The Quantitative Evaluation of Urban Transport Infrastructure Improvements[*]

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Abstract

Transport infrastructure investments are among the largest items on government budgets and their effects on the spatial organization of economic activity are central to a host of public policy issues. Existing approaches to the evaluation of these investments typically involve quasi-experimental reduced-form regressions, partial equilibrium cost-benefit analyses or mechanical input-output relationships combined with assumptions about the evolution of macroeconomic variables. In contrast, we develop a quantitative general equilibrium framework for the evaluation of transport infrastructure improvements. Our framework is sufficiently rich as to capture first-order features of the data, such as many locations that differ in characteristics and observed transport networks. Yet our framework remains parsimonious and tractable enough to permit transparent model-based counterfactuals. We illustrate the applicability of our approach with an analysis of the U5 underground line in Berlin that is currently under construction.

Keywords: agglomeration, cities, commuting, density, gravity, transportation

JEL: N34, O18, R12

Preliminary and Incomplete

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1 Introduction

The organization of economic activity within cities is crucially dependent on the transportation of people. To take just one example, the London Underground handles around 3.5 million passenger journeys per day, and its trains travel around 76 million kilometers each year (200 times the distance between the earth and the moon). Furthermore, the provision of this transport infrastructure within cities typically involves public policy intervention, whether through the direct management of services, or through explicit or implicit subsidies for the construction and operation of transport infrastructure. Indeed, funding for transport infrastructure projects is often a major item in local government budgets. To continue with our example, Transport for London had an annual operating expenditure of around £6 billion in 2014-15. Of this expenditure, around £1.7 billion was funded through direct government grants, with most of the remainder funded by charges to transportation users. While these figures relative only to operating expenditures, the investment program for Transport for London equalled around £1.7 billion over the same period.[1]

Despite the large sums of public money involved, the economic evaluation of transport infrastructure improvements is subject to both theoretical and empirical challenges. From an empirical point of view, transport infrastructure is not randomly assigned, and a growing empirical literature has sought to make use of quasi-experimental variation to address this endogeneity concern. While this literature estimates local average treatment effects of transport infrastructure on treatment relative to control locations, its focus on relative comparisons makes it hard to identify general equilibrium effects and to distinguish reallocation from the creation of new economic activity. From a theoretical perspective, to develop tractable general equilibrium models of cities, the existing literature typically makes simplifying assumptions such as monocentricity or symmetry, which limits the usefulness of these models for empirical work. Consequently, theoretical evaluations of transport infrastructure improvements often adopt partial equilibrium cost-benefit approaches or combine mechanical input-output relationships with assumptions about the evolution of macroeconomic variables.

In this paper, we develop a quantitative framework for undertaking counterfactuals for the general equilibrium impact of transport infrastructure improvements. Our framework is sufficiently rich as to capture first-order features of the data, such as many locations that differ in locational fundamentals. Yet our framework remains parsimonious and tractable enough to permit transparent model-based counterfactuals. Locations differ in terms of their productivity, amenities, density of development (the ratio of floor area to ground area), and access to transport infrastructure. Productivity depends on production externalities, which are increasing in the surrounding density of employment, and production fundamentals, such as topography and proximity to natural supplies of water. Amenities depend on residential extranalities, which are increasing in the surrounding density of residents, and residential fundamentals, such as access to forests and lakes. Congestion forces take the form of an inelastic supply of land and commuting costs that are increasing in travel time, where travel time in turn depends on the transport infrastructure network.

Our paper relates to the reduced-form empirical literature has examined the relationship between economic

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[1]The figures for the London Underground and Transport for London are taken from https://www.tfl.gov.uk/corporate/about-tfl/what-we-do/london-underground/facts-and-figures, Transport for London (2013) and Transport for London (2014).

activity and transport infrastructure, including Donaldson (2014), Baum-Snow (2007), Duranton and Turner (2012), Faber (2014), Gibbons and Machin (2005), McDonald and Osuji (1995) and Michaels (2008). The main focus of this line of research has been the use of quasi-experimental variation in transport infrastructure to estimate the average impact on treated locations relative to untreated locations. In contrast, we use a structural model of economic geography to highlight general equilibrium effects, reallocation versus the creation of new economic activity and heterogeneous treatment effects among treated and untreated locations depending on the structure of the transport infrastructure network.

The remainder of the paper is structured as follows. Section 2 introduces our theoretical framework. Section 4 shows how the model can be calibrated to the data. Section 5 uses the model to undertake counterfactuals for transport improvements and shows how the results of these counterfactuals depend on the model parameters. Section 6 concludes.

2 Theoretical Model

We use the model of internal city structure of Ahlfeldt, Redding, Sturm, and Wolf (2014) to develop a framework for the quantitative evaluation of urban transport infrastructure improvements. In the model the internal structure of the city is driven by a tension between agglomeration forces (in the form of production and residential externalities) and dispersion forces (in the form of commuting costs and an inelastic supply of land).[2] The model allows for a large number of locations that can differ from one another in productivity, amenities and access to transport infrastructure. Despite allowing for many asymmetric locations, the model remains sufficiently tractable as to be amenable to quantitative analysis, and can be fitted to detailed data on the spatial distribution of economic activity within cities.

We consider a city embedded within a wider economy. The city consists of a set of discrete locations or blocks, which are indexed by $i = 1, ..., S$. The city is populated by an endogenous measure of H workers, who are perfectly mobile within the city and larger economy. Each block has an effective supply of floor space L_i. Floor space can be used commercially or residentially, and we denote the endogenous fractions of floor space allocated to commercial and residential use by θ_i and $1 - \theta_i$, respectively.

Workers decide whether or not to move to the city before observing idiosyncratic utility shocks for each possible pair of residence and employment locations within the city. If a worker decides to move to the city, they observe these realizations for idiosyncratic utility, and pick the pair of residence and employment locations within the city that maximizes their utility. Population mobility between the city and the wider economy implies that the expected utility from moving to the city equals the reservation level of utility in the wider economy $\bar{U}$. Firms produce a single final good, which is costlessly traded within the city and larger economy, and is chosen as the numeraire ($p = 1$). [3]

Locations differ in terms of their final goods productivity, residential amenities, supply of floor space and

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[2]A more detailed discussion of the model and the technical derivations of all expressions and results reported in this section are contained in a separate web appendix.

[3]We follow the canonical urban model in assuming a single tradable final good and examine the ability of this canonical model to account quantitatively for the observed impact of division and reunification. In the web appendix, we discuss an extension of the model to introduce a non-traded good.

access to the transport network, which determines travel times between any two locations in the city. We first develop the model with exogenous values of these location characteristics, before introducing endogenous agglomeration forces below.

2.1 Workers

Workers are risk neutral and have preferences that are linear in an aggregate consumption index: $U_{ij\omega} = C_{ij\omega}$, where $C_{ij\omega}$ denotes the aggregate consumption index for worker ω residing in block i and working in block j.[4] This aggregate consumption index depends on consumption of the single final good ($c_{ij\omega}$), consumption of residential floor space ($\ell_{ij\omega}$), and three other components. First, residential amenities (B_i) that capture common characteristics that make a block a more or less attractive place to live (e.g. leafy streets and scenic views). Second, the disutility from commuting from residence block i to workplace block j ($d_{ij} \geq 1$). Third, there is an idiosyncratic shock that is specific to individual workers and varies with the worker's blocks of employment and residence ($z_{ij\omega}$). This idiosyncratic shock captures the idea that individual workers can have idiosyncratic reasons for living and working in different parts of the city. In particular, the aggregate consumption index is assumed to take the Cobb-Douglas form:[5]

$$C_{ij\omega} = \frac{B_i z_{ij\omega}}{d_{ij}} \left(\frac{c_{ij\omega}}{\beta}\right)^{\beta} \left(\frac{\ell_{ij\omega}}{1-\beta}\right)^{1-\beta}, \qquad 0 < \beta < 1, \tag{1}$$

where the iceberg commuting cost $d_{ij} = e^{\kappa \tau_{ij}} \in [1, \infty)$ increases with the travel time between blocks i and j (τ_{ij}). Travel time is measured in minutes and is computed based on the transport network, as discussed further in the data section (Section **??**). The parameter κ controls the size of commuting costs. Although we model commuting costs in terms of utility, there is an isomorphic formulation in terms of a reduction in effective units of labor, because the iceberg commuting cost $d_{ij} = e^{\kappa \tau_{ij}}$ enters the indirect utility function (3) below multiplicatively. As a result, commuting costs are proportional to wages, and hence this specification captures changes over time in the opportunity cost of travel time.

