The Misallocation of Urban Land: Car Ownership, Parking, and Commuting in General Equilibrium

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September 3, 2026

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Abstract — Parking is a salient use of urban land that is in part allocated by administrative rule rather than by price. We embed residential and employer parking in a quantitative spatial model in which workers choose a residence–workplace pair, whether to own a car, and a commuting mode, and in which both parking margins compete for the same built-up floor space as housing and production. To account for the Dutch tax exemption on employer parking, a single pass-through parameter spans employer parking charged to the driver at the margin and employer parking absorbed into the wage of every worker at a location. Car travel time is endogenous to the number of car commuters. We estimate the model on Dutch administrative microdata covering residences, workplaces, wages and vehicles, and evaluate three counterfactuals: cuts to local parking capacity, abolition of the employer parking exemption, and a welfare-maximising residential permit schedule. **[Findings: to be completed.]**

Keywords — Parking, car ownership, commuting mode choice, quantitative spatial model, urban land use.

JEL codes — R14, R21, R41, C35.

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Introduction

Cars are hungry for urban space. Besides occupying space on the road, a car needs a parking spot close to the residence and another at every destination it is driven to. In the US, parking occupies 14% of incorporated land in Los Angeles County and roughly 10% of metropolitan Phoenix, while roadways absorb close to a quarter of US urbanised land (Chester et al., 2015; Hoehne et al., 2019; Guerra et al., 2025). D. C. Shoup (2005) and Manville and D. Shoup (2005) document how minimum parking requirements have made parking the dominant use of land in many American downtowns. This central role of parking in urban environments is not a law of nature: in Japan, for instance, overnight on-street parking is banned nationwide through the 1962 Garage Act, shifting parking demand entirely onto private land.

This paper treats parking as a question of urban land allocation. In urban environments, land is scarce and construction of additional (underground) parking space is costly. Therefore, demand for parking space crowds out residential and commercial use of floor space, uses that generate city income and utility to its residents through housing and amenities. At the residence, minimum parking requirements take floor space out of the housing market and hand it to the car owner at a marginal price of zero. Municipal parking permits are often issued at rates far below the value of the floor space a spot occupies (D. C. Shoup, 2005; Ostermeijer, Koster, and Ommeren, 2019a). At the workplace, employers pass on only part of the cost of a spot to the worker who uses it, and the untaxed remainder is a subsidy per driver. Car ownership and the decision to drive to work are therefore subsidised claims on urban floor space, and land is misallocated between parking and the uses it displaces. The wedge persists because closing it is politically costly: parking revenue that does not visibly return to residents makes tighter pricing hard for a city council to introduce. How a city divides its land among competing uses is a central object of urban economics (Duranton and Puga, 2015), and minimum parking requirements belong with the land-use regulations that Glaeser and Gyourko (2018) study, with large measured effects on the area given over to parking (Cutter and Franco, 2012; Gabbe and Pierce, 2017).

Higher car ownership raises the share of floor space taken by parking, which raises the price of floor space paid by every resident and firm at that location, whether or not they drive. In a general equilibrium response, residents consume less housing, firms pay higher rents, and commercial activity shifts across locations. Brueckner and Franco (2018) give each road commuter an allotment of central land for parking and, because the central zone has a fixed area, parking land reduces what remains for central residences and production. Brueckner and Franco (2017) treat parking area as a dwelling attribute alongside floor space and analyse minimum

parking requirements in the same setting, and Franco (2017) shows how downtown parking supply reshapes urban spatial structure. All three are stylised models of one city with a single centre and at most two zones. In the taxonomy of Proost and Thisse (2019), which separates the analytical monocentric tradition, computable land-use models and the quantitative spatial tradition, the parking literature sits entirely in the first. No quantitative spatial model has incorporated parking at all.

Many studies, empirical and structural, have examined cars and parking in the context of commuting trips and location choice, but to our knowledge none has studied the effect of parking and car ownership on spatial structure through the land-use channel in a spatial equilibrium with many locations. Tsivanidis (2026) embeds car ownership as a discrete choice in a quantitative spatial model, but treats it as a fixed cost deducted from income rather than a claim on scarce urban land. Barwick et al. (2024) estimate an equilibrium sorting model of residence and commuting mode with endogenous congestion, but ownership enters only as a demographic control and as an instrument, never as an equilibrium object. Brueckner and Franco (2017) and Brueckner and Franco (2018) derive parking area, floor space and mode choice in general equilibrium, including employer-paid parking, but in monocentric space with two zones, so that the response to a parking reform is a comparative static in distance to the centre rather than a reallocation across residence and workplace pairs.

In this paper, we aim to fill this gap by incorporating parking and car ownership into a quantitative spatial model in the tradition of Ahlfeldt et al. (2015b) and Monte et al. (2018a), extended with the utility-consistent mode choice of Tsivanidis (2026) and Hendrich et al. (2026). Workers choose a residence and workplace pair, then whether to own a car, and finally a commuting mode among car, bicycle, walking and public transport. Ownership is therefore an equilibrium object carrying an option value. Parking enters at both ends of the commute. Residential parking is tied to ownership and employer parking to realised car commuting, and a single parameter, the share of the cost of a workplace spot that employers pass on to the driver, spans the polar cases in which that cost is charged to the driver at the margin or absorbed into the wage of every worker at the location. Both parking margins compete for the same built floor space as residential and commercial space, and car travel time rises with the number of car commuters (Arnott, 2013; Fosgerau, 2015). The model therefore carries four distortions that separate the private from the social cost of a car commute: employer parking is paid out of the wage bill of drivers and non-drivers alike, its value stays outside the wage-tax base, parking crowds out housing and commercial floor space, and drivers slow each other down. Our contribution is not to model the land cost of parking, which Brueckner and Franco (2017) and Brueckner and

Franco (2018) did, but to do so in a spatial equilibrium with bilateral commuting, endogenous car ownership and heterogeneous locations, so that the reallocation of floor space, workers and firms that a parking reform sets off is spatial rather than a comparative static in distance to a single centre.

Our focus is on the Netherlands, particularly Amsterdam and the surrounding cities and towns. Strict spatial regulation limits where land may be developed. These policies have restrained suburbanisation and kept housing and employment concentrated in existing urban areas, but they have also increased the scarcity of urban land (Levkovich et al., 2020), which sharpens the competition between parking and other uses of floor space. Commuting is dispersed accordingly: a large share of workers commutes between towns and cities rather than from a suburb to a single central business district. In addition, the Netherlands has a top marginal income tax rate of 49.5%, which gives employers a strong incentive to provide parking space, since employer parking is an untaxed fringe benefit and every euro paid in parking rather than wages escapes that rate.[1] Finally, Dutch administrative microdata maintained by Statistics Netherlands allow us to observe the residences, workplaces, wages and vehicles of the working population in full, so that we can estimate the model rather than calibrate it.

We evaluate our model against three counterfactual policy scenarios: local parking supply cuts, abolition of the employer parking fringe benefit, and a welfare maximising residential permit fee schedule **[Third counterfactual; tbd, counterfactual findings: tbd]**.

In our first counterfactual, we analyse the effects of a policy that reduces parking capacity in dense urban areas, for example by removing on-street parking spots. This counterfactual mirrors the policy preferences of the larger Dutch municipalities.[2] Since residential and commercial parking supplies are endogenous in our model, we implement the local capacity cuts by imposing exogenous capacities that reflect the cuts, together with endogenous lump-sum scarcity fees that equal the shadow price of a unit of additional space beyond the constrained amount, that is, the willingness of workers to pay for it.[3]

As a second exercise, we simulate the abolition of the employer-provided parking fringe benefit. Workers then jointly bear the full cost of the parking space their employer supplies to car commuters, which discourages that mode of transport. As a variant, we introduce an obligation for firms to price parking at marginal cost instead of the current, near-ubiquitous average cost pricing of employer parking, under which workers pay regardless of commuting

[1] This policy has a US counterpart: the parking fringe-benefit exclusion under IRC 132(f) (Zax, 1988).

[2] The municipality of Amsterdam aims to cut the total number of regulated parking spots by 10,000, or about 5%, between 2019 and 2025.

[3] Thus, a fee is zero if capacity is slack. If capacity binds, the fee rises until endogenous parking demand equals the available quantity.

mode.[4] This is the parking cash-out arrangement legislated in California, under which covered employers must offer the cash value of a subsidised spot to workers who decline it (D. C. Shoup, 2005). Under marginal cost pricing, each car commuter pays for their own parking spot at the workplace, which eliminates the externality on non-car commuters at the same location.

Finally, we numerically solve for a residential permit scheme that maximises welfare. **[To be completed.]**

Related literature and contribution. The paper contributes to three literatures. The first is the quantitative spatial modelling literature built on Ahlfeldt et al. (2015a), Monte et al. (2018b), and Heblich et al. (2020), and surveyed in Redding and Rossi-Hansberg (2017) and Redding (2023).[5] Floor space that clears at a single price per location (Ahlfeldt et al., 2015b), discrete-choice commuting, and a fixed urban land stock are all standard in this literature, and Tsivanidis (2026) has shown how car ownership fits into it as a discrete choice. Car ownership as a claim on that same floor space, and parking as the mechanism through which the claim is made, are new.

The second is the literature on parking and land use. Its analytical branch (Brueckner and Franco, 2017; Brueckner and Franco, 2018; Franco, 2017) gives parking an explicit land requirement and works out the consequences for urban form in a monocentric city with at most two zones. Its empirical branch has produced partial-equilibrium elasticities of car ownership, house prices, and traffic with respect to parking supply and price (Ommeren, Groote, et al., 2014b; Ommeren, Wentink, et al., 2011; Ommeren, Groote, et al., 2014a; Ostermeijer, Koster, and Ommeren, 2019b; Ostermeijer, Koster, Nunes, et al., 2022; Mingardo et al., 2015; Groote et al., 2016), and has measured how much land minimum parking requirements add to parking (Cutter and Franco, 2012; Gabbe and Pierce, 2017). Neither branch can say where the workers and floor space displaced by a parking reform end up, nor how much of any change in congestion is a traffic effect rather than a land-use effect, a distinction the traffic congestion literature (Akbar et al., 2023; Garcia-López et al., 2022; Yang et al., 2020; Daganzo, 2007; Daganzo et al., 2011) does not draw either, since it takes the built environment as given. In the terms of Proost and Thisse (2019), we move the parking question from the analytical monocentric tradition into the quantitative spatial one.

The third is the literature on sorting and spatial policy across heterogeneous workers (Fajgelbaum and Gaubert, 2020; Colas and Hutchinson, 2021; Couture et al., 2024; Teulings et al., 2018; Gaigné et al., 2022), and on the endogenous response of local amenities to who lives where, doc-

[4] For illustration, recent surveys over the years 2023 to 2026 show that 93 to 95% of workers in the province of North Holland, which includes Amsterdam, either park for free or are fully reimbursed (Ipsos, 2026).

