Welfare Benefits of Agglomeration and Worker Heterogeneity

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Abstract

The direct impact of local public goods on welfare is relatively easy to measure from land rents. However, the indirect effects on home and job location and on land use are hard to pin down. We develop a spatial general equilibrium model for the valuation of these effects. The model is estimated using data on transport infrastructure, commuting behavior, wages, land use and land rents for 3000 ZIP-codes in the Netherlands and for three levels of education. Welfare benefits are shown to differ sharply by workers' educational attainment.

JEL Codes: H4, H54, R13, R23, R4

Keywords: local public goods, spatial equilibrium, residential sorting, land rents

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1 Introduction

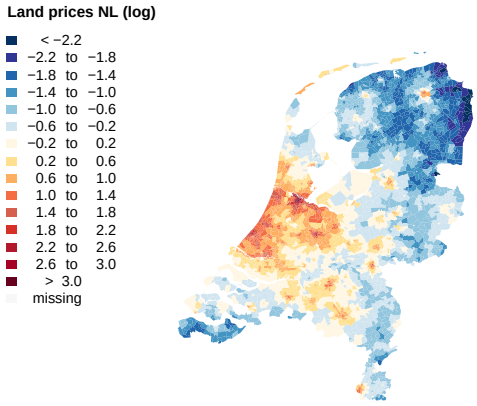
Ever since the work of Arnott and MacKinnon (1977) and Roback (1982), land rents have played a major role in the evaluation of the value of local public goods, like transport infrastructure, central business districts, concert halls, historical buildings, nice restaurants and shoppig malls. Local public goods make locations in their close proximity more attractive and hence raise the land rent at these locations. Indeed, land prices for residential real estate differ widely across locations. Figure 1 documents these differentials for the Netherlands, using a refined regional disaggregation of 3000 ZIP codes, covering areas as small as one square kilometer in central city districts. Even in a rather homogeneous country as the Netherlands, land rents vary by almost a factor 400, ranging from 3800 euro per square meter in Amsterdam's Canal Zone to some 10 euro along the North-Eastern border with Germany. Land rents peak in city centres, where these local public goods are in large supply.

However, the impact of local public goods on their neighbourhood goes beyond that on prices. An abundant supply of local public goods leads to a selection process where people with a low valuation of these goods are gradually replaced by people with high valuation. It also leads to an increase in the intensity of land use. Indeed, Figure 2 documents the wide dispersion in the composition of the population by level of education. The maps show the shares of higher and lower educated workers living in each ZIP code, leaving the middle education level as the omitted category. There is a very strong spatial segregation by education. Roughly speaking, the higher educated live in the city, the lower educated on the countryside. This outcome implies that preferences for public goods differ widely between levels of education. An evaluation of the value of local public goods should account for this preference heterogeneity. Quite likely, other characteristics like marital status (Gautier, Svarer and Teulings, 2012) are also relevant. For the sake parsimony we focus here on education.

Figure 3 documents both the population density and the value of construction per square meter. As expected, there is a strong correlation between land prices and the intensity of land use, whether it is a greater number of people per unit of construction or a greater number of units of construction per square meter of land. Both processess lead to a more efficient use of the local public goods, since neighbourhoods around the public good will be more intensily used and by people who value the presence of these goods the most. Hence, when it comes to the evaluation of the contribution of these public goods to the neighbourhood, it is

important to account for these endogenous processes, since they enhance the efficient use of the public goods. Moreover, these processes determine who will benefit from the investement in these public goods, either the land owners seeing the value of their property going up, or the people who just rent property at the location? Are the benefits the same for different levels of education? The answer to these questions is also crucial for the political economy of the investment in public goods. Political parties are unlikely to propose investments that do enhance total welfare, but not the welfare of their voters. This paper aims to swer these questions empirically: how does investment in local public goods affect the intensity of land use and the composition of people living in the their neighbourhood, and how are these gains distributed between land owners and people living at the location with various levels of education.

Figure 1. Log(land rents) in the Netherlands[1]



[1] In Figure 1, 0 corresponds to a location in Enschede with an average land price of 109 euro/m^2.