We model the heterogeneity in the utility that workers derive from living and working in different parts of the city following McFadden (1974) and Eaton and Kortum (2002). For each worker ω living in block i and commuting to block j, the idiosyncratic component of utility ($z_{ij\omega}$) is drawn from an independent Fréchet distribution:

$$F(z_{ij\omega}) = e^{-T_i E_j z_{ij\omega}^{-\epsilon}}, \qquad T_i, E_j > 0, \ \epsilon > 1, \tag{2}$$

where the scale parameter $T_i > 0$ determines the average utility derived from living in block i; the scale parameter E_j determines the average utility derived from working in block j; and the shape parameter $\epsilon > 1$ controls the dispersion of idiosyncratic utility.

After observing her realizations for idiosyncratic utility for each pair of residence and employment locations, each worker chooses her blocks of residence and employment to maximize her utility, taking as given res-

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[4]To simplify the exposition, throughout the paper, we index a worker's block of residence by i or r and her block of employment by j or s unless otherwise indicated.

[5]For empirical evidence using US data in support of the constant housing expenditure share implied by the Cobb-Douglas functional form, see Davis and Ortalo-Magné (2011). The role played by residential amenities in influencing utility is emphasized in the literature following Roback (1982). See Albouy (2008) for a recent prominent contribution.

idential amenities, goods prices, factor prices, and the location decisions of other workers and firms. Therefore workers sort across pairs of residence and employment locations depending on their idiosyncratic preferences and the characteristics of these locations. The indirect utility from residing in block i and working in block j can be expressed in terms of wages at the block of employment (w_j), commuting costs (d_{ij}), residential floor prices (Q_i), and the common (B_i) and idiosyncratic ($z_{ij\omega}$) components of amenities:[6]

$$u_{ij\omega} = \frac{z_{ij\omega} B_i w_j Q_i^{\beta-1}}{d_{ij}}, \tag{3}$$

where we have used utility maximization and the choice of the final good as numeraire.

Since indirect utility is a monotonic function of the idiosyncratic shock ($z_{ij\omega}$), which has a Fréchet distribution, it follows immediately that indirect utility for workers living in block i and working in block j also has a Fréchet distribution. Each worker chooses the bilateral commute that offers her the maximum utility, where the maximum of a sequence of Fréchet distributed random variables is itself Fréchet distributed. Using these bilateral and multilateral distributions of utility, the probability that a worker chooses to live in block i and work in block j is:

$$\pi_{ij} = \frac{T_i E_j \left(d_{ij} Q_i^{1-\beta} \right)^{-\epsilon} (B_i w_j)^\epsilon}{\sum_{r=1}^S \sum_{s=1}^S T_r E_s \left(d_{rs} Q_r^{1-\beta} \right)^{-\epsilon} (B_r w_s)^\epsilon} \equiv \frac{\Phi_{ij}}{\Phi}. \tag{4}$$

Summing these probabilities across workplaces for a given residence, we obtain the overall probability that a worker resides in block i (π_{Ri}), while summing these probabilities across residences for a given workplace, we obtain the overall probability that a worker works in block j (π_{Mi}):

$$\pi_{Ri} = \sum_{j=1}^S \pi_{ij} = \frac{\sum_{j=1}^S \Phi_{ij}}{\Phi}, \qquad \pi_{Mj} = \sum_{i=1}^S \pi_{ij} = \frac{\sum_{i=1}^S \Phi_{ij}}{\Phi}. \tag{5}$$

These residential and workplace choice probabilities have an intuitive interpretation. The idiosyncratic shock to preferences $z_{ij\omega}$ implies that individual workers choose different bilateral commutes when faced with the same prices $\{Q_i, w_j\}$, commuting costs $\{d_{ij}\}$ and location characteristics $\{B_i, T_i, E_j\}$. Other things equal, workers are more likely to live in block i, the more attractive its amenities B_i, the higher its average idiosyncratic utility as determined by T_i, the lower its residential floor prices Q_i, and the lower its commuting costs d_{ij} to employment locations. Other things equal, workers are more likely to work in block j, the higher its wage w_j, the higher its average idiosyncratic utility as determined by E_j, and the lower its commuting costs d_{ij} from residential locations.

As discussed above, although we interpret the idiosyncratic shock as affecting utility, there is an isomorphic interpretation of the model in which the idiosyncratic shock applies to effective units of labor (since $z_{ij\omega}$ enters multiplicatively with w_j in (3)). Therefore the endogenous sorting of workers across locations implies that both residence and employment locations differ in the composition of workers in terms of idiosyncratic draws for utility or effective units of labor. Residential locations with higher values of T_i have higher average draws

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[6]We make the standard assumption in the urban literature that income from land is accrued by absentee landlords and not spent within the city, although it is also possible to consider the case where it is redistributed lump sum to workers.

of utility (or effective units of labor). Similarly, employment locations with higher values of E_j have higher average draws of utility (or effective units of labor). To ensure that the general equilibrium of the model remains tractable, and because we do not observe worker characteristics in our data, we abstract from other dimensions of worker heterogeneity besides the idiosyncratic shock to preferences or effective units of labor.

These residential and workplace choice probabilities imply a gravity equation for bilateral commuting flows. Conditional on living in block i, the probability that a worker commutes to block j is:

$$\pi_{ij|i} = \frac{E_j \left(w_j/d_{ij}\right)^{\epsilon}}{\sum_{s=1}^{S} E_s \left(w_s/d_{is}\right)^{\epsilon}}, \tag{6}$$

where terms in $\{Q_i, T_i, B_i\}$ have cancelled from the numerator and denominator. Therefore the probability of commuting to block j conditional on living in block i depends on the wage (w_j), average utility draw (E_j) and commuting costs (d_{ij}) of employment location j in the numerator ("bilateral resistance") as well as the wage (w_s), average utility draw (E_s) and commuting costs (d_{is}) for all other possible employment locations s in the denominator ("multilateral resistance").

Using these conditional commuting probabilities, we obtain the following commuting market clearing condition that equates the measure of workers employed in block j (H_{Mj}) with the measure of workers choosing to commute to block j:

$$H_{Mj} = \sum_{i=1}^{S} \frac{E_j \left(w_j/d_{ij}\right)^{\epsilon}}{\sum_{s=1}^{S} E_s \left(w_s/d_{is}\right)^{\epsilon}} H_{Ri}, \tag{7}$$

where H_{Ri} is the measure of residents in block i. Since there is a continuous measure of workers residing in each location, there is no uncertainty in the supply of workers to each employment location. Our formulation of workers' commuting decisions implies that the supply of commuters to each employment location j in (7) is a continuously increasing function of its wage relative to other locations.[7]

Expected worker income conditional on living in block i is equal to the wages in all possible employment locations weighted by the probabilities of commuting to those locations conditional on living in i:

$$\mathbb{E}\left[w_s|i\right] = \sum_{s=1}^{S} \frac{E_s \left(w_s/d_{is}\right)^{\epsilon}}{\sum_{r=1}^{S} E_r \left(w_r/d_{ir}\right)^{\epsilon}} w_s, \tag{8}$$

Therefore expected worker income is high in blocks that have low commuting costs (low d_{is}) to high-wage employment locations.[8]

Finally, population mobility implies that the expected utility from moving to the city is equal to the reservation level of utility in the wider economy ($\bar{U}$):

$$\mathbb{E}\left[u\right] = \gamma \left[\sum_{r=1}^{S}\sum_{s=1}^{S} T_r E_s \left(d_{rs}Q_r^{1-\beta}\right)^{-\epsilon} \left(B_r w_s\right)^{\epsilon}\right]^{1/\epsilon} = \bar{U}, \tag{9}$$

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[7]This feature of the model is not only consistent with the gravity equation literature on commuting flows discussed above but also greatly simplifies the quantitative analysis of the model. In the absence of heterogeneity in worker productivity, small changes in wages can induce all workers residing in one location to start or stop commuting to another location, which is both empirically implausible and complicates the determination of general equilibrium with asymmetric locations.

[8]For simplicity, we model agents and workers as synonymous, which implies that labor is the only source of income. More generally, it is straightforward to extend the analysis to introduce families, where each worker has a fixed number of dependents that consume but do not work, and/or to allow agents to have a constant amount of non-labor income.

where $\mathbb{E}$ is the expectations operator and the expectation is taken over the distribution for the idiosyncratic component of utility; $\gamma = \Gamma\left(\frac{\epsilon-1}{\epsilon}\right)$ and $\Gamma(\cdot)$ is the Gamma function.

