrium (SCGE) models

A. Anas and Y. Liu, "A Regional Economy, Land Use, and Transportation Model (relu-Tran©): Formulation, Algorithm Design, and Testing*," J. Reg. Sci., vol. 47, no. 3, pp. 415-455, 2007, doi: 10.1111/j.1467-9787.2007.00515.x.

A. Anas and T. Hiramatsu, "The effect of the price of gasoline on the urban economy: From route choice to general equilibrium," Transp. Res. Part Policy Pract., vol. 46, no. 6, pp. 855-873, Jul. 2012, doi: 10.1016/j.tra.2012.02.010.

A. Anas, "A Summary of the Applications to Date of RELU-TRAN, a Microeconomic Urban Computable General Equilibrium Model," Environ. Plan. B Plan. Des., vol. 40, no. 6, pp. 959-970, Dec. 2013, doi: 10.1068/b38206.

A. Anas, "The cost of congestion and the benefits of congestion pricing: A general equilibrium analysis," Transp. Res. Part B Methodol., vol. 136, pp. 110-137, Jun. 2020, doi: 10.1016/j.trb.2020.03.003.

A. Anas and H. Chang, "Productivity benefits of urban transportation megaprojects: A general equilibrium analysis of ≪Grand Paris Express≫," Transp. Res. Part B Methodol., vol. 174, p. 102746, Aug. 2023, doi: 10.1016/j.trb.2023.03.006.

□

Robson, E. N., Wijayaratna, K. P., & Dixit, V. V. (2018). A review of computable general equilibrium models for transport and their applications in appraisal. Transportation Research Part A: Policy and Practice, 116, 31-53.

Core limitations

1) Loose/missing microeconomic foundations
2) High number of arbitrarily calibrated parameters

Quantitative Spatial Modelling

A new era in the spatial economics literature

Allen, T., & Arkolakis, C. (2014). Trade and the topography of the spatial economy. *The Quarterly Journal of Economics, 129*(3), 1085-1140.

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

Heblich, S., Redding, S. J., & Sturm, D. M. (2020). The making of the modern metropolis: Evidence from London. The *Quarterly Journal of Economics, 135*(4), 2059-2133.

Donaldson, D. (2018). Railroads of the Raj: Estimating the impact of transportation infrastructure. *American Economic Review, 108*(4-5), 899-934.

Monte, F., Redding, S. J., & Rossi-Hansberg, E. (2018). Commuting, migration, and local employment elasticities. *American Economic Review, 108*(12), 3855-90.

Allen, T., & Arkolakis, C. (2022). The welfare effects of transportation infrastructure improvements. *The Review of Economic Studies, 89*(6), 2911-2957.

Tsivanidis, N. (forthcoming). Evaluating the impact of urban transit infrastructure: Evidence from Bogota's Transmilenio. *Forthcoming in the American Economic Review*.

And a whole series of brand new contributions...

Are QSMs really new?

... and fundamentally different from other SCGE methods?

QSM properties

A. Key structural parameters can be estimated in statistical models that remain coherent with the theoretical model.

B. Model is invertible: local geographic fundamentals can be recovered from observed economic outcomes as structural residuals.

C. Analytically derived conditions under which the spatial equilibrium exists and is unique.

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Trade-off between

- spatial granularity/realism,
- micro-foundations and richness in mechanisms,
- robust calibration.

LUTI and SCGE models are successful, but QSMs have received unprecedented attention and recognition in top economics journals since the mid-2010s.

Objectives

How to bridge the gap between transport research and quantitative spatial economics?