Figure 2. Share of residents by education level: left high and right low

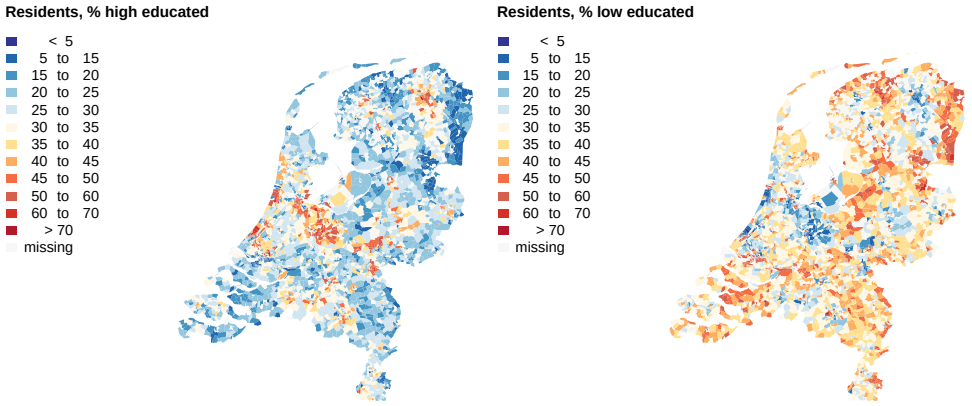
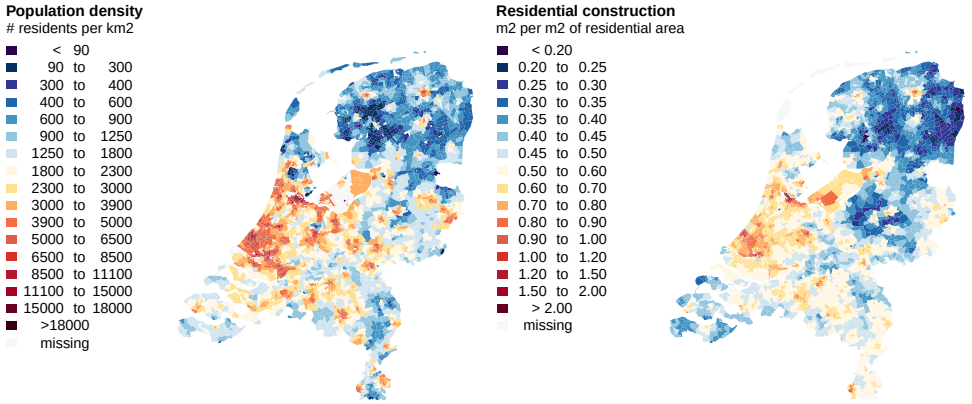


Figure 3. Population density per sq.km of land area (left) and the volume of residential construction per sq.m of residential area (right)



For this excercise, we develop a general equilibrium model for the market for residential land accross 3000 ZIP codes. Land rents clear the market at each location. People have to choose where to work and where to live, how to commute between these locations, and how much land to rent at their location of residence, taking the supply of public goods and the existing agglomeration advantages as given. Our main analytical tool is McFadden's well known utility maximizing interpretation of the logit model. This framework can be directly applied to the modal split decision for the transport mode for commuting and to the decision where to work. For the purpose of our exercise, we make three new extensions to this framework.

The first extension is our modelling of individual land use. Where most researchers take the supply of housing and hence lot size as given, we model the choice between the

consumption of land and other consumption, depending on the local land rent. One can think of this process either as a more intensive use of the existing supply of housing, e.g. by splitting or merging apartments, or as a gradual reconstruction of a neighbourhood after the land rent has changed. This extension of the model allows us to estimate the elasticity of substitution between land and other consumption, which is estimated to be around 0.75. Hence, the land share in consumption is increasing in the level of the land rent. This result is consistent with Albouy and Ehrlich (2012) who report the elasticity of substitution between land and the value of construction to be about a half for the US. One would expect the land rent elasticity of the population density to be higher than that of the construction intensity, since people adjust both when the land rent is high. The elasticity being smaller than unity implies that the share of land rent in consumption is increasing in the degree of agglomeration in the economy, implying that land lords are the main benificiaries of agglomeration.

The second extension is our modelling of the interaction between preference heterogeneity and equilibrium land rents. People choose to live in that location that offers them the highest utility, while land rents adjust to equalize supply and demand at each location. If all individuals were homogeneous, then the estimation of a logit model for home location would not make sense, since land rents would adjust to equalize utility across locations. Instead, one could better estimate a land rent equation directly to evaluate how land rents must adjust to offset regional differences. However, since our model is characterized by preference heterogeneity and since locations differ in their attractivity to various educational levels, the slope of the land rent function depends on the composition the population at that location. For example, most museums attract predominantly higher educated visitors. Building a museum will therefore have a smaller effect on land rents in a low skilled rather than in a high skilled neighbourhood. The econometrics of this problem is involved, in particular due to the high dimensionality of the problem. We show that the problem can be simplified enormously by transposing the conditionality of the probabilities, by applying Bayes' rule, see Ellickson (1981): we do not analyze the probability of an individual chosing a particular location conditional on her education, but other way around the probability of an individual having a particular education conditional on her preference for that location. This greatly reduces the computational burden. A further problem in this estimation is that the local land rent is endogenous. Hence, it has to be instrumented. We show that the option

value of job availability at a particular residential location is a natural instrument. The preferences for public goods are shown to differ widely between levels of education. For example, spatial differences in job availability explain about one third of the variation in land rents on average, but almost 40 percent for lower educated workers, while less than 30 % for the higher educated. Local consumption amenities/public goods are therefore a luxury good. Our methodology allows us to calculate the hypothetical land rents that would apply if everybody had a lower or a higher level of education, respectively. Where the standard deviation of actual log land rents among ZIP codes is 0.90, this standard deviation would be 1.35 if everybody were lower educated and 2.30 if everybody were higher educated. Since people sort into the locations in which they enjoy the greatest comparative advantage from the local attributes, this process compresses land rent differentials.