2.2 Production

We follow the canonical urban model in assuming a single final good that is costlessly traded within the city and the larger economy. Final goods production occurs under conditions of perfect competition and constant returns to scale. For simplicity, we assume that the production technology takes the Cobb-Douglas form, so that output of the final good in block j (y_j) is:

$$y_j = A_j H_{Mj}^{\alpha} L_{Mj}^{1-\alpha}, \tag{10}$$

where A_j is final goods productivity and L_{Mj} is the measure of floor space used commercially.

Firms choose their block of production and their inputs of workers and commercial floor space to maximize profits, taking as given final goods productivity A_j, the distribution of idiosyncratic utility, goods and factor prices, and the location decisions of other firms and workers. Profit maximization implies that equilibrium employment is increasing in productivity (A_j), decreasing in the wage (w_j), and increasing in commercial floor space (L_{Mj}):

$$H_{Mj} = \left(\frac{\alpha A_j}{w_j}\right)^{\frac{1}{1-\alpha}} L_{Mj}, \tag{11}$$

where the equilibrium wage is determined by the requirement that the demand for workers in each employment location (11) equals the supply of workers choosing to commute to that location (7).

From the first-order conditions for profit maximization and the requirement that zero profits are made if the final good is produced, equilibrium commercial floor prices (q_j) in each block with positive employment must satisfy:

$$q_j = (1-\alpha)\left(\frac{\alpha}{w_j}\right)^{\frac{\alpha}{1-\alpha}} A_j^{\frac{1}{1-\alpha}}. \tag{12}$$

Intuitively, firms in blocks with higher productivity (A_j) and/or lower wages (w_j) are able to pay higher commercial floor prices and still make zero profits.

2.3 Land Market Clearing

Land market equilibrium requires no-arbitrage between the commercial and residential use of floor space after taking into account the tax equivalent of land use regulations. The share of floor space used commercially (θ_i) is:

$$\begin{aligned} \theta_i &= 1 & \text{if} \quad q_i > \xi_i Q_i, \\ \theta_i &= 0 & \text{if} \quad q_i < \xi_i Q_i, \\ \theta_i &\in [0,1] & \text{if} \quad q_i = \xi_i Q_i, \end{aligned} \tag{13}$$

where $\xi_i \geq 1$ captures one plus the tax equivalent of land use regulations that restrict commercial land use relative to residential land use. We allow this wedge between commercial and residential floor prices to vary across blocks.

Therefore floor space in each block is either allocated entirely to commercial use ($q_i > \xi_i Q_i$ and $\theta_i = 1$), allocated entirely to residential use ($q_i < \xi_i Q_i$ and $\theta_i = 0$), or allocated to both uses ($q_i = \xi_i Q_i$ and $\theta_i \in (0,1)$). We assume that the observed price of floor space in the data is the maximum of the commercial and residential price of floor space: $\mathbb{Q}_i = \max\{q_i, Q_i\}$. Hence the relationship between observed, commercial and residential floor prices can be summarized as:

$$
\begin{aligned}
\mathbb{Q}_i &= q_i, & q_i > \xi_i Q_i, & \quad \theta_i = 1, \\
\mathbb{Q}_i &= q_i, & q_i = \xi_i Q_i, & \quad \theta_i \in (0,1), \\
\mathbb{Q}_i &= Q_i, & q_i < \xi_i Q_i, & \quad \theta_i = 0.
\end{aligned}
\tag{14}
$$

We follow the standard approach in the urban literature of assuming that floor space L is supplied by a competitive construction sector that uses geographic land K and capital M as inputs. Following Combes, Duranton, and Gobillon (2014) and Epple, Gordon, and Sieg (2010), we assume that the production function takes the Cobb-Douglas form: $L_i = M_i^\mu K_i^{1-\mu}$.[9] Therefore the corresponding dual cost function for floor space is $\mathbb{Q}_i = \mu^{-\mu}(1-\mu)^{-(1-\mu)}\mathbb{P}^\mu \mathbb{R}_i^{1-\mu}$, where $\mathbb{Q}_i = \max\{q_i, Q_i\}$ is the price for floor space, $\mathbb{P}$ is the common price for capital across all blocks, and $\mathbb{R}_i$ is the price for geographic land. Since the price for capital is the same across all locations, the relationships between the quantities and prices of floor space and geographical land area can be summarized as:

$$
L_i = \varphi_i K_i^{1-\mu}
\tag{15}
$$

$$
\mathbb{Q}_i = \chi \mathbb{R}_i^{1-\mu},
\tag{16}
$$

where $\varphi_i = M_i^\mu$ captures the density of development and χ is a constant.

Residential land market clearing implies that the demand for residential floor space equals the supply of floor space allocated to residential use in each location: $(1-\theta_i)L_i$. Using utility maximization for each worker and taking expectations over the distribution for idiosyncratic utility, this residential land market clearing condition can be expressed as:

$$
\mathbb{E}\left[\ell_i\right] H_{Ri} = (1-\beta)\frac{\mathbb{E}\left[w_s | i\right] H_{Ri}}{Q_i} = (1-\theta_i)L_i.
\tag{17}
$$

Commercial land market clearing requires that the demand for commercial floor space equals the supply of floor space allocated to commercial use in each location: $\theta_j L_j$. Using the first-order conditions for profit maximization, this commercial land market clearing condition can be written as:

$$
\left(\frac{(1-\alpha)A_j}{q_j}\right)^{\frac{1}{\alpha}} H_{Mj} = \theta_j L_j.
\tag{18}
$$

When both residential and commercial land market clearing ((17) and (18) respectively) are satisfied, total demand for land equals the total supply of land:

$$
(1-\theta_i)L_i + \theta_i L_i = L_i = \varphi_i K_i^{1-\mu}.
\tag{19}
$$

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[9]Empirically, we find that this Cobb-Douglas assumption provides a good approximation to confidential micro data on property transactions for Berlin that are available from 2000-2012.

2.4 General Equilibrium with Exogenous Location Characteristics

We begin by characterizing the properties of a benchmark version of the model in which location characteristics are exogenous, before relaxing this assumption to introduce endogenous agglomeration forces below. Throughout the following we use bold math font to denote vectors. Given the model's parameters $\{\alpha, \beta, \mu, \epsilon, \kappa\}$, the reservation level of utility in the wider economy $\bar{U}$ and vectors of exogenous location characteristics $\{\boldsymbol{T}, \boldsymbol{E}, \boldsymbol{A}, \boldsymbol{B}, \boldsymbol{\varphi}, \boldsymbol{K}, \xi, \boldsymbol{\tau}\}$, the general equilibrium of the model is referenced by the six vectors $\{\boldsymbol{\pi_M}, \boldsymbol{\pi_R}, \boldsymbol{Q}, \boldsymbol{q}, \boldsymbol{w}, \boldsymbol{\theta}\}$ and total city population H. These seven components of the equilibrium vector are determined by the following system of seven equations: population mobility (9), the residential choice probability (π_{Ri} in (5)), the workplace choice probability (π_{Mj} in (5)), commercial land market clearing (18), residential land market clearing (17), profit maximization and zero profits (12), and no-arbitrage between alternative uses of land (13).

Proposition 1 *Assuming exogenous, finite and strictly positive location characteristics ($T_i \in (0, \infty)$, $E_i \in (0, \infty)$, $\varphi_i \in (0, \infty)$, $K_i \in (0, \infty)$, $\xi_i \in (0, \infty)$, $\tau_{ij} \in (0, \infty) \times (0, \infty)$), and exogenous finite and non-negative final goods productivity $A_i \in [0, \infty)$ and residential amenities $B_i \in [0, \infty)$, there exists a unique general equilibrium vector $\{\boldsymbol{\pi_M}, \boldsymbol{\pi_R}, H, \boldsymbol{Q}, \boldsymbol{q}, \boldsymbol{w}, \boldsymbol{\theta}\}$.*

Proof. See Ahlfeldt, Redding, Sturm, and Wolf (2014). ∎

In this case of exogenous location characteristics, the distribution of workers and residents across locations is determined by exogenous differences in productivity A_i and amenities B_i combined with the model's dispersion forces of commuting costs, diminishing marginal returns to commercial land use, and diminishing marginal returns to residential land use. These dispersion forces ensure the existence of a unique distribution of economic activity.