Open challenges

1. Drop *iceberg* transport cost specification – **Disentangle monetary and time costs of travel and rationalise travel time valuation**.
2. Multiple trip purposes: leisure and business travel beside commuting, aggregated into traffic flows
3. Endogenous transport supply, incl pricing and capacity provision
4. Clarify links with static transport appraisal

Applications: more intensive use of counterfactual simulations in

- **Infrastructure appraisal**
- Pricing and funding/financing
- IO of transport markets

The Model

Household behaviour

Direct utility with residence i and workplace j: a fn of leisure time and consumption

$$U_{ij} = \left(\frac{L_{ij}}{1-\gamma}\right)^{1-\gamma} \left(\frac{K_{ij}}{\gamma}\right)^{\gamma} \cdot z_{ij} \quad \text{where} \quad K_{ij} = \left(\frac{C_{ij}}{\beta}\right)^{\beta} \left(\frac{H_{ij}^R}{1-\beta}\right)^{1-\beta} \tag{1}$$

Time constraint

$$\bar{L} = L_{ij} + x_{ij}(T_j + t_{ij}) \quad [\mu] \tag{2}$$

Budget constraint

$$x_{ij}(w_j - \tau_{ij}) = p_i C_{ij} + q_i H_{ij}^R \quad [\kappa] \tag{3}$$

Notation

L_{ij}: leisure time; $\bar{L}$: time endowment; T_j: duration of workday (observed)

C_{ij}: consumption; p_i: goods price – numeraire

H_{ij}^R: residential floorspace use; q_i: residential floorspace rent

t_{ij}: duration of commuting; τ_{ij}: monetary price of commuting

x_{ij}: endogenous individual labour supply

z_{ij}: idiosyncratic shock

The marginal **monetary valuation of time savings**: the marginal utility of time (μ) normalised by the marginal utility of money (κ).

FOC of individual labour supply and the resulting marginal time valuation.

$$\frac{\partial \Lambda}{\partial x_{ij}} = -\kappa(\tau_{ij} - w_j) - \mu(T_j + t_{ij}) = 0 \quad \rightarrow \quad \upsilon_{ij} = \frac{\mu}{\kappa} = \frac{w_j - \tau_{ij}}{T_j + t_{ij}} \left[\frac{\$}{\text{hour}}\right] \tag{4}$$

Other interpretations? Net hourly wage

Continuous choices: utility maximising consumption and housing in *ij*

$$C_{ij} = \beta \frac{\gamma \bar{L}\, \upsilon_{ij}}{p_i}; \quad H^R_{ij} = (1-\beta)\frac{\gamma \bar{L}\, \upsilon_{ij}}{q_i} \tag{5}$$

Indirect utility

$$u_{ij} = \bar{L}\left(\frac{\upsilon_{ij}}{p_i^{\beta} q_i^{1-\beta}}\right)^{\gamma} z_{ij} \tag{6}$$

Commuting gravity

Fréchet-distributed idiosyncratic shock for each $i - j$ combination

$$F(z_{ij}) = \exp(-X_i E_j \cdot z_{ij}^{-\epsilon}) \tag{7}$$

Choice probabilities

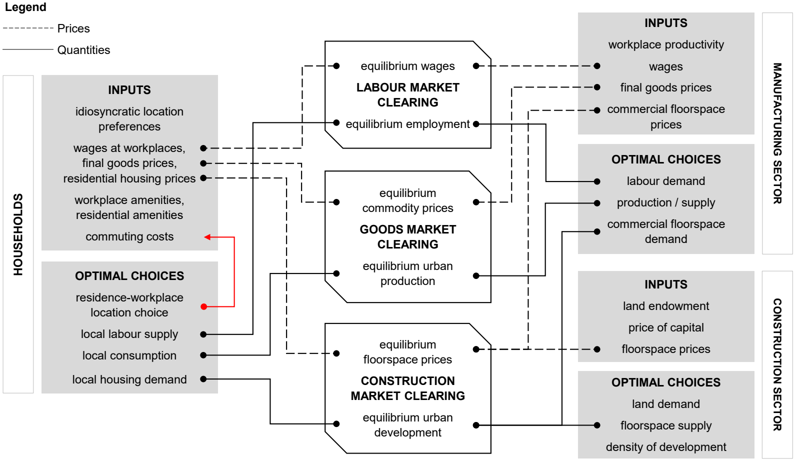
$$\lambda_{ij} = \frac{X_i E_j \left(\frac{\upsilon_{ij}}{p_i^{\beta} q_i^{1-\beta}}\right)^{\epsilon}}{\sum_r \sum_s X_r E_s \left(\frac{\upsilon_{rs}}{p_r^{\beta} q_r^{1-\beta}}\right)^{\epsilon}} \tag{8}$$