[5] Recent extensions incorporate transit and mode choice (Tsivanidis, 2026; Severen, 2023; Hendrich et al., 2026), dynamics (Kleinman et al., 2021), and endogenous congestion (Allen and Arkolakis, 2022; Herzog, 2024).

umented for Amsterdam by Almagro and Domınguez-Iino (2022). This literature treats housing, amenities, and taxes as the instruments through which sorting operates. Car ownership and parking policy are natural additions to that list, because both cost close to a fixed amount in euros per year while the incomes against which that cost is judged vary widely. The present version of the model has a single worker type and therefore cannot yet speak to sorting by income; the microdata record wages, so introducing income groups is the first extension we plan.

The remainder of the paper proceeds as follows. The next section describes parking and car ownership in the Netherlands. Section 2 sets out the model and defines its general equilibrium, Section 4 describes the structural estimation, Section 5 reports the counterfactual analysis, and Section 6 concludes.

1 Parking and car ownership in the Netherlands

Car ownership in the Netherlands is comparatively low by Western European standards but has grown steadily, driven mainly by suburban and peripheral municipalities. The national passenger car fleet passed 9 million vehicles in 2023, and ownership rose from 0.8 to nearly 1.1 cars per household between 1990 and 2020 (Centraal Bureau voor de Statistiek, 2024). Heterogeneity is substantial: about a quarter of Dutch households own no car at all, concentrated in the urban cores of the four largest cities (Amsterdam, Rotterdam, The Hague and Utrecht), while car ownership in Flevoland and other Randstad-adjacent commuter regions ranks among the highest in the EU (Eurostat, 2024). This shows that residential parking supply and car ownership are close spatial complements rather than independent margins.

The car is the main commuting mode overall, with a share of 65%. As with ownership, this modal split reverses towards the city centres, where the majority of workers cycle to work, particularly on short trips below 5 km (Hendrich et al., 2026).

Dutch parking policy is characterised by administrative rationing rather than price rationing. On-street parking in most urban areas requires a residential permit (*parkeervergunning*) issued by the municipality at a fraction of the market rate; in inner-city districts of Amsterdam, Rotterdam, and Utrecht this can generate multi-year waiting lists, effectively converting the permit into an implicit subsidy whose value rises with local scarcity (Ommeren, Groote, et al., 2014b; Ostermeijer, Koster, and Ommeren, 2019b).

Additionally, municipalities regulate off-street supply through minimum parking requirements (MPR), which mandate a minimum realised capacity per dwelling in housing development projects. Municipalities often follow MPR guidelines set in a national design manual

(CROW, 2013). Since the early 2020s, large cities have begun relaxing or abolishing MPR as part of car-restraint policies (Mingardo et al., 2015).

At the workplace, Dutch workers who commute by car generally can park for free.[6] An institutional feature specific to the Dutch tax system is the employer-provided parking fringe benefit (*nihilwaardering*), which exempts workplace parking from the wage-tax base and thereby subsidises car commuting relative to cycling or transit (Ostermeijer, Koster, Nunes, et al., 2022).

Together, permit rationing, minimum parking requirements, and the employer parking tax exemption constitute the three policy margins targeted by the counterfactuals in this paper.

1.1 Data description

[To be completed, but broadly similar to Hendrich et al. (2026).]

2 Theoretical model

Environment. The economy consists of a finite set S of discrete locations. A location is indexed by i when it is used as a place of residence and by j when it is used as a place of work; both indices run over the same set S, so that any location may serve both purposes. Outside the commuting problem, where the distinction between the two ends of a trip matters, we use j as a generic index for a location.

The four commuting modes are collected in the set $\mathcal{M} = \{\mathrm{car}, \mathrm{bc}, \mathrm{wl}, \mathrm{pt}\}$, where car stands for driving, bc for cycling, wl for walking, and pt for public transport. For each mode $m \in \mathcal{M}$, the travel time matrix τ_{ijm} records the time needed to travel from i to j by that mode. Commuters incur an iceberg commuting cost $d_{ijm} = \exp(\kappa \tau_{ijm})$, where κ is a mode-independent semi-elasticity of utility with respect to commuting time.

Three types of agents make optimising decisions in the economy. *Consumers* supply one unit of labour inelastically and choose where to live, where to work, whether to own a car, how to commute, and how to split their income between the final good and housing. *Final-good producers* hire labour and rent commercial floor space in order to produce a freely traded final good, which serves as the numéraire. *Construction firms* combine land with capital to produce built floor space, which they rent out to final-good producers and to consumers. All three types of agents are price takers.

Land is owned collectively by the city's residents, who hold equal shares in a city-wide land portfolio and rent land to construction firms at the local land rent R_j. The proceeds are returned

[6] For illustration, recent surveys over the years 2023 to 2026 show that 93 to 95% of workers in the province of North Holland, which includes Amsterdam, either park for free or are fully reimbursed (Ipsos, 2026).

to consumers as a uniform lump-sum transfer $\bar{T}$, defined alongside the construction sector below, so that land rents remain inside the economy. Built floor space is perfectly malleable across its four uses — commercial production, residential use, commercial parking, and residential parking — so that a single price q_j prevails at each location.

Preferences. Conditional on a bundle (i, j, m, a), worker ω derives utility from consumption of the final good c_i and of residential floor space l_i according to the Cobb–Douglas utility function

$$U_{ijma}(c_i, l_i; \omega) = b_i \left(\frac{c_i}{\beta}\right)^{\beta} \left(\frac{l_i}{1-\beta}\right)^{1-\beta} \frac{\xi_{ij}(\omega)\, \psi_a(\omega)\, \eta_m(\omega)}{d_{ijm}}, \tag{1}$$

where $\beta \in (0, 1)$ is the expenditure share on the final good, b_i is the residential amenity at i, d_{ijm} is the iceberg commuting cost, and ξ_{ij}, ψ_a, η_m are the three Fréchet shocks introduced above.

Choice tree. The economy is populated by a measure $\bar{H}_R$ of ex-ante identical consumers, indexed by ω. Workers choose a residence–workplace pair (i, j), then car ownership $a \in \{\text{own}, \text{noc}\}$, and finally a commuting mode. If $a = \text{noc}$ (short for *no car*), only non-car modes are feasible. If $a = \text{own}$ (short for *own a car*), the car option is added as a singleton nest. The lower-level nesting structure is defined by the non-driving nest, $\mathcal{B}_{\text{ndr}}$, and the driving singleton nest, $\mathcal{B}_{\text{car}}$, which partition the mode set $\mathcal{M}$:

$$\mathcal{B}_{\text{ndr}} = \{\text{bc}, \text{wl}, \text{pt}\}, \qquad \mathcal{B}_{\text{car}} = \{\text{car}\}. \tag{2}$$

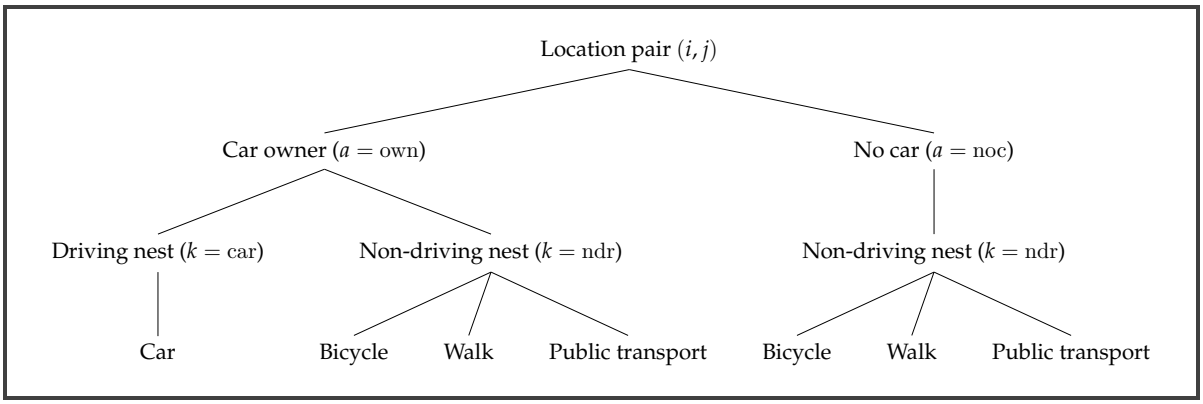
We assume that car owners can choose between car and non-car modes, while those who do not own a car can only commute by non-car modes, that is,

$$M(\text{noc}) = \mathcal{B}_{\text{ndr}}, \qquad M(\text{own}) = \mathcal{B}_{\text{car}} \cup \mathcal{B}_{\text{ndr}}. \tag{3}$$

The full choice structure of the model is summarised in Figure 1.

Shocks. Preferences feature three multiplicative Fréchet layers, one for each layer of the choice tree.[7] Residence–workplace shocks $\xi_{ij}(\omega)$ are independent across pairs; ownership shocks $\psi_a(\omega)$ are drawn conditional on (i, j) and independent across a; and mode shocks $\eta_m(\omega)$, also drawn conditional on (i, j), follow a nested multivariate Fréchet distribution with shape θ, in which the non-car modes are correlated within nest $k = \text{ndr}$ with parameter $\varrho_{\text{ndr}} = \varrho \in (0, 1]$ while the

[7] Equivalently, the three layers can be collapsed into a single generalised-extreme-value shock over bundles (i, j, m, a), with $\eta_{ijma} = \xi_{ij}\psi_a\eta_m$. The two formulations deliver identical choice probabilities; we work with the sequential representation because it makes the backward induction below transparent.



Notes: Workers choose (i, j) with Fréchet shape ε, then car ownership with shape λ, then commuting mode with shape θ. When $a = \text{own}$, the car option forms a singleton nest and the non-car modes form a separate nest with within-nest correlation parameter $\varrho \in (0, 1]$. The three shape parameters are kept distinct throughout. Consistency of the nested Fréchet structure requires $\theta \geq \lambda \geq \varepsilon > 1$.

FIGURE 1 – CHOICE STRUCTURE OF THE MODEL.

car option forms a singleton nest with $\varrho_{\text{car}} = 1$:

$$\mathbb{P}\left(\xi_{ij}(\omega) \leq x_{ij}\ \forall (i,j) \in S \times S\right) = \exp\left(-\sum_{i,j} T_i T_j x_{ij}^{-\varepsilon}\right), \tag{4}$$

$$\mathbb{P}\left(\psi_a(\omega) \leq y_a\ \forall a\right) = \exp\left(-\sum_{a} T_a y_a^{-\lambda}\right), \tag{5}$$

$$\mathbb{P}\left(\eta_m(\omega) \leq z_m\ \forall m\right) = \exp\left(-\sum_{k \in \{\text{car},\text{ndr}\}} T_k \left(\sum_{m \in \mathcal{B}_k} \left(T_m\, z_m^{-\theta}\right)^{1/\varrho_k}\right)^{\varrho_k}\right). \tag{6}$$

Non-owners draw the same shocks but maximise only over $M(\text{noc}) = \mathcal{B}_{\text{ndr}}$. We assume $\theta \geq \lambda \geq \varepsilon > 1$ throughout, so that the expected maxima used to form the inclusive values at each stage are finite, and the nesting structure satisfies the McFadden consistency conditions on the shape parameters. The vector $\mathbf{T} = (T_m, T_k, T_a, T_i, T_j)$ collects the alternative-specific constants (ASCs), which scale the corresponding distributions multiplicatively. Throughout we impose the normalisations

$$T_{\text{noc}} = T_{\text{ndr}} = T_{\text{pt}} = 1, \qquad T_{n_0} = 1, \tag{7}$$

where the last normalisation is imposed at both the residence and the workplace layer, for an arbitrary reference location $n_0 \in S$, since only relative constants are identified within each layer. The origin and destination constants T_i and T_j are carried explicitly through the choice probabilities below; in estimation they are not separately identified from residential amenities and workplace productivities, and are absorbed into them.