We establish a number of properties of the general equilibrium with exogenous location characteristics in the web appendix. Since the support of the Fréchet distribution is unbounded from above, all blocks with strictly positive amenities (B_i) attract a strictly positive measure of residents (H_{Ri}), and all blocks with strictly positive wages (w_j) attract a strictly positive measure of employment (H_{Mj}). Therefore, if all location characteristics $\{\boldsymbol{T}, \boldsymbol{E}, \boldsymbol{A}, \boldsymbol{B}, \boldsymbol{\varphi}, \boldsymbol{K}, \boldsymbol{\xi}, \boldsymbol{\tau}\}$ are exogenous, finite and strictly positive, all locations have positive residents and employment, and are incompletely specialized between commercial and residential land use. Furthermore, assuming that all other location characteristics $\{\boldsymbol{T}, \boldsymbol{E}, \boldsymbol{\varphi}, \boldsymbol{K}, \boldsymbol{\xi}, \boldsymbol{\tau}\}$ are exogenous, finite and strictly positive, a necessary and sufficient condition for zero residents is $B_i = 0$. Similarly, a necessary and sufficient condition for zero employment is $w_j = 0$, which in turn requires zero final goods productivity $A_j = 0$. Therefore the model rationalizes zero workplace employment with zero productivity (A_i) and zero residence employment with zero amenities (B_i).

2.5 Introducing Agglomeration Forces

Having established the properties of the model with exogenous location characteristics, we now introduce endogenous agglomeration forces. We allow final goods productivity to depend on production fundamentals (a_j) and production externalities (Υ_j). Production fundamentals capture features of physical geography that

make a location more or less productive independently of the surrounding density of economic activity (for example access to natural water). Production externalities impose structure on how the productivity of a given block is affected by the characteristics of other blocks. Specifically, we follow the standard approach in urban economics of modeling these externalities as depending on the travel-time weighted sum of workplace employment density in surrounding blocks:[10]

$$A_j = a_j \Upsilon_j^\lambda, \qquad \Upsilon_j \equiv \sum_{s=1}^S e^{-\delta\tau_{js}} \left(\frac{H_{Ms}}{K_s} \right), \qquad \lambda \geq 0, \delta \geq 0. \tag{20}$$

where H_{Ms}/K_s is workplace employment density per unit of geographical land area; production externalities decline with travel time (τ_{js}) through the iceberg factor $e^{-\delta\tau_{js}} \in (0,1]$; δ determines their rate of spatial decay; and λ controls their relative importance in determining overall productivity.[11]

We model the externalities in workers' residential choices analogously to the externalities in firms' production choices. We allow residential amenities to depend on residential fundamentals (b_i) and residential externalities (Ω_i). Residential fundamentals capture features of physical geography that make a location a more or less attractive place to live independently of the surrounding density of economic activity (for example green areas). Residential externalities again impose structure on how the amenities in a given block are affected by the characteristics of other blocks. Specifically, we adopt a symmetric specification as for production externalities, and model residential externalities as depending on the travel-time weighted sum of residential employment density in surrounding blocks:

$$B_i = b_i \Omega_i^\eta, \qquad \Omega_i \equiv \sum_{s=1}^S e^{-\rho\tau_{is}} \left(\frac{H_{Rs}}{K_s} \right), \qquad \eta \geq 0, \rho \geq 0, \tag{21}$$

where H_{Rs}/K_s is residence employment density per unit of geographical land area; residential externalities decline with travel time (τ_{is}) through the iceberg factor $e^{-\rho\tau_{is}} \in (0,1]$; ρ determines their rate of spatial decay; and η controls their relative importance in overall residential amenities.

3 Data

We implement our quantitative framework empirically using a remarkable dataset that we have assembled for Berlin. These data include the four key pieces of information required to take the model to the data structurally: land prices, employment by workplace, employment by residence and bilateral travel times. Berlin also provides an empirical setting in which a major new underground line is under construction (the U5 line through central Berlin from Hönow in the East to Jungfernhelde in the West). Hence we can use our quantitative framework and data from before the line's construction to evaluate its impact on the spatial distribution of economic activity within Berlin.

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[10]While the canonical interpretation of these production externalities in the urban economics literature is knowledge spillovers, as in Alonso (1964), Fujita and Ogawa (1982), Lucas (2000), Mills (1967), Muth (1969), and Sveikauskas (1975), other interpretations are possible, as considered in Duranton and Puga (2004).

[11]We make the standard assumption that production externalities depend on employment density per unit of geographical land area K_i (rather than per unit of floor area L_i) to capture the role of higher densities of development φ_i (higher ratios of floor space to geographical land area) in increasing the surrounding concentration of economic activity.

Data for Berlin is available at a number of different levels of spatial disaggregation. The finest available disaggregation is statistical blocks ("Blöcke"). In 2006 the surface of Berlin was partitioned into 15,937 blocks, of which just under 9,000 are in the former West Berlin. These blocks have a mean area of about 50,000 square meters and an average 2005 population of 274 for the 12,192 blocks with positive 2005 population.[12] Blocks can be aggregated up to larger spatial units including statistical areas ("Gebiete") and districts ("Bezirke").

Our measure of employment at the place of work is a count of the 2003 social security employment ("Sozialversicherungspflichtig Beschäftigte") in each block, which was provided by the Statistical Office of Berlin ("Senatsverwaltung für Berlin") in electronic form. We scale up social security employment in each block by the ratio of social security employment to total employment for Berlin as a whole. To construct employment at residence, we use data on the population of each block in 2005 from the Statistical Office of Berlin and scale the population data using district-level information on labor force participation.[13]

Berlin has a long history of providing detailed assessments of land values, which have been carried out by the independent Committee of Valuation Experts ("Gutachterausschuss für Grundstückswerte") in the post-war period. The committee currently has 50 members who are building surveyors, real estate practitioners and architects. Our land price data for 2006 are the land values ("Bodenrichtwerte") per square meter of geographical land area published by the Committee on detailed maps of Berlin which we have digitized and merged with the block structure. The Committee's land values capture the fair market value of a square meter of land if it was undeveloped. While the Committee does not publish the details of the valuation procedure, the land values are based on recent market transactions. As a check on the Committee's land values, we compare them to confidential micro data on property transactions that are available from 2000-2012. As shown in the web appendix, we find a high correlation between the land values reported by the Committee for 2006 and the land values that we compute from the property transactions data. Finally, the land value data also includes information on the typical density of development, measured as the ratio of floor space to ground area ("GFZ").[14] To convert land prices ($\mathbb{R}_i$) to floor prices ($\mathbb{Q}_i$), we use the assumption of a competitive construction sector with a Cobb-Douglas technology, as discussed in subsection 2.3 above.

Travel times are measured in minutes based on the transport network available in each year and assumed average travel speeds for each mode of transport. To determine travel times between each of the 15,937 blocks in our data, i.e. nearly 254 million ($15,937 \times 15,937$) bilateral connections, we distinguish between travel times by public transport and car. As described in more detail in the web appendix, we construct minimum travel times by public transport for the three years using information on the underground railway ("U-Bahn"), suburban railway ("S-Bahn"), tram ("Strassenbahn") and bus ("Bus") network of Berlin in each year. We use ArcGIS to compute the fastest connection between each pair of blocks allowing passengers to combine all modes of public

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[12]There are a number of typically larger blocks that only contain water areas, forests, parks and other uninhabited areas. Approximately 29 percent of the area of Berlin in 2006 is covered by forests and parks, while another 7 percent is accounted for by lakes, rivers and canals (Statistical Yearbook of Berlin 2007).

[13]Empirically, labor force participation is relatively constant across districts within Berlin.

[14]Note that the Committee's land values are completely different from the unit values ("Einheitswerte") used to calculate property taxes. The current unit values are still based on an assessment ("Hauptfeststellung") that took place as early as 1964 for the former West Germany and 1935 for the former East Germany. In contrast, the Committee's land values are based on contemporaneous market transactions and are regularly updated.

transport and walking to minimize travel time. We construct minimum driving times by car in 2006 using an ArcGIS shape file of the street network of Berlin. We measure overall travel times by weighting public transport and car minimum travel times using district-level data on the proportion of journeys undertaken with these two modes of transport.

In addition to our main variables, we have compiled a number of other data, which are described in detail in the web appendix. First, we have obtained data on observable block characteristics, including the location of parks and other green spaces, proximity to lakes, rivers and canals, proximity to schools, average noise level, the number of listed buildings, the extent of destruction during the Second World War, and urban regeneration programs and government buildings post reunification. Second, we have obtained survey data on individual commuting decisions in Berlin for 2008.

4   Model Calibration

We now calibrate the model so that it exactly replicates the observed data on land prices, workplace employment and residence employment as an equilibrium. We use the calibrated model to recover the implied bilateral commuting flows and distributions of income by workplace and residence in this initial equilibrium.