Expected utility of the representative household

$$E[U] = \Gamma\left(\frac{\varepsilon - 1}{\varepsilon}\right)\left[\sum_{i,j} X_i E_j \left(\frac{\upsilon_{ij}}{p_i^{\beta} q_i^{1-\beta}}\right)^{\epsilon}\right]^{1/\epsilon} \tag{9}$$

General equilibrium

Interlinks with the labour, production and housing markets



Model calibration / quantification

Aim: To avoid the need for arbitrary/guesstimated and trial-and-error approaches in calibration

Three sets of parameters calibrated in different ways.

1) Model inversion: The model is designed such that the sequence of equilibrium conditions creates a one-to-one mapping between the observed data and four sets of local characteristics:

- residential and workplace amenities,
- workplace productivity,
- density of development

2) Econometric estimation: Key structural/generic parameters of the model are estimated using aggregate econometric methods, using observed spatial data

3) Remaining generic parameters: Robust estimates from the literature

Model inversion

Conditional choice probabilities for given residence/workplace

$$\lambda_{ij|i} = \frac{E_j\left(\upsilon_{ij}\right)^{\gamma\epsilon}}{\sum_s E_s\left(\upsilon_{is}\right)^{\gamma\epsilon}}; \qquad \lambda_{ij|j} = \frac{X_i\left(\upsilon_{ij}/p_i^{\beta}q_i^{1-\beta}\right)^{\gamma\epsilon}}{\sum_r X_r\left(\upsilon_{rj}/p_r^{\beta}q_r^{1-\beta}\right)^{\gamma\epsilon}} \tag{10}$$

Conditional probability breaks down the distribution of employment by residence

$$N_j^W = \sum_i \lambda_{ij|i} \cdot N_i^R \tag{11}$$

Isolate fundamental amenity levels E_j after substituting (10) into (11)

$$E_j = N_j^W\left(\sum_i \frac{\upsilon_{ij}^{\gamma\epsilon}N_i^R}{\sum_s E_s\upsilon_{is}^{\gamma\epsilon}}\right)^{-1} \tag{12}$$

Ahlfeldt et al. (2015) prove that this system of equations has a unique solution for the vector of E_j's.

Model inversion: Step-by-step recovery of local geographical fundamentals using observed data on (equilibrium) outcomes

Step	Solution	Input data
1	Workplace amenity	Commuting matrix, transport costs, wages
2	Residential amenity	Commuting matrix, transport costs, wages, res. floorspace prices
3	Local productivity	Wages, comm. floorspace prices, mean effective density
4	Local density limits	Floorspace prices, floorspace use, land endowment

Model solution: Derive counterfactual (equilibrium) economic outcomes using geographical fundamentals and modified transport costs

Step	Solution	Input data
1	Location choice prob's	Local fundamentals + initial wages, prices, transport costs
2	Local productivities	Population distribution, mean effective density
3	Wages	Productivities, initial comm. floorspace prices
4	Res floorspace demand	Wages, initial res. floorspace prices, transport costs
5	Comm floorspace demand	Productivities, initial comm. floorspace prices
6	Floorspace prices	Residential and commercial demand, land endowment

Ahlfeldt et al. (2015) prove the uniqueness and convergence of the spatial equilibrium.

Estimating ϵ

Log-likelihood

$$\ln \mathcal{L} = \sum_{ij} N_{ij} \lambda_{ij} = \sum_{ij} N_{ij} \ln \frac{X_i E_j \left[\frac{\upsilon_{ij}}{p_i^{\beta} q_i^{1-\beta}} \right]^{\gamma \epsilon}}{\sum_r \sum_s X_r E_s \left[\frac{\upsilon_{rs}}{p_r^{\beta} q_r^{1-\beta}} \right]^{\gamma \epsilon}}, \tag{13}$$

where N_{ij} is the number of observed travellers in the commuting matrix.