Ownership costs and realised income. Ownership entails a fixed cost

$$p_{\text{own}} + \nu q_i, \tag{8}$$

where p_{own} is the non-housing ownership cost and νq_i is the residential parking cost, that is, the cost of the ν units of floor space occupied by a parking spot at the residence. Residential parking is paid directly by the household, so no question of pass-through arises and it is borne in full. Commercial parking, in contrast, is paid only if the realised commute mode is car, and reaches the worker through the mode-specific wage $w_{j,\text{car}} = w_j - \gamma\nu q_j$ derived in the firms' problem below: only the fraction γ charged at the margin is attached to the commuting decision, while the remainder is already embedded in the base wage w_j and is therefore common to all workers at j. Define the ownership-specific net income before the mode choice is made, inclusive of the lump-sum transfer $\bar{T}$ of land rents, which is defined together with the construction sector below:

$$\bar{W}_{ij,\text{noc}} = w_j + \bar{T}, \qquad \bar{W}_{ij,\text{own}} = w_j - (p_{\text{own}} + \nu q_i) + \bar{T}. \tag{9}$$

The mode- and ownership-specific realised income is then

$$W_{ijma} = \begin{cases} w_j + \bar{T}, & a = \text{noc},\ m \in \mathcal{B}_{\text{ndr}}, \\ w_j - (p_{\text{own}} + \nu q_i) + \bar{T}, & a = \text{own},\ m \in \mathcal{B}_{\text{ndr}}, \\ w_j - (p_{\text{own}} + \nu q_i) - \gamma\nu q_j + \bar{T}, & a = \text{own},\ m \in \mathcal{B}_{\text{car}}. \end{cases} \tag{10}$$

Conditional on ownership, define the mode-specific wedge

$$\delta_{ijma} \equiv \frac{W_{ijma}}{\bar{W}_{ija}}, \tag{11}$$

so that $W_{ijma} = \bar{W}_{ija}\delta_{ijma}$. Because $\bar{T}$ enters every branch of W_{ijma} additively, it is absorbed into $\bar{W}_{ija}$ and the multiplicative separability of income is preserved. Hence

$$\delta_{ijm,\text{noc}} = 1 \quad \text{for all } m \in \mathcal{B}_{\text{ndr}}, \qquad \delta_{ijm,\text{own}} = 1 \quad \text{for all } m \in \mathcal{B}_{\text{ndr}}, \tag{12}$$

and

$$\delta_{ij,\text{car,own}} = \frac{w_j - (p_{\text{own}} + \nu q_i) - \gamma\nu q_j + \bar{T}}{w_j - (p_{\text{own}} + \nu q_i) + \bar{T}} = 1 - \frac{\gamma\,\nu q_j}{w_j - (p_{\text{own}} + \nu q_i) + \bar{T}}. \tag{13}$$

The wedge δ_{ijma} therefore isolates the only channel through which the commute mode affects income: the share γ of workplace parking that is charged at the margin, paid exclusively by

owners who actually drive. Two features are worth noting. First, the transfer enters the wedge through its denominator, so a larger $\bar{T}$ makes workplace parking a smaller share of income and moves $\delta_{ij,\text{car,own}}$ closer to unity. Second, under average-cost pricing, the wedge collapses to $\delta_{ij,\text{car,own}} = 1$ for every pair: the cost of workplace parking is still borne by workers, but through the base wage w_j rather than through the commuting decision, so it survives only as a level effect on the attractiveness of j as a workplace.[8] Note that any $\gamma > 0$ (i.e., any deviation from average-cost pricing) implies, all else equal, less commuting by car.

Utility maximisation and indirect utility. Given (i, j, m, a), the worker maximises $U_{ijma}(c_i, l_i; \omega)$ subject to the static budget constraint

$$c_i + q_i l_i = W_{ijma}, \tag{14}$$

where realised income W_{ijma} is inclusive of the lump-sum transfer, so that workers spend the share $1 - \beta$ of labour income *and* transfer income on housing. Solving the Cobb–Douglas problem gives

$$c_i = \beta W_{ijma}, \qquad l_i = \frac{(1-\beta) W_{ijma}}{q_i}. \tag{15}$$

Substituting the optimal bundle back into the utility function, and using $W_{ijma} = \bar{W}_{ija}\delta_{ijma}$, indirect utility is

$$U_{ijma}(\omega) = \frac{b_i}{q_i^{1-\beta}} \bar{W}_{ija}\, \xi_{ij}(\omega) \psi_a(\omega)\, \frac{\delta_{ijma}\eta_m(\omega)}{d_{ijm}}. \tag{16}$$

Because the ASCs are embedded in the distributions of ξ_{ij}, ψ_a and η_m, the indirect-utility expression contains no separate constant terms; the ASCs surface only once the maximisation over the shocks is carried out. This is what makes their later use in estimation consistent with the model formulation.

The choice problem is solved by backward induction, in the reverse of the order in which the layers are chosen: mode first, then car ownership, then the residence–workplace pair.

Conditional mode choice. Conditional on (i, j, a), the terms

$$\frac{b_i}{q_i^{1-\beta}}, \qquad \bar{W}_{ija}, \qquad \xi_{ij}(\omega), \qquad \psi_a(\omega) \tag{17}$$

[8] We assume throughout that $w_j - (p_{\text{own}} + \nu q_i) - \gamma\nu q_j + \bar{T} > 0$ whenever car commuting is feasible. In the empirical setting that motivates the model, this condition is satisfied in the observed data.

are common across all feasible modes and therefore cancel out. Mode choice is governed by

$$\max_{m \in M(a)} \frac{\delta_{ijma} \eta_m(\omega)}{d_{ijm}}, \tag{18}$$

with shape parameter θ at the mode layer and within-nest correlation ϱ in the non-driving nest.

The conditional probabilities for non-owners are

$$\pi_{m|ij,\text{noc}} = \frac{T_m^{1/\varrho} \, d_{ijm}^{-\theta/\varrho}}{\sum_{m' \in \mathcal{B}_{\text{ndr}}} T_{m'}^{1/\varrho} \, d_{ijm'}^{-\theta/\varrho}}, \qquad m \in \mathcal{B}_{\text{ndr}}, \tag{19}$$

where the mode-specific ASCs T_m enter through the Fréchet scale shifters defined above. For owners, the probability of commuting by car is

$$\pi_{\text{car}|ij,\text{own}} = \frac{T_{\text{car}} \, \delta_{ij,\text{car,own}}^{\theta} d_{ij,\text{car}}^{-\theta}}{T_{\text{car}} \, \delta_{ij,\text{car,own}}^{\theta} d_{ij,\text{car}}^{-\theta} + d_{ij,\text{ndr}}^{-\theta}}, \tag{20}$$

where the non-driving inclusive value aggregates modes within the non-driving nest:

$$d_{ij,\text{ndr}}^{-\theta} \equiv \left(\sum_{m \in \mathcal{B}_{\text{ndr}}} T_m^{1/\varrho} \, d_{ijm}^{-\theta/\varrho} \right)^{\varrho}. \tag{21}$$

The probability that an owner commutes by one of the non-car modes is

$$\pi_{m|ij,\text{own}} = \frac{d_{ij,\text{ndr}}^{-\theta}}{T_{\text{car}} \, \delta_{ij,\text{car,own}}^{\theta} d_{ij,\text{car}}^{-\theta} + d_{ij,\text{ndr}}^{-\theta}} \cdot \frac{T_m^{1/\varrho} \, d_{ijm}^{-\theta/\varrho}}{\sum_{m' \in \mathcal{B}_{\text{ndr}}} T_{m'}^{1/\varrho} \, d_{ijm'}^{-\theta/\varrho}}, \qquad m \in \mathcal{B}_{\text{ndr}}. \tag{22}$$

Note that the nest-level ASC T_{ndr} cancels from all within-nest probabilities; only T_{car} matters at the car-versus-non-driving margin, consistent with the normalisation $T_{\text{ndr}} = 1$.

We denote the mode-inclusive values for each ownership type by D_{ija}, defined so that

$$D_{ij,\text{noc}}^{-\theta} \equiv d_{ij,\text{ndr}}^{-\theta} = \left(\sum_{m \in \mathcal{B}_{\text{ndr}}} T_m^{1/\varrho} \, d_{ijm}^{-\theta/\varrho} \right)^{\varrho}, \tag{23}$$

$$D_{ij,\text{own}}^{-\theta} = T_{\text{car}} \, \delta_{ij,\text{car,own}}^{\theta} d_{ij,\text{car}}^{-\theta} + D_{ij,\text{noc}}^{-\theta}. \tag{24}$$

Ownership choice. Using the mode-inclusive commute term, the ownership-level utility is

$$U_{ija}(\omega) = \frac{\bar{W}_{ija} \, b_i}{D_{ija} q_i^{1-\beta}} \xi_{ij}(\omega) \psi_a(\omega), \tag{25}$$

where the ownership-level shock ψ_a has Fréchet shape λ and scale $T_a^{1/\lambda}$, with $T_{\text{noc}} = 1$. The ownership ASC T_{own} therefore enters the choice probabilities as a multiplicative shifter. Hence, conditional on (i, j),

$$\pi_{\text{own}|ij} = \frac{T_{\text{own}}\,\bar{W}_{ij,\text{own}}^{\lambda} D_{ij,\text{own}}^{-\lambda}}{\bar{W}_{ij,\text{noc}}^{\lambda} D_{ij,\text{noc}}^{-\lambda} + T_{\text{own}}\,\bar{W}_{ij,\text{own}}^{\lambda} D_{ij,\text{own}}^{-\lambda}}, \qquad \pi_{\text{noc}|ij} = \frac{\bar{W}_{ij,\text{noc}}^{\lambda} D_{ij,\text{noc}}^{-\lambda}}{\bar{W}_{ij,\text{noc}}^{\lambda} D_{ij,\text{noc}}^{-\lambda} + T_{\text{own}}\,\bar{W}_{ij,\text{own}}^{\lambda} D_{ij,\text{own}}^{-\lambda}}. \tag{26}$$

Define the ownership-inclusive value

$$\Omega_{ij} \equiv \left(\bar{W}_{ij,\text{noc}}^{\lambda} D_{ij,\text{noc}}^{-\lambda} + T_{\text{own}}\,\bar{W}_{ij,\text{own}}^{\lambda} D_{ij,\text{own}}^{-\lambda}\right)^{1/\lambda}. \tag{27}$$

Option value of car ownership. Car ownership has an option value because owners retain access to both commuting technologies. This is captured by

$$D_{ij,\text{own}}^{-\theta} = T_{\text{car}}\,\delta_{ij,\text{car,own}}^{\theta} d_{ij,\text{car}}^{-\theta} + d_{ij,\text{ndr}}^{-\theta}, \tag{28}$$

whereas non-owners face only

$$D_{ij,\text{noc}} = d_{ij,\text{ndr}}. \tag{29}$$

An improvement in non-driving commuting raises utility for both owners and non-owners, but it benefits non-owners proportionally more. Therefore, better non-driving commuting lowers the odds of car ownership.