4.1   Parameters

To calibrate the model's parameters $\{\alpha, \beta, \mu, \epsilon, \kappa, \lambda, \delta, \eta, \rho\}$, we use central values from the existing empirical literature. We set the share of consumer expenditure on residential floor space $(1 - \beta)$ equal to 0.25, which is consistent with the estimates in Davis and Ortalo-Magné (2011). We assume that the share of firm expenditure on commercial floor space $(1 - \alpha)$ is 0.20, which is in line with the findings of Valentinyi and Herrendorf (2008). We set the share of land in construction costs $(1 - \mu)$ equal to 0.25, which is consistent with the estimates in Combes, Duranton, and Gobillon (2014) and Epple, Gordon, and Sieg (2010) and with micro data on property transactions that is available for Berlin from 2000-2012, as discussed in the web appendix.

We use the estimates of the model's commuting parameters $\{\epsilon, \kappa\}$ from Ahlfeldt, Redding, Sturm, and Wolf (2014). We set the Fréchet shape parameter that determines the heterogeneity in workers' commuting decisions (ϵ) equal to 6.83. We assume that the semi-elasticity of commuting costs to travel times (κ) is 0.01. Together these parameters imply a semi-elasticity of commuting flows to travel times $(\epsilon\kappa)$ of 0.07.[15]

We consider a range of values for the model's production and residential externalities parameters $\{\lambda, \delta, \eta, \rho\}$. As summarized by Rosenthal and Strange (2004), "doubling city size seems to increase productivity by an amount that ranges from 3-8 percent," and studies that control for worker sorting find estimated spillovers towards the lower end of this range, as in Combes, Duranton, and Gobillon (2008).[16] We explore the role of

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[15]The use of reduced-form gravity equations for commuting flows has a long tradition in urban and regional economics, as reviewed in McDonald and McMillen (2010). Fortheringham and O'Kelly (1989) argue that the consensus in the literature is that a semi-log specification provides the best fit to commuting data within cities. A recent contribution to this literature using a semi-log specification and travel times is McArthur, Kleppe, Thorsen, and Uboe (2011), which finds a similar semi-elasticity of commuting flows with respect to travel times similar to the estimates of Ahlfeldt, Redding, Sturm, and Wolf (2014) for Berlin.

[16]In a recent meta-analysis of estimates of urban agglomeration economies, Melo, Graham, and Noland (2009) report a mean estimate of 0.058 across 729 estimates from 34 studies, consistent with Rosenthal and Strange (2004).

these agglomeration parameters in determining the economic impact of transport improvements.

4.2 Wages and Implied Bilateral Commuting Flows

We now use the observed data on workplace employment (H_{Mi}), residence employment (H_{Ri}) and travel times τ_{ij} to solve for implied wages and bilateral commuting flows. The commuting market clearing (7) provides a system of equations that can be used to solve for unique values of adjusted wages for each location (up to a choice of units in which to measure wages):

$$H_{Mj} = \sum_{i=1}^{S} \frac{(\tilde{w}_j / e^{\kappa \tau_{ij}})^{\epsilon}}{\sum_{s=1}^{S} (\tilde{w}_s / e^{\kappa \tau_{ij}})^{\epsilon}} H_{Ri},$$

where adjusted wages ($\tilde{w}_j = E_j^{1/\epsilon} w_j$) capture both (i) wages (w_j) in employment location j and (ii) the Fréchet scale parameter that determines the average utility (or effective units of labor) for commuters to that employment location ($E_j^{1/\epsilon}$). These variables enter the commuting market clearing condition isomorphically and hence only their composite value can be recovered from the data. We choose units for adjusted wages such that they have a geometric mean of one across locations.

In Figure 3, we display net commuting for each block within Berlin, defined as observed residence employment minus workplace employment. Surpluses (light colors) correspond to blocks that are net exporters of commuters, where deficits (dark colors) correspond to blocks that are net importers of commuters. As apparent from the figure, blocks close to the main central business districts (CBD) in Berlin – in Mitte in East Berlin and the area along the Kudamm ("Kurfürstendamm") in Charlottenburg and Wilbersdorf in West Berlin – tend to be net importers of commuters. In contrast, outlying residential neighborhoods – such as Marzahn and Zehlendorf – tend to be net exporters of commuters. More striking is the remarkable degree of heterogeneity in commuting patterns across neighboring blocks. Even in central districts such as Mitte, blocks that are net exporters of commuters alternate with blocks that are net importers of commuters.

4.3 Productivity and Production Fundamentals

We now combine the observed data on floor prices and workplace employment together with our solutions for adjusted wages to determine adjusted productivity and production fundamentals. Floor space is assumed to be allocated between commercial and residential land use to arbitrage away differences in commercial and residential floor prices net of the tax equivalent of land use regulations. Therefore observed floor prices ($\mathbb{Q}_i$) equal commercial floor prices (q_i) if a block is completely specialized in commercial activity; they equal residential floor prices (Q_i) if a block is completely specialized in residential activity; and they equal commercial floor prices and a multiple of residential floor prices for incompletely specialized blocks:

$$\mathbb{Q}_i = \zeta_{Mi} q_i = \zeta_{Ri} Q_i, \tag{22}$$

$$\begin{aligned} \zeta_{Mi} &= 1, & i &\in \{\Im_M \cup \Im_S\}, \\ \zeta_{Ri} &= 1, & i &\in \Im_R, \\ \zeta_{Ri} &= \xi_i, & i &\in \Im_S. \end{aligned}$$

where ζ_{Mi} and ζ_{Ri} relate observed floor prices to commercial and residential floor prices respectively; ξ_i is the tax equivalent of land use regulations that introduce a wedge between commercial and residential floor prices; $\Im_M$ is the set of locations specialized in commercial activity ($\theta_i = 1$); $\Im_S$ is the set of incompletely specialized locations ($\theta_i \in (0,1)$); and $\Im_R$ is the set of locations specialized in residential activity ($\theta_i = 0$).

From observed land prices and adjusted wages, profit maximization and zero profits (12) determines the value that adjusted final goods productivity must take in an equilibrium with positive production (up to the choice of units in which to measure land prices and adjusted wages):

$$\mathbb{Q}_j = (1-\alpha)\left(\frac{\alpha}{\tilde{w}_j}\right)^{\frac{\alpha}{1-\alpha}} \tilde{A}_j^{\frac{1}{1-\alpha}}, \tag{23}$$

where adjusted final goods productivity ($\tilde{A}_j^{\frac{1}{1-\alpha}} = E_j^{\frac{\alpha}{\epsilon(1-\alpha)}} A_j^{\frac{1}{1-\alpha}}$) captures both (i) final goods productivity (A_j) and (ii) the Fréchet scale parameter that determines the average utility (or effective units of labor) for commuters to that location ($E_j^{\frac{\alpha}{\epsilon(1-\alpha)}}$). These variables enter the zero profit condition isomorphically and hence only the composite value of adjusted final goods productivity can be recovered from the data. Adjusted final good productivity (and hence adjusted wages) are zero for all locations with zero workplace employment.

From our specification of productivity (20), adjusted productivity $\{\tilde{A}_j\}$ can be further decomposed into production externalities (Υ_j^λ) and adjusted production fundamentals ($\tilde{a}_j$):

$$\tilde{a}_i = \tilde{A}_i \Upsilon_i^{-\lambda}, \qquad \Upsilon_i = \left[\sum_{s=1}^{S} e^{-\delta\tau_{is}} \frac{H_{Ms}}{K_s}\right],$$

where adjusted production fundamentals ($\tilde{a}_i = E_i^{\alpha/\epsilon} a_i$) captures both (i) production fundamentals (a_i) and (ii) the Fréchet scale parameter that determines the average utility from commuting to an employment location ($E_i^{\alpha/\epsilon}$). These variables both enter adjusted final goods productivity isomorphically and hence only the composite value of adjusted production fundamentals ($\tilde{a}_i$) can be recovered from the data. In the special case of exogenous productivity ($\lambda = 0$), adjusted final goods productivity ($\tilde{A}_j$) equals adjusted production fundamentals ($\tilde{a}_j$). Adjusted production fundamentals (and hence adjusted final goods productivity and adjusted wages) are zero for all locations with zero workplace employment.