We estimate ϵ by exploiting the gravity nature of the choice probability expression,

$$\ln \mathcal{L} = \sum_{ij} N_{ij} \left[K + \bar{X}_i + \bar{E}_j + \gamma \epsilon \ln \upsilon_{ij} \right], \tag{14}$$

using state-of-the art methods in the international trade literature and our own GLMM.

- Poisson Pseudo-Maximum Likelihood (PPML),
- Delta Pseudo-Maximum Likelihood (DPML),
- Generalised Linear Mixed Model (GLMM).

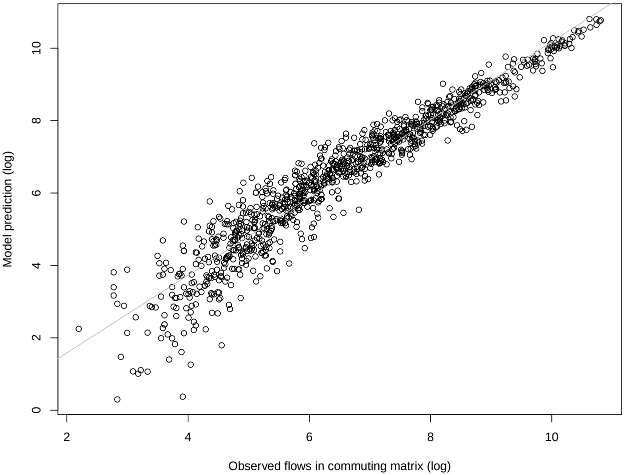
Head, K., & Mayer, T. (2014). Gravity equations: Workhorse, toolkit, and cookbook. In Handbook of international economics (Vol. 4, pp. 131-195). Elsevier.

Data for an illustrative application

Local authority districts in London – Later on extended to MSOA or even higher level of granularity with restricted data.

- Commuting matrix: ONS 2011 Census
- Residential and workplace populations: ONS 2011 Census
- Wages + hours at workplace: Annual Survey of Hours and Earnings
- Commercial floorspace prices: UK Valuation Office Agency administrative data
- Residential floorspace prices: Tenant Services Authority RSR
- Road network: UK Ordnance Survey / OSM data

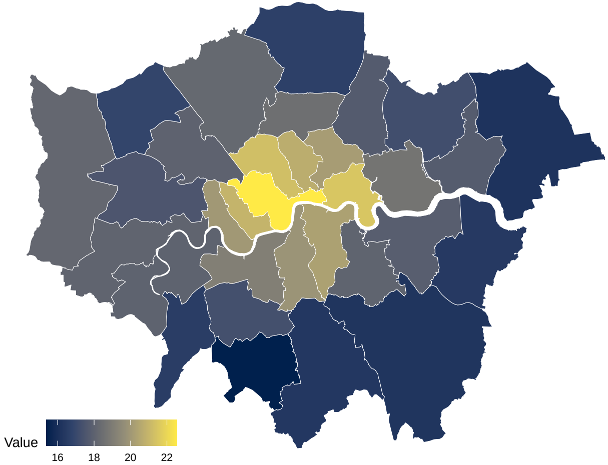
Recovering commuting flows



Spatial heterogeneity of the value of time

Mean value of time by residence

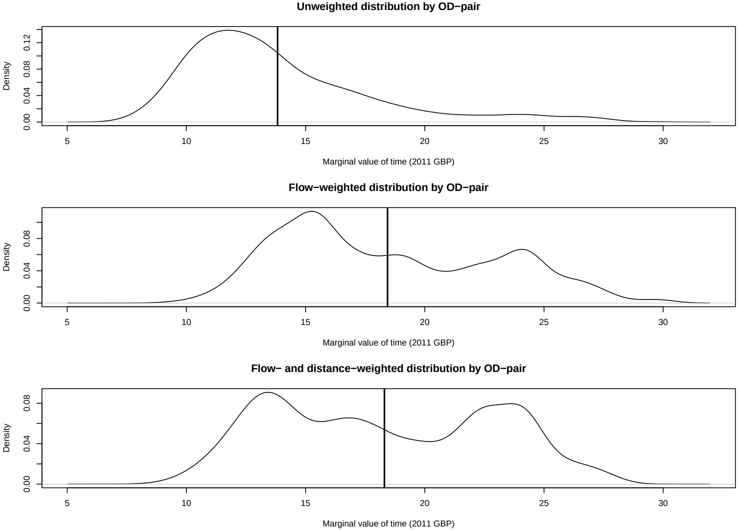
Based on observed wages, hours and travel time data