Residence–workplace choice. At the upper level, expected utility from (i, j) is

$$U_{ij}(\omega) = \frac{b_i \Omega_{ij}}{q_i^{1-\beta}}\,\xi_{ij}(\omega), \tag{30}$$

where ξ_{ij} has Fréchet shape ε and scale $(T_i T_j)^{1/\varepsilon}$. Define residential commuting market access

$$\Phi_i^R = \sum_{j \in S} T_j\,\Omega_{ij}^{\varepsilon}. \tag{31}$$

Then

$$\pi_{ij|i} = \frac{T_j\,\Omega_{ij}^{\varepsilon}}{\Phi_i^R}. \tag{32}$$

The joint probability of choosing residence i and workplace j is

$$\pi_{ij} = \frac{T_i T_j\,\Omega_{ij}^{\varepsilon} b_i^{\varepsilon} q_i^{-(1-\beta)\varepsilon}}{\sum_{r \in S}\sum_{s \in S} T_r T_s\,\Omega_{rs}^{\varepsilon} b_r^{\varepsilon} q_r^{-(1-\beta)\varepsilon}}. \tag{33}$$

Hence the residential and employment marginals are

$$\pi_{Ri} = \sum_{j \in S} \pi_{ij}, \qquad \pi_{Mj} = \sum_{i \in S} \pi_{ij}. \tag{34}$$

Since total population is $\bar{H}_R$,

$$H_{Ri} = \bar{H}_R \, \pi_{Ri}, \qquad H_{Mj} = \bar{H}_R \, \pi_{Mj}, \tag{35}$$

where H_{Mj} is the employment level taken as given in the firm problem above.

Final-good firms and mode-specific wages. Final-good firms at location j are perfectly competitive and produce with a Cobb–Douglas technology in labour and commercial floor space, taking the exogenous productivity A_j and the floor space price q_j as given. Car commuters and non-car commuters are perfect substitutes in production, but a car commuter requires a parking spot at the workplace, while a non-car commuter does not. One parking spot occupies ν units of floor space, so the resource cost of commercial parking per car commuter is νq_j, the parking area times the floor space price.

Firms differ in the extent to which they pass this cost on to the workers who generate it, and we index the pricing rule by an exogenously defined parameter $\gamma \in [0, 1]$. A car commuter is charged the fraction γ of the cost of the spot she occupies through a lower wage, while the remaining fraction $1 - \gamma$ is borne by the workforce at j as a whole. Writing w_j for the wage of a non-car commuter, the pricing rule is

$$w_{j,\mathrm{ndr}} = w_j, \qquad w_{j,\mathrm{car}} = w_j - \gamma \, \nu q_j. \tag{36}$$

The two polar cases are *marginal-cost pricing*, $\gamma = 1$, in which each car commuter pays the full cost of her own spot, and *average-cost pricing*, $\gamma = 0$, in which parking is free at the point of use and its cost is spread across all workers at the location.

The two arrangements describe different institutions. Marginal-cost pricing fits workers who park off the employer's premises, the self-employed, and employers who charge explicitly for the days a spot is used; average-cost pricing fits employers who neither ration parking nor charge for it, since with a competitive labour market the average cost of provision is subtracted from every worker's wage (Katz and Mankiw, 1985). The latter is especially relevant where employer-provided parking is not taxed as income, which gives firms an incentive to supply parking without charging users its full cost. Leaving γ free therefore lets the model span both arrangements and ties it to the share of workers who face a price at the margin.

Throughout we treat γ as a single parameter common to all locations. It could be made to depend on the composition of the workforce at j, so that the fraction of the parking bill charged at the margin rises with the share of workers who drive; the derivations below go through unchanged for any γ fixed at the location level.

Let H_{Mj}^{car} and H_{Mj}^{ndr} denote, respectively, the number of car-commuting and non-car-commuting workers hired at j, let $H_{Mj} = H_{Mj}^{\text{ndr}} + H_{Mj}^{\text{car}}$ denote total employment at j, let F_j^F denote the commercial floor space rented, and let

$$s_j \equiv \frac{H_{Mj}^{\text{car}}}{H_{Mj}} \tag{37}$$

denote the share of workers at j who commute by car. Firms can neither screen applicants on their commuting mode nor condition compensation on it beyond the posted charge $\gamma \nu q_j$, so the firm hires undifferentiated labour and takes s_j as given.[9] Firms therefore solve

$$\max_{H_{Mj},\, F_j^F} \Pi_j = A_j H_{Mj}^{\alpha} F_j^{F\,1-\alpha} - w_{j,\text{car}} H_{Mj}^{\text{car}} - w_{j,\text{ndr}} H_{Mj}^{\text{ndr}} - q_j F_j^F - \nu q_j H_{Mj}^{\text{car}}, \qquad H_{Mj}^{\text{car}} = s_j H_{Mj}, \tag{38}$$

subject to the pricing rule above. Let output be

$$Y_j = A_j H_{Mj}^{\alpha} F_j^{F\,1-\alpha}. \tag{39}$$

Substituting the pricing rule, total labour and parking expenditure equals $\left[w_j + (1-\gamma)\nu q_j s_j\right] H_{Mj}$: the firm pays the base wage w_j to every worker and additionally bears the unrecovered share $(1-\gamma)\nu q_j$ of the parking cost for each of the $s_j H_{Mj}$ workers who drive. The first-order condition for labour is therefore

$$\alpha \frac{Y_j}{H_{Mj}} = w_j + (1-\gamma)\, \nu q_j s_j, \tag{40}$$

so that

$$w_j = \alpha \frac{Y_j}{H_{Mj}} - (1-\gamma)\, \nu q_j s_j, \qquad w_{j,\text{car}} = w_j - \gamma\, \nu q_j. \tag{41}$$

A worker who commutes by car therefore forgoes $\gamma \nu q_j$ relative to a colleague who does not, while every worker at j — driver or not — bears $(1-\gamma)\nu q_j s_j$ through a lower base wage. Under marginal-cost pricing the second term vanishes and the car commuter internalises the full cost of her spot. Under average-cost pricing the first term vanishes instead, and employer parking

[9] The assumption is essential: a car commuter costs the firm $w_j + (1-\gamma)\nu q_j$ against w_j for a non-car commuter, so a firm free to choose the composition of its workforce would hire no drivers at all whenever $\gamma < 1$. That firms do not screen on commuting mode is precisely the institutional feature that makes average-cost pricing possible; in equilibrium, s_j coincides with the realised car share of workers employed at j.

becomes a common resource: each driver imposes νq_j on the workforce as a whole and internalises none of it. The first-order condition with respect to floor space is unaffected and gives commercial floor space demand and the wage equation,

$$F_j^F = H_{Mj}\left(\frac{(1-\alpha)A_j}{q_j}\right)^{1/\alpha}, \qquad w_j = \alpha A_j\left(\frac{F_j^F}{H_{Mj}}\right)^{1-\alpha} - (1-\gamma)\,\nu q_j s_j. \tag{42}$$

The floor space requirement per car commuter, ν, and hence the resource cost νq_j of a spot, are independent of γ: the pricing rule governs the incidence of the parking cost, not its magnitude. Total commercial parking floor space νH_{Mj}^{car} does of course respond to γ in equilibrium, since γ shapes the commuting decision through the wedge derived below.

Construction sector and the density of development. We follow the standard approach in the urban literature of assuming that built floor space F is supplied by a competitive construction sector that uses geographic land L and capital K as inputs. Following Ahlfeldt et al. (2015b), we assume that the production function takes the Cobb–Douglas form

$$F_j = K_j^{\mu} L_j^{1-\mu}, \qquad \mu \in (0,1), \tag{43}$$

where μ is the cost share of capital in construction. The corresponding dual cost function for floor space is

$$q_j = \mu^{-\mu}(1-\mu)^{-(1-\mu)}\, p_K^{\mu} R_j^{1-\mu}, \tag{44}$$

where q_j is the price of floor space, p_K is the common price of capital across all locations, and R_j is the price of geographic land. Since the price of capital is the same across all locations, the relationship between the quantities of floor space and geographic land area can be summarised as

$$F_j = \phi_j L_j^{1-\mu}, \tag{45}$$

where $\phi_j = K_j^{\mu}$ captures the *density of development*.

The density of development is treated as an exogenous location characteristic, recovered in the quantification rather than solved for.[10] The supply of built floor space $F_j = \phi_j L_j^{1-\mu}$ is therefore inelastic, and the floor space price q_j clears the floor space market at each location.

[10] Because ϕ_j is treated as a fundamental, the capital input is fixed at $K_j = \phi_j^{1/\mu}$ and the capital first-order condition does not hold at a common p_K, so the dual cost function holds only up to a location-specific factor. We therefore do not impose the further relationship $q_j = \chi R_j^{1-\mu}$, with $\chi \equiv \mu^{-\mu}(1-\mu)^{-(1-\mu)} p_K^{\mu}$, that Ahlfeldt et al. (2015b) use to convert observed land prices into floor space prices: imposing it alongside land market clearing would overdetermine the system, since q_j is already pinned down by floor space market clearing.

Land is likewise supplied inelastically at L_j, so that the land market clears at the rent

$$R_j = (1-\mu)\,\frac{q_j F_j}{L_j}, \tag{46}$$

and land absorbs the share $1-\mu$ of floor space revenue.

Land income and the lump-sum transfer. Each worker holds an equal share of the city-wide land portfolio and therefore receives the uniform lump-sum transfer

$$\bar{T} = \frac{1}{\bar{H}_R}\sum_{j\in S} R_j L_j = \frac{1-\mu}{\bar{H}_R}\sum_{j\in S} q_j F_j, \tag{47}$$

where the second equality follows from land market clearing together with the Cobb–Douglas cost shares of the construction sector derived above. Although $\bar{T}$ is common to all workers and independent of (i, j, m, a), it is not neutral for behaviour: it raises the income base against which the fixed cost of ownership and the cost of parking are evaluated, and therefore shifts both the ownership and the mode margin below.

Returning land rents as a uniform lump sum keeps them inside the economy without attaching them to any of the margins the model is meant to measure, which a rule based on labour income or on the location of residence would not do. The same instrument will carry the revenue of the parking fees introduced in the counterfactuals, so that adding a fee changes only the definition of $\bar{T}$ and leaves every other equilibrium condition intact.