The third innovation in our modelling regards the way we establish the marginal utility of income, as this is a crucial factor for the valuation of public goods by revealed location preferences. The standard method would be to use variation in income. This does not work in this case for two reasons. First, variation in income due to individual variation in human capital cannot be used since we are interested in preference heterogeneity between education levels. Second, variation in wages between job locations cannot be used because this variation is correlated with job amenities at that location, e.g. jobs requiring working in shifts are less attractive and hence pay higher wages. We offer two solutions. First, we use the cost of commuting. Identification comes from non-linearities in the relation between travel time and cost. Second, we apply Shephard's lemma to the derive the demand for residential land from the indirect utility function with income and land rent as its arguments. We show that the weight of the land rent in the home location choice model should be equal to the share of land rent in total consumption. Both methods for establishing the marginal valuation of money should yield approximately the same answer, as they do empirically.

We show the effect of selection education levels and shifts in the intensity of land use by using the model for a policy experiment. The city of Amsterdam is located just South of a major canal, connecting the Amsterdam harbour to the North Sea. Many people commute from the area North of the canal to jobs in Amsterdam and the neighbouring municipality of Haarlemmermeer (the location of Schiphol airport). The main connections between Amsterdam and the area North of the canal are five highway tunnels and two train tunnels. As a policy experiment, we calculate a counterfactual in which the train tunnels are

closed. The availability of the tunnels leads to a shift in the modal split from the car to the train and to a shift of jobs to Amsterdam. The focus of attention in this paper is on shifts in residential location choices. We document substantial price increases for locations close to railway stations North of the canal and shifts in the composition of the group of people living there towards more higher educated workers. Land owners in the North gain, as the share spend on land rents goes up. Land owners elsewhere in the country loose an almost equal amount, since their locations become relatively less attractive. High skilled workers capture the lion's share of the gain, low skilled workers gain a small bit. This distribution of gains and losses has profound implications for the political economy of investments in public goods.

This paper contributes to a number of strands in the literature. Haughwout (2002) develops a spatial general equilibrium framework with aggregate investment in regional transport infrastructure. Others examine the effects of infrastructure investments on the house prices, see Klaiber and Smith (2010), Bowes and Ihlandfeldt (2001), and Gibbons and Macchin (2005). Baum-Snow and Kahn (2000) address changes in the modal shift. Anas and Liu (2007) model the interaction between land use and transportation infrastructure, while Inoa et al. (2014) analyse the interdependence of home and job location. Our paper is also related to the recent literature on the effect of transport infrastructure on the spatial distribution of economic activity. Baum-Snow (2007, 2010) finds empirical evidence for the prediction that investment in infrastructure increases the demand for housing in suburbs for the USA in the second part of the 20th century. Baum-Snow and Lutz (2011) report relocation of people following the mandatory desegregation of large urban public school districts in the US. Gamper-Rabindran and Timmins (2011) and Hornbeck (2012) document residential migration following exogenous shocks to environmental quality. Duranton and Turner (2012) estimate a model explaining the joint evolution of highways and employment in American cities. Desmet and Rossi-Hansberg (2013) explain the city size distribution from differences in congestion costs, amenities and productivity.

The structure of the paper is as follows. Section 2 discusses the model, Section 3 the estimation strategy, Section 4 deals with data, while Section 5 discusses the estimation results. Section 6 discusses the method for solving the model and the methodology of the welfare analysis. Section 7 discusses the policy experiment and Section 8 concludes.

2 The model

We construct a general equilibrium model of the market for residential land in an economy consisting H locations. People choose a location to live and a location to work, they choose how to commute between both locations, and they choose how much residential land to consume at their home location. The geography of these locations is described by a matrix of commuting costs for every pair of locations and every transport mode, by the amenities available at each home location, the attractivity of each job location, and the area of residential land available at each location. We distinguish four transport modes (car, train, other public transport, and bicycle/walking) and three levels of education s. The nation wide supply of workers for each education level N_s is fixed and each worker supplies a fixed amount of labour. We ignore houshold formation. Land rent adjusts to clear the market for residential land at each location.

2.1 Workers' utility

Worker i is characterized by the following utility function:

$$v_{ihjm} = \underbrace{\mu_{Hs}^{-1}\left(\alpha_s' a_h + z_h + \ln K_h\right)}_{\text{home amenities}} + \underbrace{\omega_s\left(y_{sj} - x^c_{shjm} - \rho_s \ln R^*_h\right)}_{\text{job amenities, income \& land rent}} - \underbrace{\gamma_s' x_{shjm}}_{\text{commuting}} + e_{ihjm}, \quad (1)$$

where $\ln R^*_h \equiv \ln R_h + \psi R_h$. The suffix i implies a value of s; hence, we omit s whenever there is an index i.