4.4 Amenities and Residential Fundamentals

We now combine the observed data on floor prices and residence employment together with our solutions for adjusted wages to determine adjusted amenities and residential fundamentals. Choosing units in which to measure expected utility such that $\left(\bar{U}/\gamma\right)^\epsilon / \bar{H} = 1$, adjusted amenities ($\tilde{B}_i$) can be recovered from the residential choice probabilities (5) using expected utility (9):

$$H_{Ri} = \sum_{s=1}^{S} \left(d_{is}\mathbb{Q}_i^{1-\beta}\right)^{-\epsilon} \left(\tilde{B}_i \tilde{w}_s\right)^\epsilon, \tag{24}$$

where adjusted amenities ($\tilde{B}_i = B_i T_i^{1/\epsilon} \zeta_{Ri}^{1-\beta}$) capture both (i) residential amenities (B_i), (ii) the Fréchet scale parameter ($T_i^{1/\epsilon}$) that determines the average utility (or effective units of labor) for commuters from location

i, and (iii) the relationship between observed and residential floor prices ($\zeta_{Ri}^{1-\beta}$). These variables enter the residential choice probabilities isomorphically and hence only the composite value of adjusted residential amenities ($\tilde{B}_i$) can be recovered from the data. Adjusted residential amenities must be equal to zero for all locations with zero residence employment.

From our specification of amenities (21), adjusted amenities ($\tilde{B}_i$) can be further decomposed into residential externalities (Ω_i^η) and adjusted residential fundamentals ($\tilde{b}_i$):

$$\tilde{b}_i = \tilde{B}_i \Omega_i^{-\eta}, \qquad \Omega_i = \left[\sum_{s=1}^{S} e^{-\rho \tau_{is}} \frac{H_{Rs}}{K_s} \right], \tag{25}$$

where adjusted residential fundamentals ($\tilde{b}_i = b_i T_i^{1/\epsilon} \zeta_{Ri}^{1-\beta}$) include both (i) residential fundamentals (b_i), (ii) the Fréchet scale parameter that determines the average utility (or effective units of labor) for commuters from location i ($T_i^{1/\epsilon}$), and (iii) the relationship between observed and residential floor prices ($\zeta_{Ri}^{1-\beta}$). These variables enter adjusted amenities isomorphically and hence only their composite value can be recovered from the data. In the special case of exogenous amenities ($\eta = 0$), adjusted amenities ($\tilde{B}_i$) equals adjusted residential fundamentals ($\tilde{b}_i$). Adjusted residential fundamentals (and hence adjusted amenities) are zero for all locations with zero residence employment.

5 Counterfactuals

We now show how the system of equations for equilibrium in the model can be used to undertake counterfactuals for the impact of transport infrastructure improvements on the spatial equilibrium distribution of economic activity. The counterfactual equilibrium can be determined from the following system of equations:

$$\hat{H}_{ij} = \left(\hat{d}_{ij} \hat{Q}_i^{1-\beta} \right)^{-\epsilon} \left(\hat{\tilde{w}}_j \right)^{\epsilon}, \tag{26}$$

$$\hat{H}_{Ri} H_{Ri} = \sum_{s=1}^{S} \left(\hat{d}_{is} \hat{Q}_i^{1-\beta} \right)^{-\epsilon} \left(\hat{\tilde{w}}_s \right)^{\epsilon} H_{is}, \tag{27}$$

$$\hat{H}_{Mi} H_{Mi} = \sum_{s=1}^{S} \left(\hat{d}_{ri} \hat{Q}_r^{1-\beta} \right)^{-\epsilon} \left(\hat{\tilde{w}}_i \right)^{\epsilon} H_{ri}, \tag{28}$$

$$\hat{Y}_i = \hat{H}_{Mi}^{\alpha} \hat{L}_{Mi}^{1-\alpha}, \tag{29}$$

$$\hat{w}_i = \frac{\hat{Y}_i}{\hat{H}_{Mi}}, \tag{30}$$

$$\hat{W}_{Ri} W_{Ri} = \sum_{s=1}^{S} \hat{H}_{is} \hat{\tilde{w}}_s H_{is} \tilde{w}_s, \tag{31}$$

$$\hat{\mathbb{Q}}_i = \hat{Y}_i, \qquad i \in \Im_M, \tag{32}$$

$$\hat{\mathbb{Q}}_i = \hat{W}_{Ri}, \qquad i \in \Im_R, \tag{33}$$

$$\hat{\mathbb{Q}}_i \mathbb{Q}_i = \frac{(1-\alpha)\hat{Y}_i Y_i + (1-\beta)\hat{W}_{Ri} W_{Ri}}{\tilde{L}_i}, \qquad i \in \Im_S, \tag{34}$$

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$$\hat{\tilde{L}}_{Mi} = 1, \qquad i \in \Im_M, \tag{35}$$

$$\hat{\tilde{L}}_{Ri} = 1, \qquad i \in \Im_R, \tag{36}$$

$$\hat{\tilde{L}}_{Mi}\tilde{L}_{Mi} = \left[\frac{(1-\alpha)\hat{Y}_i Y_i}{(1-\alpha)\hat{Y}_i Y_i + (1-\beta)\hat{W}_{Ri} W_{Ri}} \right] \tilde{L}_i, \qquad i \in \Im_S, \tag{37}$$

$$\hat{\tilde{L}}_{Ri}\tilde{L}_{Ri} = \left[\frac{(1-\beta)\hat{W}_{Ri} W_{Ri}}{(1-\alpha)\hat{Y}_i Y_i + (1-\beta)\hat{W}_{Ri} W_{Ri}} \right] \tilde{L}_i, \qquad i \in \Im_S, \tag{38}$$

$$\hat{\bar{H}}\bar{H} = \left[\sum_{r=1}^{S} \sum_{s=1}^{S} \left(\hat{d}_{rs}\hat{\mathbb{Q}}_r^{1-\beta} \right)^{-\epsilon} \left(\hat{\tilde{w}}_s \right)^{\epsilon} H_{rs} \right]. \tag{39}$$

6 Conclusions

Determining the economic impact of transport infrastructure improvements is an important public policy issue. Evaluations of the economic impact of such transport improvements face a number of theoretical and empirical challenges. We develop a theoretical framework for undertaking counterfactuals for the spatial equilibrium impact of transport improvements. Our framework features a rich spatial structure, with locations differing in productivity, amenities and access to transport infrastructure. Nonetheless this framework remains tractable and amenable to quantitative analysis. We find substantial effects of empirically plausible transport infrastructure improvements on land rents, internal city structure and aggregate city economic activity.

References

AHLFELDT, G., S. REDDING, D. STURM, AND N. WOLF (2014): "The Economics of Density: Evidence from the Berlin Wall," *NBER Working Paper*, 20354.

ALBOUY, D. (2008): "Are Big Cities Bad Places to Live? Estimating Quality of Life across Metropolitan Areas," *NBER Working Paper*, 14472.

ALONSO, W. (1964): *Location and Land Use.* Harvard, Cambridge MA.

ARZAGHI, M., AND J. V. HENDERSON (2008): "Networking Off Madison Avenue," *Review of Economic Studies*, 75(4), 1011–1038.

BAUM-SNOW, N. (2007): "Did Highways Cause Suburbanization?," *Quarterly Journal of Economics*, 122(2), 775–780.

COMBES, P.-P., G. DURANTON, AND L. GOBILLON (2008): "Spatial Wage Disparities: Sorting Matters!," *Journal of Urban Economics*, 63(2), 723–747.

——— (2014): "The Costs of Agglomeration: Land Prices in French Cities," Wharton, mimeograph.

DAVIS, M. A., AND F. ORTALO-MAGNÉ (2011): "Housing Expenditures, Wages, Rents," *Review of Economic Dynamics*, 14(2), 248–261.

DONALDSON, D. (2014): "Railroads of the Raj: Estimating the Impact of Transportation Infrastructure," *American Economic Review*, forthcoming.

DURANTON, G., AND D. PUGA (2004): "Micro-Foundations of Urban Agglomeration Economies," in *Handbook of Regional and Urban Economics*, ed. by J. V. Henderson, and J.-F. Thisse, vol. 4, pp. 2063–2117. Elsevier, Amsterdam.

DURANTON, G., AND M. A. TURNER (2011): "The Fundamental Law of Road Congestion: Evidence from US Cities," *American Economic Review*, 101(6), 2616–52.

——— (2012): "Urban Growth and Transportation," *Review of Economic Studies*, 79(4), 1407–1440.

EATON, J., AND S. KORTUM (2002): "Technology, Geography, and Trade," *Econometrica*, 70(5), 1741–1779.

EPPLE, D., B. GORDON, AND H. SIEG (2010): "A New Approach to Estimating the Production Function for Housing," *American Economic Review*, 100(3), 905–924.

FABER, B. (2014): "Integration and the Periphery: The Unintended Effects of New Highways in a Developing Country," *Review of Economic Studies*, forthcoming.

FORTHERINGHAM, S., AND M. O'KELLY (1989): *Spatial Interaction Models: Formulations and Applications.* Kluwer, Dordrecht.

FUJITA, M., AND H. OGAWA (1982): "Multiple Equilibria and Structural Transformation of Non-monocentric Urban Configurations," *Regional Science and Urban Economics*, 12(2), 161–196.