The car share, commercial parking, and employer parking pass-through. The firm problem above takes as given the share s_j of workers at j who commute by car. That share is determined by the choices just derived. The number of car commuters employed at j is

$$H_{Mj}^{\text{car}} = \sum_{i\in S} H_{Ri}\,\pi_{ij|i}\,\pi_{\text{own}|ij}\,\pi_{\text{car}|ij,\text{own}}, \tag{48}$$

the sum over residences of the workers who choose to live at i, work at j, own a car, and then drive. Since each car commuter occupies exactly one spot, commercial parking demand at j coincides with this count, $N_j^{P,F} = H_{Mj}^{\text{car}}$, and the car share is

$$s_j = \frac{H_{Mj}^{\text{car}}}{H_{Mj}} = \frac{N_j^{P,F}}{H_{Mj}} = \frac{1}{H_{Mj}}\sum_{i\in S} H_{Ri}\,\pi_{ij|i}\,\pi_{\text{own}|ij}\,\pi_{\text{car}|ij,\text{own}}. \tag{49}$$

Each firm treats s_j parametrically, since it can neither screen on commuting mode nor price it beyond the posted charge, but in equilibrium the parametric value must coincide with the

realised share implied by workers' residence, ownership, and mode choices.

This closes a loop between the labour market and the commuting problem that is absent from the standard model. The car share determines the base wage w_j through the labour first-order condition; w_j enters ownership-specific income $\bar{W}_{ija}$ and hence the wedge $\delta_{ij,\text{car},\text{own}}$; and the wedge shapes the ownership and mode choices that generate s_j in the first place. The loop operates with strength $1-\gamma$ and is severed entirely under marginal-cost pricing, where $w_j = \alpha Y_j / H_{Mj}$ no longer depends on the car share.

With three distinct shapes, the chain product does not collapse to a single-exponent expression. Using

$$\pi_{ij|i} = \frac{T_j\,\Omega_{ij}^{\varepsilon}}{\Phi_i^R}, \qquad \pi_{\text{own}|ij} = \frac{T_{\text{own}}\,\bar{W}_{ij,\text{own}}^{\lambda} D_{ij,\text{own}}^{-\lambda}}{\Omega_{ij}^{\lambda}}, \qquad \pi_{\text{car}|ij,\text{own}} = \frac{T_{\text{car}}\,\delta_{ij,\text{car},\text{own}}^{\theta} d_{ij,\text{car}}^{-\theta}}{D_{ij,\text{own}}^{-\theta}}, \tag{50}$$

one obtains

$$\pi_{ij|i}\,\pi_{\text{own}|ij}\,\pi_{\text{car}|ij,\text{own}} = \frac{T_j\,T_{\text{own}}\,T_{\text{car}}\,\Omega_{ij}^{\varepsilon-\lambda}\,\bar{W}_{ij,\text{own}}^{\lambda} D_{ij,\text{own}}^{\theta-\lambda}\,\delta_{ij,\text{car},\text{own}}^{\theta}\,d_{ij,\text{car}}^{-\theta}}{\Phi_i^R}. \tag{51}$$

Therefore, commercial parking demand at j is

$$N_j^{P,F} = \sum_{i\in S} \frac{H_{Ri}\,T_j\,T_{\text{own}}\,T_{\text{car}}\,\Omega_{ij}^{\varepsilon-\lambda}\,\bar{W}_{ij,\text{own}}^{\lambda} D_{ij,\text{own}}^{\theta-\lambda}\,\delta_{ij,\text{car},\text{own}}^{\theta}\,d_{ij,\text{car}}^{-\theta}}{\Phi_i^R}. \tag{52}$$

Residential parking demand. Residential parking demand at residential location i depends on ownership rather than on realised commute mode. Hence

$$N_i^{P,R} = H_{Ri} \sum_{j\in S} \pi_{ij|i}\,\pi_{\text{own}|ij}. \tag{53}$$

Using the expressions above,

$$\pi_{ij|i}\,\pi_{\text{own}|ij} = \frac{T_j\,T_{\text{own}}\,\Omega_{ij}^{\varepsilon-\lambda}\,\bar{W}_{ij,\text{own}}^{\lambda} D_{ij,\text{own}}^{-\lambda}}{\Phi_i^R}, \tag{54}$$

and symmetrically for non-owners. Define

$$\Phi_{i,\text{own}}^R \equiv \sum_{j\in S} T_j\,T_{\text{own}}\,\Omega_{ij}^{\varepsilon-\lambda}\,\bar{W}_{ij,\text{own}}^{\lambda} D_{ij,\text{own}}^{-\lambda}, \qquad \Phi_{i,\text{noc}}^R \equiv \sum_{j\in S} T_j\,\Omega_{ij}^{\varepsilon-\lambda}\,\bar{W}_{ij,\text{noc}}^{\lambda} D_{ij,\text{noc}}^{-\lambda}. \tag{55}$$

The identity $\Phi_i^R = \Phi_{i,\text{own}}^R + \Phi_{i,\text{noc}}^R$ continues to hold, because $T_{\text{own}} \bar{W}_{ij,\text{own}}^{\lambda} D_{ij,\text{own}}^{-\lambda} + \bar{W}_{ij,\text{noc}}^{\lambda} D_{ij,\text{noc}}^{-\lambda} = \Omega_{ij}^{\lambda}$ and $\Omega_{ij}^{\varepsilon-\lambda} \cdot \Omega_{ij}^{\lambda} = \Omega_{ij}^{\varepsilon}$. Therefore

$$N_i^{P,R} = H_{Ri} \frac{\Phi_{i,\text{own}}^R}{\Phi_i^R}. \tag{56}$$

Expected realised income. Expected realised income conditional on residence is

$$\mathbb{E}[W_{ijma} \mid i] = \sum_{j \in S} \frac{\pi_{ij}}{\pi_{Ri}} \left[\pi_{\text{noc}|ij} \, \bar{W}_{ij,\text{noc}} + \pi_{\text{own}|ij} \, \bar{W}_{ij,\text{own}} \left(1 - (1 - \delta_{ij,\text{car,own}}) \pi_{\text{car}|ij,\text{own}} \right) \right]. \tag{57}$$

3 General equilibrium definition

Take as given the set of locations S, the set of non-driving modes $\mathcal{B}_{\text{ndr}}$, bilateral travel costs $\{d_{ijm}\}$, fundamentals $\{A_j, b_i, L_j, \phi_j\}$, aggregate population $\bar{H}_R$, and parameters

$$\alpha, \beta, \gamma, \mu, \varepsilon, \lambda, \theta, \varrho, \kappa, \nu, p_{\text{own}}, p_K, \qquad \text{and ASCs} \quad \{T_m\}_{m \in \mathcal{B}_{\text{ndr}}}, \; T_{\text{car}}, \; T_{\text{own}}, \; \{T_i\}_{i \in S}, \; \{T_j\}_{j \in S},$$

with the normalisations $T_{\text{noc}} = T_{\text{ndr}} = T_{\text{pt}} = 1$ and $T_{n_0} = 1$ at both the residence and the workplace layer for a reference location $n_0 \in S$. A general equilibrium is a collection of pair-specific and location-specific endogenous variables such that, for all $i, j \in S$, the following conditions hold. Following the convention of the Environment, location-level objects are written with the generic index j except where the residence end of a commute is specifically meant; since i and j run over the same set S, an object such as $N^{P,R}$ is understood to be evaluated at whichever location is under consideration.

Lower nest. For non-owners,

$$D_{ij,\text{noc}}^{-\theta} = \left(\sum_{m \in \mathcal{B}_{\text{ndr}}} T_m^{1/\varrho} \, d_{ijm}^{-\theta/\varrho} \right)^{\varrho}. \tag{58}$$

For owners,

$$D_{ij,\text{own}}^{-\theta} = T_{\text{car}} \, \delta_{ij,\text{car,own}}^{\theta} d_{ij,\text{car}}^{-\theta} + D_{ij,\text{noc}}^{-\theta}. \tag{59}$$

The car-mode wage wedge satisfies

$$\delta_{ij,\text{car,own}} = 1 - \frac{\gamma \, \nu q_j}{w_j - (p_{\text{own}} + \nu q_i) + \bar{T}}. \tag{60}$$

Land income. The uniform lump-sum transfer satisfies

$$\bar{T} = \frac{1}{\bar{H}_R} \sum_{j \in S} R_j L_j = \frac{1-\mu}{\bar{H}_R} \sum_{j \in S} q_j F_j. \tag{61}$$

Ownership nest. Ownership-specific net incomes are

$$\bar{W}_{ij,\text{noc}} = w_j + \bar{T}, \tag{62}$$

$$\bar{W}_{ij,\text{own}} = w_j - (p_{\text{own}} + \nu q_i) + \bar{T}. \tag{63}$$

Ownership-inclusive value satisfies

$$\Omega_{ij}^{\lambda} = \bar{W}_{ij,\text{noc}}^{\lambda} D_{ij,\text{noc}}^{-\lambda} + T_{\text{own}}\, \bar{W}_{ij,\text{own}}^{\lambda} D_{ij,\text{own}}^{-\lambda}, \tag{64}$$

where $D_{ija}^{-\lambda} = (D_{ija}^{-\theta})^{\lambda/\theta}$. Ownership probabilities are

$$\pi_{\text{own}|ij} = \frac{T_{\text{own}}\, \bar{W}_{ij,\text{own}}^{\lambda} D_{ij,\text{own}}^{-\lambda}}{\Omega_{ij}^{\lambda}}, \tag{65}$$

$$\pi_{\text{noc}|ij} = \frac{\bar{W}_{ij,\text{noc}}^{\lambda} D_{ij,\text{noc}}^{-\lambda}}{\Omega_{ij}^{\lambda}}. \tag{66}$$

Conditional mode choice. The probability that an owner commutes by car is

$$\pi_{\text{car}|ij,\text{own}} = \frac{T_{\text{car}}\, \delta_{ij,\text{car,own}}^{\theta} d_{ij,\text{car}}^{-\theta}}{D_{ij,\text{own}}^{-\theta}}. \tag{67}$$

Upper nest. The residential commuting market access object is

$$\Phi_i^R = \sum_{j \in S} T_j\, \Omega_{ij}^{\varepsilon}. \tag{68}$$

Conditional workplace choice is

$$\pi_{ij|i} = \frac{T_j\, \Omega_{ij}^{\varepsilon}}{\Phi_i^R}. \tag{69}$$

Joint residence–workplace probabilities are

$$\pi_{ij} = \frac{T_i T_j\, b_i^{\varepsilon} q_i^{-(1-\beta)\varepsilon} \Omega_{ij}^{\varepsilon}}{\sum_{r \in S} \sum_{s \in S} T_r T_s\, b_r^{\varepsilon} q_r^{-(1-\beta)\varepsilon} \Omega_{rs}^{\varepsilon}}. \tag{70}$$

Residential and employment marginals.

$$\pi_{Ri} = \sum_{j \in S} \pi_{ij}, \tag{71}$$

$$\pi_{Mj} = \sum_{i \in S} \pi_{ij}. \tag{72}$$

$$H_{Ri} = \bar{H}_R \pi_{Ri}, \tag{73}$$

$$H_{Mj} = \bar{H}_R \pi_{Mj}. \tag{74}$$

Parking demands. Commercial parking demand is

$$N_j^{P,F} = \sum_{i \in S} \frac{H_{Ri}\, T_j\, T_{\text{own}}\, T_{\text{car}}\, \Omega_{ij}^{\varepsilon-\lambda}\, \bar{W}_{ij,\text{own}}^{\lambda}\, D_{ij,\text{own}}^{\theta-\lambda}\, \delta_{ij,\text{car,own}}^{\theta}\, d_{ij,\text{car}}^{-\theta}}{\Phi_i^R}. \tag{75}$$