The first term measures the amenities at the home location $h \in H$. The vector a_h measures the observed amenities at the home location, like the scenery in neighbourhood, the number of monuments, and the availability of restaurants and shops. The fixed effect z_h measures unobserved amenities that are uncorrelated to a_h and have expectation zero with $\mathrm{E}[z_h] = 0$. The term $\ln K_h$ measures the number of houses that are availabe at location h. Later on, we explain why a larger number of houses increases the attractivity of a location.

The second term measures the attractivity of the job location $j \in J$.and the effect of earned income and paid land rent. The fixed job location effect y_{sj} measures the attractivity of location j for a worker with education level s. One can think of y_{sj} is being the sum of the log wage $\ln W_{sj}$ that a worker of education level s earns at location j and non-monetary job amenities, denoted u_{sj} with zero expectation $\mathrm{E}[u_{sj}] = 0$. Hence: $y_{sj} = \ln W_{sj} + u_{sj}$. The term x^c_{shjm} are the monetary cost of commuting between location h and j as a share of

the wage W_{sj}, denoted x^c_{shjm}. Hence, ignoring non-monetary job amenities for the moment, $y_{sj} - x^c_{shjm}$ measures the log wage income of worker net of the cost of commuting, using $1 - x^c_{shjm} \cong e^{-x^c_{shjm}}$ for small x^c_{shjm}.

R_h is the land rent per square meter. Hence, $\ln R^*_h \equiv \ln R_h + \psi R_h$ is non-linear transformation of the land rent. Hence, while the first term offers a direct representation of the utility function in term of inputs, the second term offers an indirect representation in terms of prices and income. Income net of commuting cost is spent on two commodities, land use at the residential location and other consumption, where the price of other consumption is normalized to unity. Note that the parameter ω_s measures the marginal utility of an increase in log income. This parameter is crucial for the computation of welfare effects via equivalent variations. Its proper estimation is therefore key to the purpose of this paper.

The third term, x_{hjm} is a vector of physical characteristics of commuting from location h to j by transport mode $m \in M$. Where x^c_{shjm} measures the monetary cost of commuting, $\gamma'_s x_{shjm}$ measures the non-monetary cost.

Finally, the term e_{ihjm} is a stochast, which is independent of any other variable in the utility function and which captures individual preferences for the mode of transport m, for the job location j, for an individual house at the home h for each individual i. This error term can be decomposed in three components driving the preferences for h, j and m:

$$e_{ihjm} = \widetilde{e}_{ih} + \widetilde{e}_{ihj} + \widetilde{e}_{ihjm},$$

where components $\widetilde{e}_\chi$ are uncorrelated for all χ, see e.g. Ben-Akiva and Lerman (1985). The composite components $\widetilde{e}_{ihjm}$, $(\widetilde{e}_{ihj} + \widetilde{e}_{ihjm})$, and $(\widetilde{e}_{ih} + \widetilde{e}_{ihj} + \widetilde{e}_{ihjm})$ all follow a Gumbel or type I extreme value distribution with location parameter zero and scale parameters μ^{-2}_{Ms}, μ^{-2}_{Js}, and μ^{-2}_{Hs} respectively, $1 = \mu_{Ms} \geqq \mu_{Js} \geqq \mu_{Hs}$, where μ_{Ms} is normalized to unity without loss of generality. In equilibrium, every worker occupies one house. For individual i, each house at location h is characterized by a unique draw $\widetilde{e}_{ih}$. If she chooses to live in location h, she chooses that house that yields the highest utility. The term $\ln K_h$ captures the gain in expected utility from being able to choose between K_h houses.[2] Note that the number of houses K_h at location h is endogenous, since it depends on the land rent R_h: the higher is the land rent, the lower is the land use per worker, and hence the higher is number of houses that fit within the area of land A_h that is available for residential use.

[2] The max of K Gumbel distributed stochasts with scale parameter μ_{Hs} has a mean $(\ln K + \gamma)/\mu_{Hs}$, where γ is Euler's constant.

Workers choose their home location h, their job location j, their transport mode m, their land use L_{shj} and their other consumption C_{shj} as to maximize their utility (1), subject to their budget constraint:

$$W_{sj}e^{-x^c_{hjm}} = R_h L_{shj} + C_{shj}. \tag{2}$$

The next section derives the decision rules that go with this maximization problem and describes how these rules can be applied for empirical inference. We discuss these decisions in reversed order. First we analyse the modal split for commuting conditional on the home and job location and the choice of job location conditional on the home location. These steps are largely standard. The next to steps contain the innovations compared to the previous literature. First, we analyse how much land a worker chooses to rent at the home location h, conditional on his choice for that location. Finally, having taken all previous decisions conditional on the choice of the home location, we analyze what is the optimal home location. Since the supply and demand for residential land have to be in equilibrium, land rents R_h will adjust to clear the market. In model with only a single worker type, this final step would be equivalent to the analysis of land rents that make people indifferent between locations. Since workers differ by their level of education in our model, this analysis will be more involved.

3 Estimation

3.1 The modal split and job location logits

Since the modal split and job location logits are standard, their estimation is discussed only briefly. The derivation of these models from utility maximization is relegated to Appendix A.