Local Authority Districts, London, 2011 data

Recall: $v_{ij} = \mu/\kappa = (w_j - \tau_{ij})/(T_j + t_{ij})$

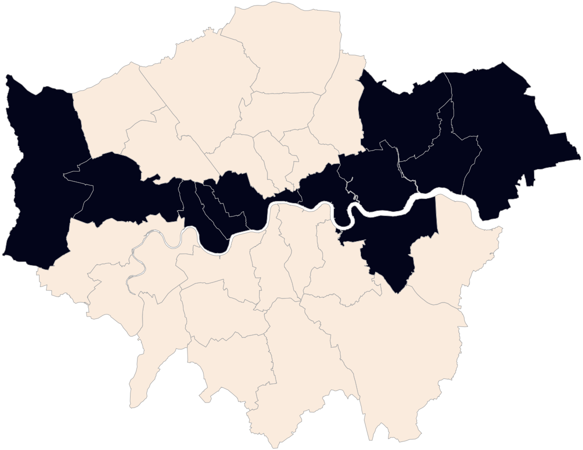
Heterogeneity of the value of time



Policy simulation: Crossrail/Elizabeth Line

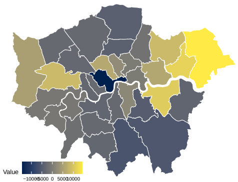
Locations connected by transport improvement

Elizabeth Line counterfactual



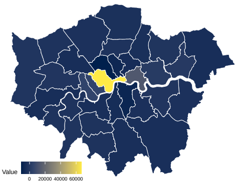
Local Authority Districts, London

A) Change in residential population
Counterfactual outcome



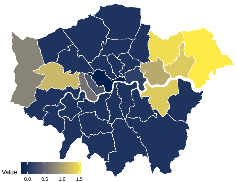
Local Authority Districts, London, 2011 data

B) Change in workplace population
Counterfactual outcome



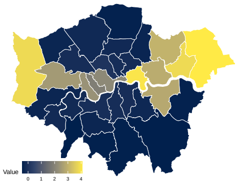
Local Authority Districts, London, 2011 data

C) Change in mean value of time by residence
Counterfactual outcome



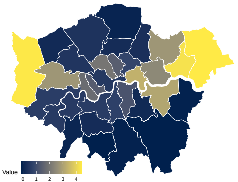
Local Authority Districts, London, 2011 data

D) Change in firm productivity
Counterfactual outcome



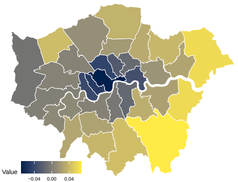
Local Authority Districts, London, 2011 data

E) Change in wage by workplace
Counterfactual outcome



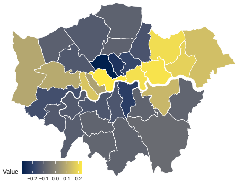
Local Authority Districts, London, 2011 data

F) Change in individual labour supply by workplace
Counterfactual outcome



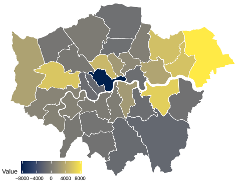
Local Authority Districts, London, 2011 data

G) Change in floorspace prices
Counterfactual outcome



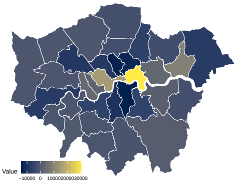
Local Authority Districts, London, 2011 data

H) Change in residential floorspace supply
Counterfactual outcome



Local Authority Districts, London, 2011 data

I) Change in commercial floorspace supply
Counterfactual outcome



Local Authority Districts, London, 2011 data

Benchmarking alternative appraisal methods

Randomised experiment – We select 20 arbitrary residence–workplace combinations and halve the baseline commuting time.