Residential parking demand is

$$N_i^{P,R} = H_{Ri} \frac{\Phi_{i,\text{own}}^R}{\Phi_i^R}, \tag{76}$$

with

$$\Phi_{i,\text{own}}^R = \sum_{j \in S} T_j\, T_{\text{own}}\, \Omega_{ij}^{\varepsilon-\lambda}\, \bar{W}_{ij,\text{own}}^{\lambda} D_{ij,\text{own}}^{-\lambda}, \tag{77}$$

$$\Phi_{i,\text{noc}}^R = \sum_{j \in S} T_j\, \Omega_{ij}^{\varepsilon-\lambda}\, \bar{W}_{ij,\text{noc}}^{\lambda} D_{ij,\text{noc}}^{-\lambda}, \tag{78}$$

and

$$\Phi_i^R = \Phi_{i,\text{own}}^R + \Phi_{i,\text{noc}}^R. \tag{79}$$

Employer parking pass-through. Each car commuter occupies exactly one commercial parking spot, so $H_{Mj}^{\text{car}} = N_j^{P,F}$ and the car share taken as given by the firm satisfies, in equilibrium,

$$s_j = \frac{N_j^{P,F}}{H_{Mj}}. \tag{80}$$

Construction, land and floor space supply. Given the exogenous density of development ϕ_j, the supply of built floor space is

$$F_j = \phi_j L_j^{1-\mu}, \tag{81}$$

and land market clearing, with land supplied inelastically at L_j, gives the land rent

$$R_j = (1-\mu)\, \frac{q_j F_j}{L_j}, \tag{82}$$

so that land absorbs the share $1-\mu$ of floor space revenue at every location. Floor space supply is inelastic, and q_j is determined by floor space market clearing (88) below.

Floor space block. Commercial parking floor space is

$$F_j^{P,F} = \nu N_j^{P,F}. \tag{83}$$

Residential parking floor space is

$$F_j^{P,R} = \nu N_j^{P,R}. \tag{84}$$

Commercial floor space demand is

$$F_j^F = H_{Mj}\left(\frac{(1-\alpha)A_j}{q_j}\right)^{1/\alpha}. \tag{85}$$

Residential floor space demand is

$$F_j^R = \frac{1-\beta}{q_j} H_{Rj}\,\mathbb{E}[W_{ijma} \mid j], \tag{86}$$

where

$$\mathbb{E}[W_{ijma} \mid j] = \sum_{s\in S} \frac{\pi_{js}}{\pi_{Rj}}\left[\pi_{\text{noc}|js}\,\bar{W}_{js,\text{noc}} + \pi_{\text{own}|js}\,\bar{W}_{js,\text{own}}\left(1-(1-\delta_{js,\text{car,own}})\pi_{\text{car}|js,\text{own}}\right)\right]. \tag{87}$$

Floor space market clearing and build-up shares. Floor space market clearing is

$$F_j = F_j^{P,F} + F_j^{P,R} + F_j^F + F_j^R. \tag{88}$$

Commercial parking share, residential parking share, and total parking share are

$$\iota_j^C = \frac{F_j^{P,F}}{F_j}, \qquad \iota_j^R = \frac{F_j^{P,R}}{F_j}, \qquad \iota_j = \iota_j^C + \iota_j^R. \tag{89}$$

The commercial share in non-parking floor space is

$$\sigma_j = \frac{F_j^F}{F_j^F + F_j^R}, \tag{90}$$

so that $(1-\iota_j)\sigma_j = F_j^F/F_j$ and $(1-\iota_j)(1-\sigma_j) = F_j^R/F_j$.

Wages. The base wage $w_j \equiv w_{j,\text{ndr}}$ received by a non-car commuter, net of the averaged component of employer parking, satisfies

$$w_j = \alpha A_j \left(\frac{F_j^F}{H_{Mj}} \right)^{1-\alpha} - (1-\gamma)\, \nu q_j s_j, \tag{91}$$

or equivalently

$$w_j = \alpha A_j \left(\frac{(1-\iota_j)\sigma_j \phi_j L_j^{1-\mu}}{H_{Mj}} \right)^{1-\alpha} - (1-\gamma)\, \nu q_j s_j, \tag{92}$$

and the wage received by a car commuter is

$$w_{j,\text{car}} = w_j - \gamma\, \nu q_j. \tag{93}$$

Note that neither w_j nor $w_{j,\text{car}}$ is the average wage at j. Writing $\bar{w}_j$ for the employment-weighted average, the two mode-specific wages can be expressed as

$$w_{j,\text{ndr}} = \bar{w}_j + \gamma\, \nu q_j s_j, \qquad w_{j,\text{car}} = \bar{w}_j - \gamma\, \nu q_j (1-s_j), \qquad \bar{w}_j \equiv \alpha A_j \left(\frac{F_j^F}{H_{Mj}} \right)^{1-\alpha} - \nu q_j s_j. \tag{94}$$

The pass-through parameter therefore rotates the wage schedule around $\bar{w}_j$, with the pivot determined by the car share: the total wage bill $\alpha Y_j - \nu q_j N_j^{P,F}$ is invariant to γ, and only its division between drivers and non-drivers responds. The redistribution between the two regimes is proportional to $s_j(1-s_j)$, and therefore vanishes at workplaces where almost all or almost none of the workforce arrives by car.

3.1 Model inversion

To be completed.

4 Structural estimation

The model's three-layer Fréchet structure maps exactly onto a three-level nested logit, making conditional maximum-likelihood estimation tractable (McFadden, 1978; Train, 2009). The key identity is exact: for any Fréchet layer with shape parameter σ, the log-odds between two alternatives equal σ times the log-ratio of their systematic values.[11] The mode layer (shape θ, within-nest correlation ϱ) governs commuting mode given the pair (i, j) and ownership status

[11] This follows from the max-stability of the Fréchet distribution, which makes the maximum over a nest itself Fréchet with the same shape.

a; the ownership layer (shape λ) governs ownership given (i, j), with the mode-level log-sum entering it; and the location layer (shape ε) governs the residence–workplace pair, with the ownership-level log-sum entering in turn.

We estimate the mode and ownership layers by joint maximum likelihood, which is asymptotically more efficient than sequential estimation and avoids carrying generated regressors between the two.[12] The location layer is kept separate: it ranges over all $|S|^2$ residence–workplace pairs, and folding it into the same likelihood would buy little, since it enters only through an inclusive value the lower layers already determine.

The alternative-specific constants estimated below are the scale shifters T_m, T_{car} and T_{own} of the Fréchet shocks, normalised at $T_{\text{pt}} = T_{\text{ndr}} = T_{\text{noc}} = 1$. They are model primitives, so the estimates feed directly into the inclusive values $D_{ij,a}$ and Ω_{ij} and into the counterfactual baseline.

4.1 Identifying variation

Written in log-odds, each layer shows its identifying variation directly, since differencing two alternatives removes the inclusive value.

Within the non-driving nest, differencing mode m against a reference mode m_0 in (22) leaves

$$\log \frac{\pi_{m|ij,a,\text{ndr}}}{\pi_{m_0|ij,a,\text{ndr}}} = \frac{1}{\varrho} \log \frac{T_m}{T_{m_0}} - \frac{\theta\kappa}{\varrho}(\tau_{ijm} - \tau_{ijm_0}). \tag{95}$$

With $m_0 = \text{pt}$, relative travel times across cycling, walking and public transport identify the composite $\theta\kappa/\varrho$, and the intercepts are the structural $\frac{1}{\varrho}\log T_m$. Since $\delta_{ijm,a} = 1$ for every non-driving mode, this margin is shared by owners and non-owners.

Differencing the car branch against the non-driving nest in (20) gives

$$\log \frac{\pi_{\text{car}|ij,\text{own}}}{\pi_{\text{ndr}|ij,\text{own}}} = \log T_{\text{car}} + \theta \log \delta_{ij,\text{car,own}} - \theta\kappa\, \tau_{ij,\text{car}} - \log D_{ij,\text{noc}}^{-\theta}. \tag{96}$$

This is the only margin that separates θ from κ. The parking wedge $\delta_{ij,\text{car,own}} = 1 - \nu q_j / \bar{W}_{ij,\text{own}}$ moves the driving share without moving car travel time, so workplace parking costs and commuting times enter through distinct regressors.[13]

At the ownership layer, differencing (26) and substituting $\bar{W}_{ij,\text{noc}} = w_j$, $\bar{W}_{ij,\text{own}} = w_j -$

[12] Sequential estimation would also be consistent, since each stage's conditional likelihood is correctly specified given the true parameters of the stages below it (McFadden, 1978).

[13] For non-owners the branch is degenerate, $\pi_{\text{ndr}|ij,\text{noc}} = 1$, because the choice set $M(\text{noc}) = \mathcal{B}_{\text{ndr}}$ holds no car option; within that nest they still choose freely among the three non-driving modes.

$(p_{\text{own}} + \nu q_i)$ and $\pi_{\text{ndr}|ij,\text{own}} = (D_{ij,\text{own}}/D_{ij,\text{noc}})^{\theta}$ gives

$$\log \frac{\pi_{\text{own}|ij}}{\pi_{\text{noc}|ij}} = \log T_{\text{own}} + \lambda \log\Big(1 - \frac{p_{\text{own}} + \nu q_i}{w_j}\Big) - \frac{\lambda}{\theta} \log \pi_{\text{ndr}|ij,\text{own}}. \tag{97}$$

The share of income absorbed by ownership and residential parking, $(p_{\text{own}} + \nu q_i)/w_j$, identifies λ, and the intercept is the ownership ASC $\log T_{\text{own}}$. Residential parking costs enter here and nowhere else, which separates the ownership margin from the mode margin.

4.2 Joint maximum likelihood for the mode and ownership layers

Sample and primitives. The full sample: car owners ($a = \text{own}$) face $\mathcal{M}_{ij,\text{own}} = \{\text{car}\} \cup \mathcal{B}_{\text{ndr}}$, non-owners ($a = \text{noc}$) face only $\mathcal{B}_{\text{ndr}}$. The mode-level shocks $\eta_{ijm}(\omega)$ are jointly Fréchet with shape θ: modes in $\mathcal{B}_{\text{ndr}}$ are correlated within-nest at $\varrho \in (0, 1]$, and $\{\text{car}\}$ is a singleton nest. This GEV structure delivers the closed forms below, and it makes θ and ϱ distributional shape parameters, which constrains how they may be optimised over and how their standard errors are formed. The ASCs enter as scale shifters: the marginal scale of η_{ijm} is $(T_{k(m)} T_m)^{1/\theta}$, with the singleton car nest merged into T_{car}.