The modal split logit model conditional on the home and job location reads:

$$\begin{aligned} \Pr[m|shj] &= \exp(c_{shj} - c_{shjm}), \\ c_{shjm} &\equiv \gamma_s' x_{hjm} + \omega_s x^c_{shjm}, \\ c_{shj} &\equiv \ln\left[\sum_{m\in M} \exp c_{shjm}\right]. \end{aligned} \tag{3}$$

The variable c_{shjm} measures the utility cost from using mode m on the connecton $h- j$ minus its monetary cost x^c_{shjm}. The logsum term c_{shj} can be interpreted as a generalized

measure of the transport cost for the connection $h-j$. A reduction in the cost of one alternative, e.g. a reduction train fares, reduces the utility cost c_{shjm} for that alternative and hence the generalized measure of transport cost c_{shj}, see the third line in equation (9). However, a change in the cost will have a much smaller effect for a low probability alternative (one for which c_{shjm} is high) than for a high probability alternative.

This model can be estimated from individual data on x_{hjm}, x^c_{shjm} and the actual choices of transport mode, yielding estimates for the parameters γ_s and ω_s. The attractive feature of the specification of the utility function (1) is that the choice of transport mode depends only on the error term $\widetilde{e}_{ihjm}$ and can therefore be analysed indepently of the other choices made be individuals, compare Ahlfeldt et.al. (2015). Note that the estimation of the modal split logit yields an estimate for the marginal utility of log income ω_s, which is central to our analysis. It is identified from the amount of income people want to give up for a more convenient mode of transport, for example because it requires them less time to commute from h to j.

The logit model for the job location choice conditional on the home location h reads:

$$\begin{aligned} \Pr[j|sh] &= \exp\left(g_{shj}-g_{sh}\right), \qquad (4)\\ g_{shj} &\equiv \mu_{Js}\left(c_{shj}+\omega_s y_{sj}\right),\\ g_{sh} &\equiv \ln\left[\sum_{j\in H}\exp g_{shj}\right]. \end{aligned}$$

The variable g_{shj} measures the attractivity of job location j for somebody living at location h. It accounts both for the attractivity of location j in general, as measured by the fixed effect $\omega_s y_{sj}$, and for the accessibility of j when living at h, as is measured by the generalized transport indicator c_{shj}. The log sum g_{sh} is therefore a generalized job attractivity measure for the home location h: how easy it is to find an attractive job when living in h.

This logit model can be estimated using the calculated values for c_{shj} from the estimation results of model (3). The estimation of this model yields estimates for μ_{Js} and the fixed effects $\omega_s y_{sj}$ for each job location $j\in H$; ω_s and y_{sj} are not separately identified in this model, but an estimate for ω_s is obtained from model (3). The coefficient μ_{Js} is identified from the differences in job location choice between home locations, due to variation in the generalized commuting cost c_{shj} between home locations. While the main component in the fixed effect y_{sj} is likely to be the log wage $\ln W_{sj}$, we do not enter it as a regressor. The reason is that $\ln W_{sj}$ is likely to be negatively correlated to the unobserved job location amenities

u_{sj}, because a job location with unattractive jobs will have to pay high wages to attract enough workers. Hence, estimating ω_s via data on log wages yields a downwardly biased estimate. Experiments with models including data on $\ln W_{sj}$ confirmed this argument. The problem in obtaining a direct estimate on ω_s makes the indirect route via the monetary cost of commuting x^c_{shjm} the more valuable.

3.2 Land use

The second step is analysis of the worker's decision of how much residential land to rent at the home location. This step is the first innovation of this paper. Equation (1) specifies an indirect utility function with income and land rents as its arguments. Shephard's lemma therefore applies. Hence, the share of land rents in total consumption satisfies:

$$\begin{aligned} \frac{L_{shj}R_h}{W_{sj}-X_{hjm}} &= \frac{\partial\left(\ln W_{sj}-x^c_{shjm}\right)}{\partial \ln R_h}=\rho_s \ln R_h^+, \\ \ln R_h^+ &\equiv \frac{d\ln R_h^*}{d\ln R_h}=1+\psi R_h. \end{aligned} \tag{5}$$

The elasticity of substitution η between land use and other consumption reads:[3]

$$\eta = 1-\frac{\rho_s\psi R_h}{\rho_s \ln R_h^+\left(1-\rho_s \ln R_h^+\right)}. \tag{6}$$

When $\psi=0$, the translog indirect utility function reduces to the Cobb-Douglas form where $\eta=1$ and where the land share in disposable income is constant, $R_h L_{shj}=\rho_s e^{-x^c_{shjm}}W_{sj}$. For $\psi>0$, the elasticity of substitution is smaller than unity and the land share is increasing in the land rent R_h.