Method 1 Consumer surplus from travel time savings and the mean value of time (currently applied in appraisal).

Method 2 Surplus from travel time savings with values of time differentiated by residence–workplace pairs.

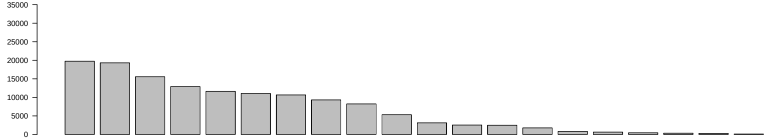
$$\Delta CS = \sum_{i,j} 0.5 \cdot N(\lambda_{ij}^0 + \lambda_{ij}^1) \cdot \upsilon_{(ij)}(t_{ij}^1 - t_{ij}^0) \tag{15}$$

Method 3 Compensating income in the quantitative model: extra income which increases expected utility (below) to the same extent as the transport improvement:

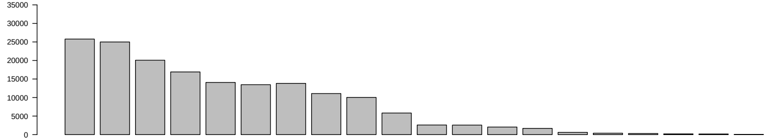
$$E[U(\text{wage}_0 + \text{CI}; \text{travel times}_0)] = E[U(\text{wage}_1; \text{travel times}_1)] \tag{16}$$

+ change in land values.

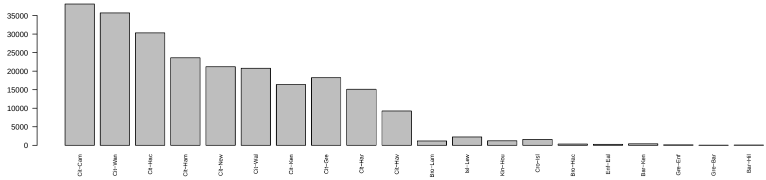
Method 1: CS with mean VoT

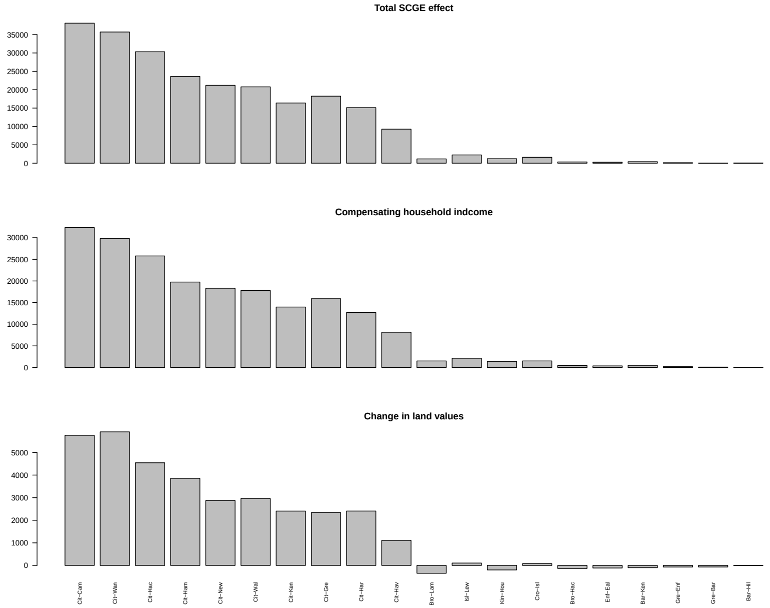


Method 2: CS with differentiated VoT



Method 3: S.G.E. compensating income + land value




Total SCGE effect
35000
30000
25000
20000
15000
10000
5000
0
Compensating household indcome
30000
25000
20000
15000
10000
5000
0
Change in land values
5000
4000
3000
2000
1000
0
Cit−Cam
Cit−Wan
Cit−Hac
Cit−Ham
Cit−New
Cit−Wal
Cit−Ken
Cit−Gre
Cit−Har
Cit−Hav
Bro−Lam
Isl−Lew
Kin−Hou
Cro−Isl
Bro−Hac
Enf−Eal
Bar−Ken
Gre−Enf
Gre−Bar
Bar−Hil