Choice probabilities. The likelihood uses the choice probabilities in level form, as the model states them. With $d_{ijm} = \exp(\kappa \tau_{ijm})$, define

$$D_{ij,\text{noc}}^{-\theta} \equiv \left(\sum_{m' \in \mathcal{B}_{\text{ndr}}} T_{m'}^{1/\varrho} \, d_{ijm'}^{-\theta/\varrho} \right)^{\varrho}, \qquad D_{ij,\text{own}}^{-\theta} = T_{\text{car}} \, \delta_{ij,\text{car,own}}^{\theta} \, d_{ij,\text{car}}^{-\theta} + D_{ij,\text{noc}}^{-\theta}. \tag{98}$$

Since $\delta_{ijm,a} = 1$ for all $m \in \mathcal{B}_{\text{ndr}}$ regardless of a, the within-nest mode probability is shared and carries no ownership subscript:

$$\pi_{ij}(m \mid \text{ndr}) = \frac{T_m^{1/\varrho} \, d_{ijm}^{-\theta/\varrho}}{\sum_{m' \in \mathcal{B}_{\text{ndr}}} T_{m'}^{1/\varrho} \, d_{ijm'}^{-\theta/\varrho}}, \qquad m \in \mathcal{B}_{\text{ndr}}. \tag{99}$$

The owner branch probabilities are

$$\pi_{ij}(\text{car} \mid \text{own}) = \frac{T_{\text{car}} \, \delta_{ij,\text{car,own}}^{\theta} \, d_{ij,\text{car}}^{-\theta}}{D_{ij,\text{own}}^{-\theta}}, \qquad \pi_{ij}(\text{ndr} \mid \text{own}) = \frac{D_{ij,\text{noc}}^{-\theta}}{D_{ij,\text{own}}^{-\theta}}, \tag{100}$$

and, at the ownership-layer shape λ with $D_{ij,a}^{-\lambda} = (D_{ij,a}^{-\theta})^{\lambda/\theta}$, $\bar{W}_{ij,\text{noc}} = w_j$, $\bar{W}_{ij,\text{own}} = w_j - (p_{\text{own}} + \nu q_i)$ and $T_{\text{noc}} = 1$, the ownership probabilities are

$$\pi_{ij}(\text{own}) = \frac{T_{\text{own}}\, \bar{W}_{ij,\text{own}}^{\lambda} D_{ij,\text{own}}^{-\lambda}}{\bar{W}_{ij,\text{noc}}^{\lambda} D_{ij,\text{noc}}^{-\lambda} + T_{\text{own}}\, \bar{W}_{ij,\text{own}}^{\lambda} D_{ij,\text{own}}^{-\lambda}}, \qquad \pi_{ij}(\text{noc}) = 1 - \pi_{ij}(\text{own}). \tag{101}$$

Terminal probabilities multiply the layers: $P_{ij}(\text{own}, \text{car}) = \pi_{ij}(\text{own})\pi_{ij}(\text{car} \mid \text{own})$, $P_{ij}(\text{own}, m) = \pi_{ij}(\text{own})\pi_{ij}(\text{ndr} \mid \text{own})\pi_{ij}(m \mid \text{ndr})$ and $P_{ij}(\text{noc}, m) = \pi_{ij}(\text{noc})\pi_{ij}(m \mid \text{ndr})$ for $m \in \mathcal{B}_{\text{ndr}}$.

Log-likelihood. Let $N_{ij,\text{car}}^{\text{own}}$, N_{ijm}^{own} and N_{ijm}^{noc} denote owner-car, owner-mode-m and non-owner-mode-m counts at (i, j), with $N_{ij,\text{ndr}}^{\text{own}} \equiv \sum_m N_{ijm}^{\text{own}}$, $N_{ij}^{\text{own}} \equiv N_{ij,\text{car}}^{\text{own}} + N_{ij,\text{ndr}}^{\text{own}}$ and $N_{ij}^{\text{noc}} \equiv \sum_m N_{ijm}^{\text{noc}}$.[14] Weighting the terminal probabilities by these counts and collecting terms,

$$\begin{aligned} \mathcal{L}(\theta, \kappa, \varrho, \lambda, \mathbf{T}) = & \sum_{i,j} \Big[N_{ij}^{\text{own}} \log \pi_{ij}(\text{own}) + N_{ij}^{\text{noc}} \log \pi_{ij}(\text{noc}) \Big] \\ & + \sum_{i,j} \Big[N_{ij,\text{car}}^{\text{own}} \log \pi_{ij}(\text{car} \mid \text{own}) + N_{ij,\text{ndr}}^{\text{own}} \log \pi_{ij}(\text{ndr} \mid \text{own}) \Big] \\ & + \sum_{i,j} \sum_{m \in \mathcal{B}_{\text{ndr}}} (N_{ijm}^{\text{own}} + N_{ijm}^{\text{noc}}) \log \pi_{ij}(m \mid \text{ndr}), \end{aligned} \tag{102}$$

whose three lines are the ownership margin, the owner branch margin and the pooled within-nest margin, the last being where owner and non-owner data combine. The estimator is

$$(\hat{\theta}, \hat{\kappa}, \hat{\varrho}, \hat{\lambda}, \hat{\mathbf{T}}) = \arg \max_{\theta, \kappa, \varrho, \lambda, \mathbf{T}} \mathcal{L}(\theta, \kappa, \varrho, \lambda, \mathbf{T}), \qquad \theta > 0,\ \lambda > 0,\ \varrho \in (0, 1],\ \mathbf{T} > 0, \tag{103}$$

with $\mathbf{T} \equiv (T_{\text{bc}}, T_{\text{wl}}, T_{\text{car}}, T_{\text{own}})$ under $T_{\text{pt}} = T_{\text{ndr}} = T_{\text{noc}} = 1$.

Pooling owners and non-owners sharpens ϱ through the shared within-nest margin, and it is what allows λ to be estimated off the ownership margin, but it adds no identifying variation for θ and κ: those still come only from the owner branch margin in the second line of (102). A workplace-parking reform therefore moves the data through a single margin, and the precision of $\hat{\theta}$ rests on how much independent variation that margin contains.

[14] Because τ_{ijm}, $\delta_{ij,\text{car},\text{own}}$ and $\bar{W}_{ij,a}$ vary only at the (i, j) or (i, j, m) level, individuals sharing (i, j, a) are i.i.d. draws from the same terminal distribution, so (102) is the individual log-likelihood written in cell counts. The equivalence would fail with individual-level regressors, such as income, not already fixed by (i, j, a, m).

4.3 Location choice

At the location layer no differencing is needed, since a residential fixed effect absorbs the denominator directly. The conditional workplace probability implies

$$\log \pi_{ij|i} = \log T_j \; + \; \varepsilon \, \log \Omega_{ij} \; + \; \mathrm{FE}_i, \tag{104}$$

where T_j is the structural workplace ASC, FE_i absorbs $\log \Phi_i^R$, and $\log \Omega_{ij} = \lambda^{-1} \log(\bar{W}_{ij,\mathrm{noc}}^{\lambda} D_{ij,\mathrm{noc}}^{-\lambda} + T_{\mathrm{own}} \bar{W}_{ij,\mathrm{own}}^{\lambda} D_{ij,\mathrm{own}}^{-\lambda})$ is the ownership-level inclusive value, with T_{own} and the mode-level ASCs already inside the $D_{ij,a}$. This is a gravity regression (Monte et al., 2018a): ε is the elasticity of workplace choice with respect to the full commuting access object.

Using $\bar{W}_{ij,\mathrm{noc}} = w_j$ and $\bar{W}_{ij,\mathrm{own}} = w_j(1 - (p_{\mathrm{own}} + \nu q_i)/w_j)$, factoring w_j^{λ} out of the inclusive value isolates the wage:

$$\log \Omega_{ij} = \log w_j + \underbrace{\frac{1}{\lambda} \log\left(D_{ij,\mathrm{noc}}^{-\lambda} + T_{\mathrm{own}} \left[1 - \frac{p_{\mathrm{own}} + \nu q_i}{w_j}\right]^{\lambda} D_{ij,\mathrm{own}}^{-\lambda} \right)}_{h_{ij}}. \tag{105}$$

The term h_{ij} is itself in logs, and it is not free of w_j.[15] Substituting (105) into (104) leaves two additive pieces that vary only with the workplace, $\log T_j$ and $\varepsilon \log w_j$, which a destination fixed effect absorbs together.

The joint-ML estimates $(\hat{\theta}, \hat{\kappa}, \hat{\varrho}, \hat{\lambda}, \hat{\mathbf{T}})$ then deliver

$$\widehat{\Omega}_{ij} = \left(\bar{W}_{ij,\mathrm{noc}}^{\hat{\lambda}} \widehat{D}_{ij,\mathrm{noc}}^{-\hat{\lambda}} + \widehat{T}_{\mathrm{own}} \, \bar{W}_{ij,\mathrm{own}}^{\hat{\lambda}} \widehat{D}_{ij,\mathrm{own}}^{-\hat{\lambda}} \right)^{1/\hat{\lambda}}, \tag{106}$$

which summarises the expected value of commuting between residence i and workplace j, integrating over both the ownership and the mode margin. Location choice is estimated on aggregated residence–workplace flows,

$$\log \pi_{ij|i} = \varepsilon \log \widehat{\Omega}_{ij} + \mathrm{FE}_i + u_{ij}, \tag{107}$$

or equivalently, with destination wages factored out,

$$\log \pi_{ij|i} = \varepsilon \widehat{h}_{ij} + \mathrm{FE}_i + \mathrm{FE}_j + u_{ij}. \tag{108}$$

Because FE_j absorbs $\log T_j + \varepsilon \log w_j$ jointly, the workplace ASC cannot be read off the destina-

[15] Both $(p_{\mathrm{own}} + \nu q_i)/w_j$ and the car wedge $D_{ij,\mathrm{own}}$, through $\delta_{ij,\mathrm{car,own}} = 1 - \nu q_j / \bar{W}_{ij,\mathrm{own}}$, still depend on w_j, q_i and q_j.

tion fixed effect: recovering T_j needs $\hat{\varepsilon}$ and observed wages, and belongs to the model inversion. Since $\widehat{D}_{ij,a}$ and $\widehat{\Omega}_{ij}$ are generated regressors, we bootstrap the two steps jointly, so that the reported standard errors carry the first-stage estimation error.

4.4 Identification strategy

[To be completed.]

5 Counterfactual analysis

[To be completed]

6 Conclusion

[To be completed]

Conflict of interest statement

The authors declare that they have no financial or other interests that give rise to any conflicts of interest with respect to the research described in this paper.

References

Ahlfeldt, G. M., S. J. Redding, D. M. Sturm, and N. Wolf (2015a). "The Economics of Density: Evidence From the Berlin Wall". en. In: *Econometrica* 83.6, pp. 2127–2189. DOI: 10.3982/ECTA10876.

— (2015b). "The Economics of Density: Evidence from the Berlin Wall". In: *Econometrica* 83.6, pp. 2127–2189.

Akbar, P., V. Couture, G. Duranton, and A. Storeygard (2023). "Mobility and congestion in urban India". In: *American Economic Review* 113.4, pp. 1083–1111.

Allen, T. and C. Arkolakis (Nov. 2022). "The Welfare Effects of Transportation Infrastructure Improvements". In: *The Review of Economic Studies* 89.6, pp. 2911–2957. DOI: 10.1093/restud/rdac001.