Data for land use per level of education are not available. Hence, we calculate total land use per home location from equation (5)

$$\frac{A_h R_h}{\overline{W}_h}=\overline{\rho}\left(1+\psi R_h\right)+\zeta_h, \tag{7}$$

[3] The log cost function reads (leaving out the suffix h of R_h)

$$w\left(\ln R,\ln P\right)=\rho_s \ln R+\left(1-\rho_s\right)\ln P+\rho_s\psi\exp\left(\ln R-\ln P\right)$$

where P is the price of other consumption, which is normalized to unity (note: this function is homogeneous of degree one: 1% increase in all prices increases $w(\cdot)$ by 1%). The elasticity of substitution is equal to $1+w_{12}/\left(w_1 w_2\right)$, where the suffices refer to the partial derivatives. Using $P=1$ and simplification yields the expression in the text.

where $\overline{W}_h$ is total wage income at location h minus the average monetary cost of commuting[4], where $\overline{\rho}$ is a weighted average of ρ_s[5] and where ζ_h is an error term capturing unexplained variation in the land use. This equation can be estimated by OLS. The estimated value for ψ can then be used to construct the transformed log land rents $\ln R_h^*$ and $\ln R_h^+$.

3.3 The home location logit

The final step, the estimation of the logit model for the home location, is more involved. This step contains the second innovation of the paper. Analogously to the modal split and job location logits, a logit model for home location can be derived:

$$\begin{aligned} \Pr[h|s] &= \exp(z_h + q_{sh} + \ln K_h - q_s), \\ q_{sh} &\equiv \alpha_s' a_h + \mu_{Hs} g_{sh}^* - \rho_s^* \ln R_h^*, \\ q_s &\equiv \ln\left[\sum_{h\in H} \exp(z_h + q_{sh} + \ln K_h)\right], \end{aligned} \tag{8}$$

where $\rho_s^* \equiv \mu_{Hs}\omega_s\rho_s$ and $g_{sh}^* \equiv \mu_{Js}^{-1} g_{sh}$. However, the estimation of (8) is a close to impossible task due to two problems:

(i) since each alternative location has its own fixed effect z_h and since there are serveral thousand alternatives in our model, the computational burden of the estimation of this model is enormous;

(ii) since locations with high unobserved amenities z_h are more attractive than others and since the transformed land rents $\ln R_h^*$ must close the market for residential land at each location, z_h and $\ln R_h^*$ are correlated. Hence, the estimate of the coefficient ρ_s is downwardly biased.

The crucial insight is that the estimation of the model in equation (8) can be simplified enormously by a strategy similar to Berry et al. (1995) and Bayer et al. (2004). Our procedure involves two steps. First, we transpose the conditionality of the probabilities in model (8) using Bayes' rule. The estimation of this transposed logit model is a piece of cake.

[4] The average is taken over transport modes, where we use the probabilities $\Pr[m|shj]\Pr[j|sh]\Pr[s|h]$ to calculate the expectation.

[5] Strictly speaking, the average $\overline{\rho}$ varies across h, depending on the fractions of each education level s living at location h. As long as the differentials in ρ_s are not too big, ignoring this variation will not affect the estimation results for ψ much.

The second step estimates the land market clearing condition: land rents must make people indifferent between locations. Here, we correct for the selectivity of the different education levels preferring different locations using a method that is similar to Heckman's two step method for the estimation of Tobit models. Where that method lost its appeal for labour supply models, it turns out to work very well in the current context. For this second step, our procedure yields a new instrument to solve for endogeneity of prices: differences in the job attractivity g^*_{sh} at location h between levels of education. Some locations are attractive to high educated workers, others to low educated workers. Both steps are explained in more detail below.

First, instead of estimating $Pr[h|s]$, the probability of home location h conditional on the worker's education level s, we estimate $Pr[s|h]$, the probability of worker's education level s conditional on the home location h. So, instead of analysing what home location is chosen by a particular worker-type, we analyze what worker-type chooses this particular home location. By Bayes' rule and equation (8) we have:

$$\Pr[s|h] = \frac{\Pr[h|s]\Pr[s]}{\Sigma_{k\in S}\Pr[h|s=k]\Pr[s=k]} = \frac{\exp(q_{sh}+\rho^o_s)}{\sum_{k\in S}\exp(q_{kh}+\rho^o_k)}. \tag{9}$$

where $\rho^o_s \equiv \ln N_s - q_s$ and where as before $q_{sh} \equiv \alpha'_s a_h + \mu_{Hs} g^*_{sh} - \rho^*_s \ln R^*_h$. The first equality applies Bayes' rule. The second equality substitutes the probability $\Pr[s]$ for the actual frequencies of that level of education in the data $\Pr[s] = N_s/N$, where $N \equiv \Sigma_{s\in S} N_s$. This is again a logit model. However, this transposition of the original logit model (8) reduces the number of alternatives from the number of home locations (several thousand) to the number of education levels (just three). Furthermore, the fixed location effects z_h drop out. Instead, we have to estimate only three additional intercepts ρ^o_s, one for each level of education. This reduces the computational burden from several days to several minutes. This approach can be extended easily to a larger number of socioeconomic groups than the three education levels considered in this paper.