GIBBONS, S., AND S. MACHIN (2005): "Valuing Rail Access Using Transport Innovations," *Journal of Urban Economics*, 57(1), 148–169.

LUCAS, R. E. (2000): "Externalities and Cities," *Review of Economic Dynamics*, 4(2), 245–274.

MCARTHUR, D. P., G. KLEPPE, I. THORSEN, AND J. UBOE (2011): "The Spatial Transferability of Parameters in a Gravity Model of Commuting Flows," *Journal of Transport Geography*, 19(4), 596–605.

MCDONALD, J., AND D. MCMILLEN (2010): *Urban Economics and Real Estate: Theory and Policy*. John Wiley & Sons, Hoboken, NJ.

MCDONALD, J. F., AND C. I. OSUJI (1995): "The Effect of Anticipated Transportation Improvement on Residential Land Values," *Regional Science and Urban Economics*, 25(3), 261–278.

MCFADDEN, D. (1974): "The Measurement of Urban Travel Demand," *Journal of Public Economics*, 3(4), 303–328.

MELO, P. C., D. J. GRAHAM, AND R. B. NOLAND (2009): "A Meta-analysis of Estimates of Urban Agglomeration Economies," *Regional Science and Urban Economics*, 39(3), 332–342.

MICHAELS, G. (2008): "The Effect of Trade on the Demand for Skill: Evidence from the Interstate Highway System," *Review of Economics and Statistics*, 90(4), 683–701.

MILLS, E. S. (1967): "An Aggregative Model of Resource Allocation in a Metropolitan Centre," *American Economic Review*, 57(2), 197–210.

MUTH, R. (1969): *Cities and Housing*. University of Chicago Press, Chicago.

ROBACK, J. (1982): "Wages, Rents and the Quality of Life," *Journal of Political Economy*, 90(6), 1257–1278.

ROSENTHAL, S. S., AND W. C. STRANGE (2004): "Evidence on the Nature and Sources of Agglomeration Economics," in *Handbook of Regional and Urban Economics*, ed. by J. V. Henderson, and J. Thisse, vol. 4. Elsevier North Holland, Amsterdam.

ROSSI-HANSBERG, E., P.-D. SARTE, AND R. I. OWENS (2010): "Housing Externalities," *Journal of Political Economy*, 118(3), 485–535.

SVEIKAUSKAS, L. A. (1975): "The Productivity of Cities," *Quarterly Journal of Economics*, 89(3), 393–413.

TRANSPORT FOR LONDON (2013): "Investment Program Report," Mayor of London, London.

——— (2014): "TfL Budget 2014/2015," Mayor of London, London.

VALENTINYI, A., AND B. HERRENDORF (2008): "Measuring Factor Income Shares at the Sectoral Level," *Review of Economic Dynamics*, 11(4), 820–835.
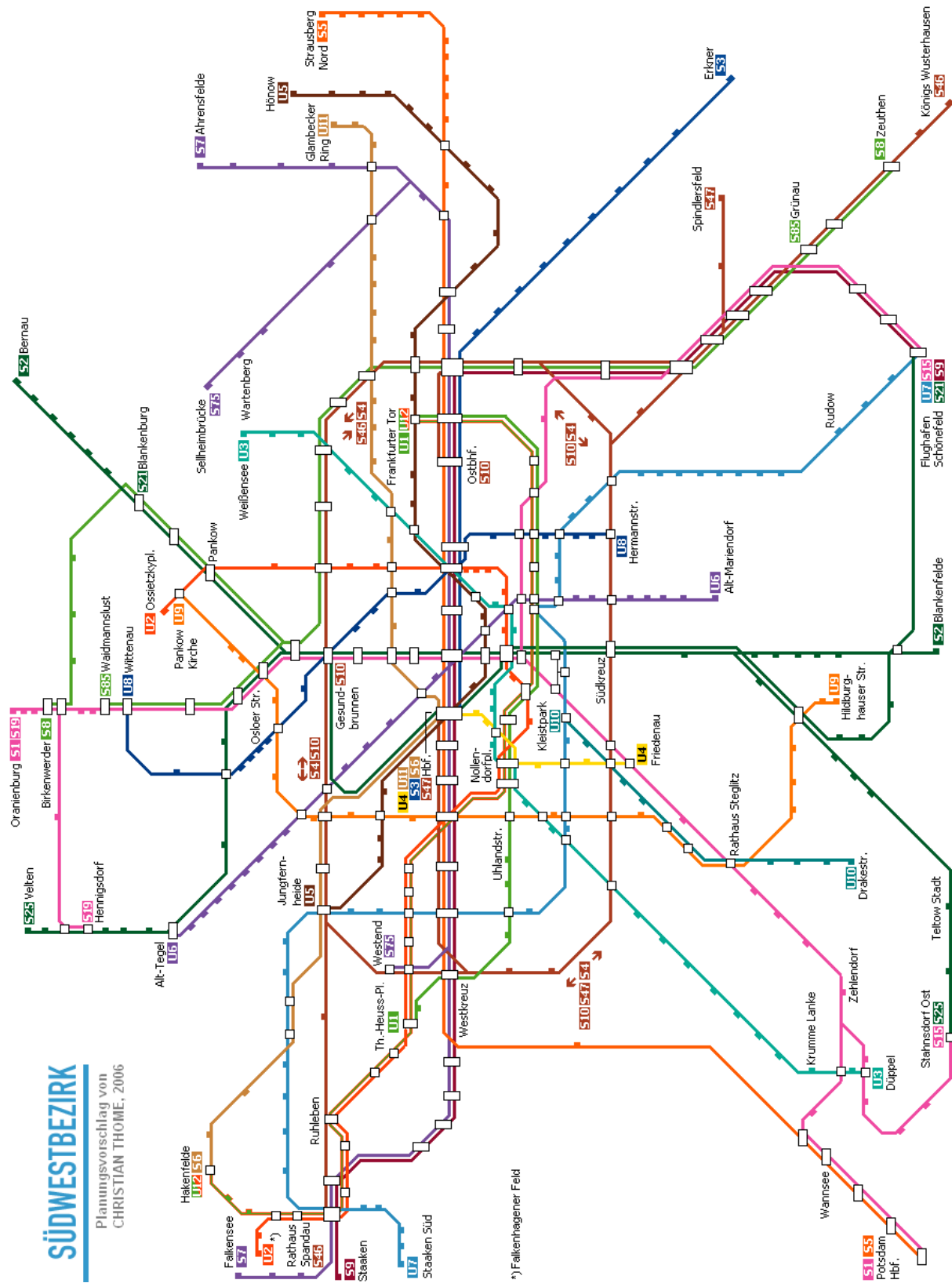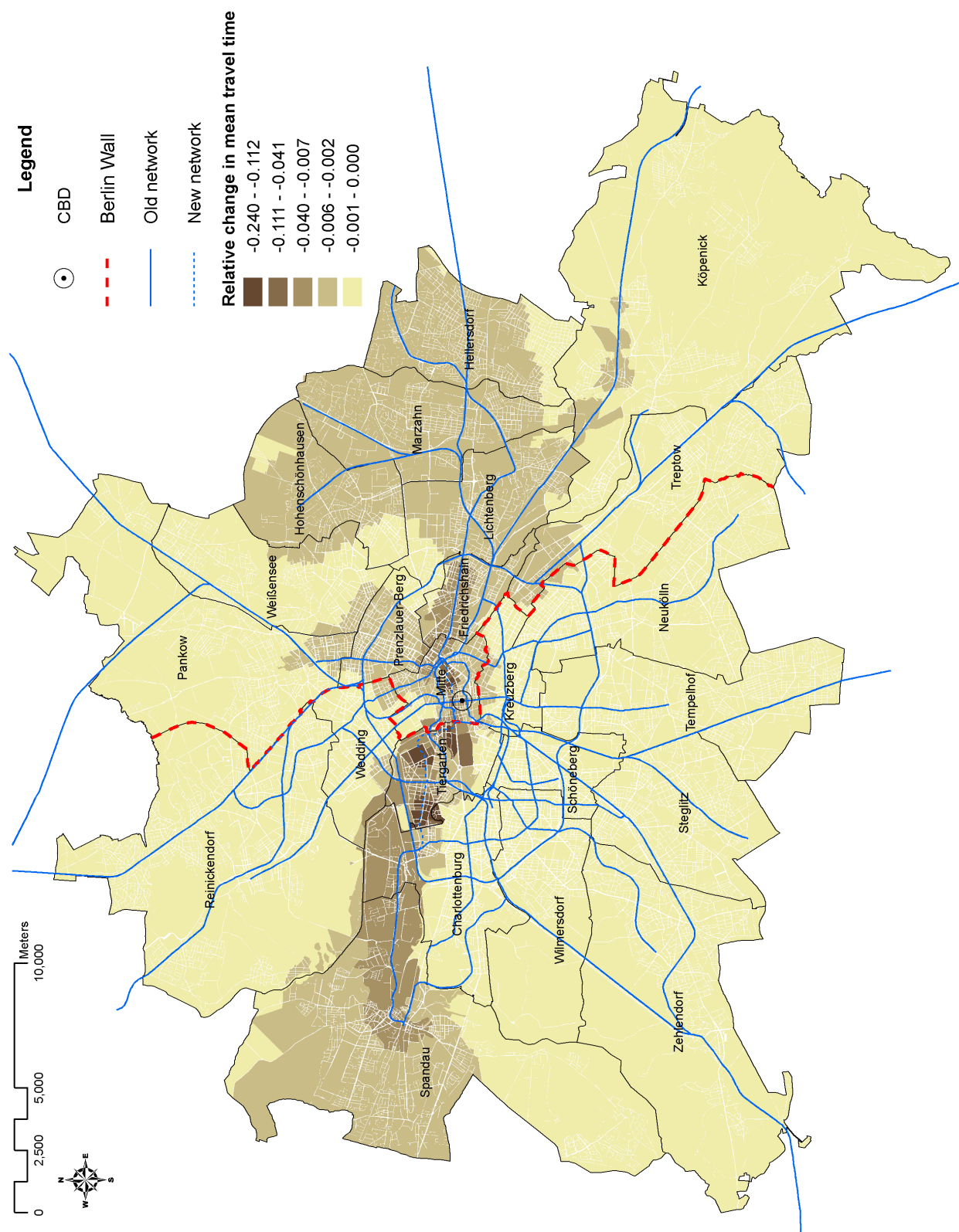
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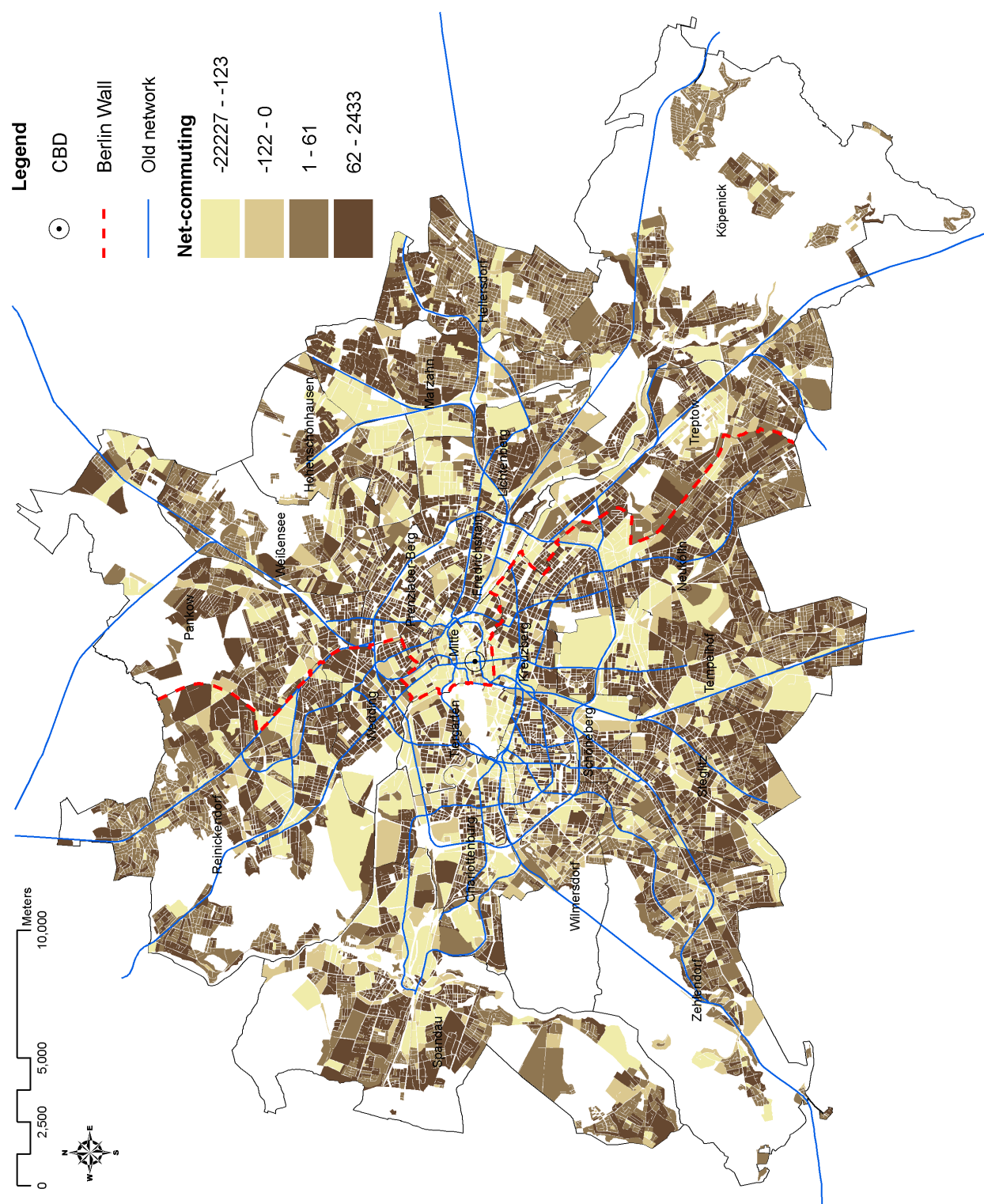
Figure 2: Relative Change in Travel Times