Almagro, M. and T. Domınguez-Iino (2022). "Location Sorting and Endogenous Amenities: Evidence from Amsterdam". en. In.

Arnott, R. (2013). "A Bathtub Model of Downtown Traffic Congestion". In: *Journal of Urban Economics* 76, pp. 110–121. DOI: 10.1016/j.jue.2013.01.001.

Barwick, P. J., S. Li, A. Waxman, J. Wu, and T. Xia (2024). "Efficiency and Equity Impacts of Urban Transportation Policies with Equilibrium Sorting". In: *American Economic Review* 114.10, pp. 3161–3205. DOI: 10.1257/aer.20220212.

Brueckner, J. K. and S. F. Franco (2017). "Parking and Urban Form". In: *Journal of Economic Geography* 17.1, pp. 95–127. DOI: 10.1093/jeg/lbv048.

— (2018). "Employer-Paid Parking, Mode Choice, and Suburbanization". In: *Journal of Urban Economics* 104, pp. 35–46.

Centraal Bureau voor de Statistiek (2024). *Autobezit per huishouden, 1 januari 2023*. CBS maatwerktabel.

Chester, M., A. Fraser, J. Matute, C. Flower, and R. Pendyala (2015). "Parking Infrastructure: A Constraint on or Opportunity for Urban Redevelopment? A Study of Los Angeles County Parking Supply and Growth". In: *Journal of the American Planning Association* 81.4, pp. 268–286. DOI: 10.1080/01944363.2015.1092879.

Colas, M. and K. Hutchinson (May 2021). "Heterogeneous Workers and Federal Income Taxes in a Spatial Equilibrium". en. In: *American Economic Journal: Economic Policy* 13.2, pp. 100–134. DOI: 10.1257/pol.20180529.

Couture, V., C. Gaubert, J. Handbury, and E. Hurst (Mar. 2024). "Income Growth and the Distributional Effects of Urban Spatial Sorting". In: *The Review of Economic Studies* 91.2, pp. 858–898. DOI: 10.1093/restud/rdad048.

CROW (2013). *ASVV 2021*.

Cutter, W. B. and S. F. Franco (2012). "Do Parking Requirements Significantly Increase the Area Dedicated to Parking? A Test of the Effect of Parking Requirements Values in Los Angeles County". In: *Transportation Research Part A: Policy and Practice* 46.6, pp. 901–925. DOI: 10.1016/j.tra.2012.02.012.

Daganzo, C. F. (2007). "Urban gridlock: macroscopic modeling and mitigation approaches". In: *Transportation Research Part B: Methodological* 41.1, pp. 49–62.

Daganzo, C. F., V. V. Gayah, and E. J. Gonzales (2011). "Macroscopic relations of urban traffic variables: bifurcations, multivaluedness and instability". In: *Transportation Research Part B: Methodological* 45.1, pp. 278–288.

Duranton, G. and D. Puga (2015). "Urban Land Use". In: *Handbook of Regional and Urban Economics*. Ed. by G. Duranton, J. V. Henderson, and W. C. Strange. Vol. 5. Amsterdam: Elsevier. Chap. 8, pp. 467–560. DOI: 10.1016/B978-0-444-59517-1.00008-8.

Eurostat (2024). *Stock of Vehicles at Regional Level*. Statistics Explained.

Fajgelbaum, P. D. and C. Gaubert (May 2020). "Optimal Spatial Policies, Geography, and Sorting*". In: *The Quarterly Journal of Economics* 135.2, pp. 959–1036. DOI: 10.1093/qje/qjaa001.

Fosgerau, M. (2015). "Congestion in the bathtub". In: *Economics of Transportation* 4.4, pp. 241–255.

Franco, S. F. (2017). "Downtown Parking Supply, Work-Trip Mode Choice and Urban Spatial Structure". In: *Transportation Research Part B: Methodological* 101, pp. 107–122. DOI: 10.1016/j.trb.2017.03.012.

Gabbe, C. J. and G. Pierce (2017). "Hidden Costs and Deadweight Losses: Bundled Parking and Residential Rents in the Metropolitan United States". In: *Housing Policy Debate* 27.2, pp. 217–229.

Gaigné, C., H. R. A. Koster, F. Moizeau, and J.-F. Thisse (Mar. 2022). "Who lives where in the city? Amenities, commuting and income sorting". en. In: *Journal of Urban Economics* 128, p. 103394. DOI: 10.1016/j.jue.2021.103394.

Garcia-López, M.-À., I. Pasidis, and E. Viladecans-Marsal (2022). "Congestion in highways when tolls and railroads matter: evidence from European cities". In: *Journal of Economic Geography* 22.5, pp. 931–960.

Glaeser, E. and J. Gyourko (2018). "The Economic Implications of Housing Supply". In: *Journal of Economic Perspectives* 32.1, pp. 3–30.

Groote, J. de, J. van Ommeren, and H. R. Koster (2016). "Car Ownership and Residential Parking Subsidies: Evidence from Amsterdam". In: *Economics of Transportation* 6, pp. 25–37. DOI: 10.1016/j.ecotra.2016.07.001.

Guerra, E., G. Duranton, and X. Ma (2025). "Urban Roadway in America: The Amount, Extent, and Value". In: *Journal of the American Planning Association* 91.1, pp. 102–116. DOI: 10.1080/01944363.2024.2368260.

Heblich, S., S. J. Redding, and D. M. Sturm (2020). "The making of the modern metropolis: Evidence from London". In: *The Quarterly Journal of Economics* 135.4, pp. 2059–2133.

Hendrich, T., H. R. Koster, N. Loumeau, and J. Van Ommeren (Sept. 2026). "Cycling cities: Mode choice, car congestion, and urban structure". en. In: *Journal of Urban Economics*, p. 103906. DOI: 10.1016/j.jue.2026.103906.

Herzog, I. (2024). "The city-wide effects of tolling downtown drivers: Evidence from london's congestion charge". In: *Journal of Urban Economics* 144, p. 103714.

Hoehne, C. G., M. V. Chester, A. M. Fraser, and D. A. King (2019). "Valley of the Sun-Drenched Parking Space: The Growth, Extent, and Implications of Parking Infrastructure in Phoenix". In: *Cities* 89, pp. 186–198. DOI: 10.1016/j.cities.2019.02.007.

Katz, A. and N. G. Mankiw (1985). "How Should Fringe Benefits Be Taxed?" In: *National Tax Journal* 38.1, pp. 37–46.

Kleinman, B., E. Liu, and S. J. Redding (2021). *Dynamic spatial general equilibrium*. Tech. rep. National Bureau of Economic Research.

Levkovich, O., J. Rouwendal, and J. van Ommeren (May 2020). "The impact of highways on population redistribution: the role of land development restrictions". In: *Journal of Economic Geography* 20.3, pp. 783–808. DOI: 10.1093/jeg/lbz003.

Manville, M. and D. Shoup (2005). "Parking, People, and Cities". In: *Journal of Urban Planning and Development* 131.4, pp. 233–245. DOI: 10.1061/(ASCE)0733-9488(2005)131:4(233).

McFadden, D. (1978). "Modelling the Choice of Residential Location". In: *Cowles Foundation Discussion Papers*.

Mingardo, G., B. van Wee, and T. Rye (2015). "Urban parking policy in Europe: A conceptualization of past and possible future trends". In: *Transportation Research Part A: Policy and Practice* 74, pp. 268–281.

Monte, F., S. J. Redding, and E. Rossi-Hansberg (2018a). "Commuting, Migration, and Local Employment Elasticities". In: *American Economic Review* 108.12, pp. 3855–3890. DOI: 10.1257/aer.20151507.

Monte, F., S. J. Redding, and E. Rossi-Hansberg (Dec. 2018b). "Commuting, Migration, and Local Employment Elasticities". en. In: *American Economic Review* 108.12, pp. 3855–3890. DOI: 10.1257/aer.20151507.

Ommeren, J. van, J. de Groote, and G. Mingardo (2014a). "Residential Parking Permits and Parking Supply". In: *Regional Science and Urban Economics* 45, pp. 33–44. DOI: 10.1016/j.regsciurbeco.2013.11.003.

Ommeren, J. van, J. de Groote, and G. Mingardo (2014b). "Residential parking permits and parking supply". In: *Regional Science and Urban Economics* 45, pp. 33–44.

Ommeren, J. van, D. Wentink, and J. Dekkers (2011). "The Real Price of Parking Policy". In: *Journal of Urban Economics* 70.1, pp. 25–31. DOI: 10.1016/j.jue.2011.02.005.

Ostermeijer, F., H. R. A. Koster, L. Nunes, and J. van Ommeren (2022). "Citywide parking policy and traffic: Evidence from Amsterdam". In: *Journal of Urban Economics* 128, pp. 1–15.

Ostermeijer, F., H. R. A. Koster, and J. van Ommeren (2019a). "Residential parking costs and car ownership: Implications for parking policy and automated vehicles". In: *Regional Science and Urban Economics* 77, pp. 276–288.

— (2019b). "Residential parking costs and car ownership: Implications for parking policy and automated vehicles". In: *Regional Science and Urban Economics* 77.

Proost, S. and J.-F. Thisse (2019). "What Can Be Learned from Spatial Economics?" In: *Journal of Economic Literature* 57.3, pp. 575–643. DOI: 10.1257/jel.20181414.

Redding, S. J. (May 2023). "Quantitative Urban Models: From Theory to Data". en. In: *Journal of Economic Perspectives* 37.2, pp. 75–98. DOI: 10.1257/jep.37.2.75.

Redding, S. J. and E. Rossi-Hansberg (2017). "Quantitative Spatial Economics". In: *Annual Review of Economics* 9.1, pp. 21–58. DOI: 10.1146/annurev-economics-063016-103713.

Severen, C. (Sept. 2023). "Commuting, Labor, and Housing Market Effects of Mass Transportation: Welfare and Identification". In: *The Review of Economics and Statistics* 105.5, pp. 1073–1091. DOI: 10.1162/rest_a_01100.

Shoup, D. C. (2005). *The High Cost of Free Parking*. Chicago: Planners Press, American Planning Association.

Teulings, C. N., I. V. Ossokina, and H. L. de Groot (Jan. 2018). "Land use, worker heterogeneity and welfare benefits of public goods". en. In: *Journal of Urban Economics* 103, pp. 67–82. DOI: 10.1016/j.jue.2017.10.004.

Train, K. (2009). *Discrete Choice Methods with Simulation*. en. Cambridge University Press.

Tsivanidis, N. (Feb. 2026). "Evaluating the Impact of Urban Transit Infrastructure: Evidence from Bogotá's TransMilenio". In: *American Economic Review* 116.2, pp. 418–63. DOI: 10.1257/aer.20190874.

Yang, J., A.-O. Purevjav, and S. Li (2020). "The marginal cost of traffic congestion and road pricing: evidence from a natural experiment in Beijing". In: *American Economic Journal: Economic Policy* 12.1, pp. 418–453.

Zax, J. S. (Nov. 1988). "Fringe benefits, income tax exemptions, and implicit subsides". en. In: *Journal of Public Economics* 37.2, pp. 171–183. DOI: 10.1016/0047-2727(88)90069-2.