Estimation of this logit model yields estimates for α_s, ρ^*_s, and ρ^o_s up to a normalization for a reference alternative, for which the parameters is normalize to zero, at this stage without loss of generality. This is standard in logit models. We can only estimate the difference of these parameters relative to the unknown value for the reference alternative. However, such a normalization is not required for the parameter μ_{Hs}, since the corresponding variable g^*_{sh} varies between alternatives s. Hence, we have estimates for μ_{Hs} for every education level.

The second step uses the land market clearing condition. Bayes' rule implies $\Pr[h|s] =$

$\Pr[s|h]\Pr[h]/\Pr[s]$. Taking logs and rearranging terms and using equation (8) to substitute for $\ln\Pr[h|s]$ yields:

$$\begin{aligned}\ln\Pr[s|h] &= -\ln\Pr[h]+\ln\Pr[s]+q_{sh}+z_h-q_s+\ln K_h \\ &= \ln N_s+q_{sh}+z_h-q_s \\ &= \rho_s^o+\alpha_s'a_h+\mu_{Hs}g_{sh}^*-\rho_s^*\ln R_h^*+z_h. \end{aligned} \tag{10}$$

The second line substitutes the unconditional probabilities by their actual frequencies in the data, $\Pr[h]=K_h/N$ and $\Pr[s]=N_s/N$. Like the log probability $\ln\Pr[s|h]$, the transformed land rent $\ln R_h^*$ is correlated with the unobserved location characteristics z_h. Since we know $\mu_{Hs}g_{sh}^*$ from the first stage, we can use this variable as an instrument for $\ln R_h^*$. This boils down to a 2SLS estimation of the following equation:[6]

$$\ln\Pr[s|h]-\mu_{Hs}g_{sh}^*=\rho_s^o+\alpha_s'a_h-\rho_s^*\ln R_h^*+z_h. \tag{11}$$

One can follow two approaches for the calculation of $\ln\Pr[s|h]$ for the estimation of this equation. First, one can use the estimated coefficients from the logit model (9). The disadvantage of this approach is that calculation of the standard errors of the parameters becomes messy since the estimation errors of the first step enter the second step. Instead, one can substitute the log probability $\ln\Pr[s|h]$ for the log of the actual frequencies observed in the data, $\ln N_{sh}-\ln\sum_s N_{sh}$. This approach works if the number of observations for which s and h are known is sufficiently large. If not, the number of cells for which N_{sh} is (close to) zero becomes too large. The sample for which all of s,h,j, and m are known is small, but the sample for which just s and h are known is large. Hence, we can use the second approach.

The estimation of the models (11) and (9) yields estimates of $\rho_s^*\equiv\mu_{Hs}\omega_s\rho_s$ and μ_{Hs}, while the modal split logit (3) yields an estimate of ω_s. Hence, we can backout an estimate for ρ_s. The average value of ρ_s should be equal to the parameter $\overline{\rho}$ for the land use model, see equation (7). The intuition for this results is simple. Other things equal, the higher the land rent at a location, the less attractive is that location. Equation (10) analyses the weight workers attach to this factor in their location preference. This weight must be equal to share of land in their total consumption. An extreme case clarifies this argument. If the share of land in consumption would be zero, high land rents would not matter at all for

[6] We thank Guido Imbens for this idea.

workers' location preference. People should worry equally about land rents when choosing their location as when deciding on their consumption of land. Since there is nothing in the estimation procedure that guarantees this equality to be met, this relationship offers a test to the model. The availability of this test matters, as it lends credibility to our interpretation of ω_s as the marginal utility of log income. Our calculation of welfare hinges upon this interpretation.

Equation (11) can be written as a land rent equation:

$$\ln R_h^* + \rho_s^{*-1} \ln \Pr[s|h] = \rho_s^{*-1} (\rho_s^o + \alpha_s' a_h + \mu_{Hs} g_{sh}^* + z_h). \tag{12}$$

The term $\rho_s^{*-1} \ln \Pr[s|h]$ on the left hand side deserves a further analysis. This term accounts for the degree of selectivity in stochastic term $\widetilde{e}_{ih} + \widetilde{e}_{ih}^*$ of those workers who choose to live in h. Suppose that for a particular location h, $\Pr[s|h] \to 1$: all workers living in this location have education level s. Hence, there is no selectivity and the term drops out and equation (12) simplifies to:

$$\ln R_h^* = \rho_s^{*-1} (\rho_s^o + \alpha_s' a_h + \mu_{Hs} g_{sh}^* + z_h).$$

Hence, the left hand side variable $\ln R_h^* + \rho_s^{*-1} \ln \Pr[s|h]$ can be interpreted as the log land rent that would have applied if all workers had education level s.

Now, suppose to the contrary that $\Pr[r|h] \to 1$ and hence $\Pr[s|h] \to 0$, implying $q_{rh} \to \infty$, see equation (9). Then, equation (12) converges to:[7]

$$\ln R_h^* = \rho_r^{*-1} (\rho_r^o + \alpha_r' a_h + \mu_{Hr} g_{rh}^* + z_h).$$

Which set of coefficients determines the marginal contribution of amenities a_h to $\ln R_h^*$, whether it is α_s/ρ_s^* or α_r/ρ_r^*, depends therefore on the composition of the group of workers who prefer to live in location h: the higher the share of education level s, the more the marginal contributions converge to coefficients α_s/ρ_s^*.