Figure 3: Net Commuting

Parameter	Definition	Value
$(1 - \beta)$	Consumer expenditure residential floor space	0.25
$(1 - \alpha)$	Firm expenditure commercial floor space	0.20
$(1 - \mu)$	Share of Land in Construction Costs	0.25
ν	Semi-elasticity Commuting Flows and Travel Times	0.07
ϵ	Fréchet Shape Parameter Commuting Decisions	6.83

Parameter	Definition	Value
λ	Production Externalities Elasticity	0.05
δ	Production Externalities Decay	0.05
η	Residential Externalities Elasticity	0.05
ρ	Residential Externalities Decay	0.05

Table 1: Assumed Parameter Values

	Counterfactual / Actual	
Percentage Increase	Exogenous	Endogenous
Utility	0.22%	0.33%
Net City Employment	0%	0%
Value Total City Income	0.02%	0.11%
Value Total City Land Rents	0.02%	0.11%
Total Factor Productivity	0.03%	0.13%
Sum of Absolute Changes as Percent of Aggregate	Exogenous	Endogenous
Workplace Employment	0.70%	0.92%
Residence Employment	0.36%	0.44%
Output	0.58%	0.78%

Table 2: Aggregate Effects (Immobile Population)

	Counterfactual / Actual	
Percentage Increase	Exogenous	Endogenous
Utility	0%	0%
Net City Employment	0.55%	1.06%
Value Total City Income	0.46%	1.01%
Value Total City Land Rents	0.46%	1.01%
Total Factor Productivity	0.03%	0.18%
Sum of Absolute Changes as Percent of Aggregate	Exogenous	Endogenous
Workplace Employment	0.58%	1.06%
Residence Employment	0.55%	1.06%
Output	0.49%	1.01%

Table 3: Aggregate Effects (Mobile Population)

Variable	Exogenous	Endogenous
Berlin GDP (2012 1,000s Euro)	105,148,850	
Increase GDP (2012 1,000s Euro)	479,421	1,056,767
Increase Land Rents (2012 1,000s Euro)	39,952	88,064
NPV Increase GDP (60 year, 3%)	13,747,679	30,303,380
NPV Increase GDP (60 year, 5%)	9,554,528	21,060,609
NPV Increase GDP (60 year, 10%)	5,257,890	11,589,726
NPV Increase Land Rents (60 year, 3%)	1,145,640	2,525,282
NPV Increase Land Rents (60 year, 5%)	796,211	1,755,051
NPV Increase Land Rents (60 year, 10%)	438,157	965,811
Construction U5 (2012 1,000s Euro)	650,000	
Operating U5 (2%, 2012 1000s Euro)	13,000	
NPV Total Cost (3% discount rate)	1,022,782	
NPV Total Cost (5% discount rate)	909,081	
NPV Total Cost (10% discount rate)	792,573	

Table 4: Aggregate Effects (Mobile Population)