Project ranking according to the four appraisal methods

Link endpoints	Method 1	Method 2	Method 3
City of London and Westminster–Camden	1	1	1
City of London and Westminster–Wandsworth	2	2	2
City of London and Westminster–Hackney	3	3	3
City of London and Westminster–Hammersmith and Fulham	4	4	4
City of London and Westminster–Newham	5	5	5
City of London and Westminster–Waltham Forest	6	7	6
City of London and Westminster–Kensington and Chelsea	7	6	8
City of London and Westminster–Greenwich	8	8	7
City of London and Westminster–Harrow	9	9	9
City of London and Westminster–Havering	10	10	10
Bromley–Lambeth	11	11	14
Islington–Lewisham	12	12	11
Kingston upon Thames–Hounslow	13	13	13
Croydon–Islington	14	14	12
Bromley–Hackney	15	15	16
Enfield–Ealing	16	16	17
Barking and Dagenham–Kensington and Chelsea	17	17	15
Greenwich–Enfield	18	18	18
Greenwich–Barnet	19	19	20
Barking and Dagenham–Hillingdon	20	20	19

Do the benefits increase in a general equilibrium model?

Not necessarily!

Link endpoints	M1	M2	M3	%Δ(M3-M1)	%Δ(M3-M2)
City and Westminster–Camden	19,751	25,773	38,108	+93	+48
City and Westminster–Wandsworth	19314	24,990	35,705	+85	+43
City and Westminster–Hackney	15,567	20,069	30,327	+95	+51
City and Westminster–Hammersmith and Fulham	12,912	16,911	23,609	+83	+40
City and Westminster–Newham	11,630	14,073	21,195	+82	+51
City and Westminster–Waltham Forest	11,050	13,469	20,780	+88	+54
City and Westminster–Kensington and Chelsea	10,658	13,828	16,384	+54	+18
City and Westminster–Greenwich	9,317	11,076	18,240	+96	+65
City and Westminster–Harrow	8,236	10,043	15,121	+84	+51
City and Westminster–Havering	5,327	5,825	9,263	+74	+59
Bromley–Lambeth	3,130	2,595	1,170	-63	-55
Islington–Lewisham	2,535	2,569	2,251	-11	-12
Kingston upon Thames–Hounslow	2,480	2,043	1,218	-51	-40
Croydon–Islington	1,773	1,689	1,601	-10	-5
Bromley–Hackney	828	620	343	-59	-45
Enfield–Ealing	632	386	268	-58	-31
Barking and Dagenham–Kensington and Chelsea	452	308	404	-10	31
Greenwich–Enfield	336	199	128	-62	-36
Greenwich–Barnet	282	171	34	-88	-80
Barking and Dagenham–Hillingdon	110	72	66	-40	-8

Endogenising the transport cost matrix

Aim: Integrate mode and route choice under congestion into the SGE framework.

We see multiple promising options

1. Simultaneous location and transport decisions (Allen and Arkolakis, 2022)
2. Nested Fréchet/logit mode and route choice (Tsivanidis, 2023)
3. Iterative spatial and transport assignment modules (Anas, 2007)
4. Integrate QSM with common transport assignment software (black box threat)
5. Integrate QSM with MFD assignment (eager to explore)

Conclusions

- Contributions
  - To the transport field: The paper documents an effort to **bring spatial general equilibrium closer to transport appraisal** methodology.
  - To quantitative urban modelling: "Iceberg" commuting cost replaced with a leisure–labour trade-off in which travel expenses are constraints and individual labour supply is endogenous.
- The method reveals **spatial heterogeneity in travel time valuations**.
- Crossrail counterfactual: we quantify counterfactual changes in time valuation and labour supply after a "transformative" transport improvement.
- Initial randomised experiment suggests that
  - **SGE does not imply fundamental rearrangement in project ranking**;
  - Centrifugal [centripetal] projects become easier [more difficult] to justify.