4 Data and descriptives

The data on commuting are based on the 2004–2011 national travel survey for the Netherlands (Mobiliteitsonderzoek Nederland MON 2004–2009 and Onderzoek Verplaatsingen in

[7] Equation (9) implies $\lim_{q_{rh}\to\infty} \exp(q_{rh} - q_{sh}) \Pr[s|h] = 1$. Taking logs yields $\lim_{q_{rh}\to\infty} (q_{rh} - q_{sh} + \ln \Pr[s|h]) = 0$. Hence, $\ln \Pr[s|h]$ converges to $q_{sh} - q_{rh}$. Substitution in equation (12) yields the result.

Nederland OVIN 2010–2011). Respondents have been asked to report all their trips on a particular day. The response rate varies between 55 and 82%. Table 1 reports data selection. From the respondents for which home and job ZIP codes are available,[8] we select those aged between 18 and 65, not in full time education, working at least 12 hours per week. We drop respondents for whom education data are missing, with a home or work address outside the Netherlands or on one of the islands in the North Sea, reporting a post-office box as work address, or having made more than eight trips on the day of survey. We restrict the set of transportation modes to four alternatives: car as a driver, train, bus/tram/metro, bike/walk, deleting respondents commuting by other modes. The remaining dataset is merged with data on travel times, costs and distances for each transportation mode provided by the Dutch Ministry of Transportation for every combination of home and job ZIP codes for 2004. Details of these travel data are discussed in Appendix B.

Table 1 Data selection

# persons	MON	OVIN
	2004–09	2010–11
total respondents	310003	84339
working with known home and job ZIP code	75147	18463
selection on status and data availability (see text)	62130	14311
restriction to car, train, bus/tram/metro, bike/walk	56912	12964
travel data available and recorded correctly (see text)	53842	12003
land rents at home & job location available	53504	11835

Data on living amenities originate from three sources. Data on the area of nature are derived from the digital map "Land use" by Statistics Netherlands, 2006. Data on the accessibility of amenities are derived from the dataset "Proximity of amenities" by Statistics Netherlands, 2009. Data on the number of monuments are derived from the "Register of monuments" by Cultural Heritage Agency of the Netherlands. Data on residential land use are derived from the digital map "Land use" by Statistics Netherlands, 2006.

Data on land prices for the years 2004–2006 have been calculated from microdata on 2.5 million housing transactions provided by the Dutch Association of Real Estate Brokers (NVM). The method for decomposing the value of the land and the value of the construction

[8] A four-digit ZIP code contains on average 2000 houses. In urban areas, a ZIP code covers approximately a square kilometre.

is discussed in Groot et al. (2014). Land prices are converted into land rents per working day using capital cost of 4.2% per year and 228 working days per year, see Dijk and Romijn (2010).

5 Estimation results

5.1 Land use

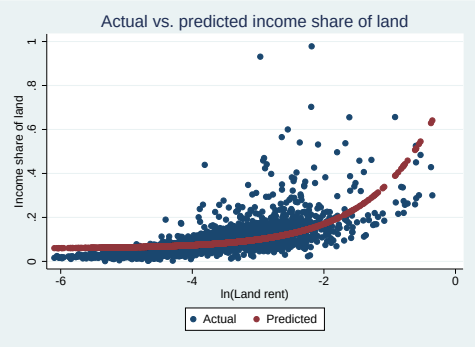
Table 2 reports estimates of equation (7). The coefficient ψ is positive and highly significant. Hence, the elasticity of substitution between land use and other consumption is less than one. Equation (6) implies an elasticity of 0.71 for the mean value of $\ln R_h$. This is consistent with Albouy and Ehrlich (2012) who report the elasticity of substitution between land and the value of construction to be about one-half, using US data. One would expect the land rent elasticity of the population density to be higher than that the intensity of construction, since people adjust both the intensity of construction per unit of land and the use of construction per person when the land rent is high.

Table 2 Residential land use

parameter	coefficient	t-value
ψ	14.184	(20.9)
$\overline{\rho}$	0.058	(38.9)
R^2		0.71
# observations		2812

Figure 3 shows that the model fits the general pattern in the data well, although it overestimates the land share for low levels of $\ln R_h$ substantially. This figure clarifies the reason for choosing a specification that combines a logarithmic term with a level term, $\ln R_h^* = \ln R_h + \psi R_h$, see equation (5): the second order polynomial in $\ln R_h$ as usually applied in a translog cost function is unable to capture the curvature in the data. The predicted land share in consumption varies from about 6% for the ZIP codes with the lowest land rents to well above 50% for the most expensive ZIP codes.

Figure 3. Actual vs. predicted income share of land



5.2 Modal split

Table 3 reports the estimation results for the modal split logit (3). Most variables are highly significant.[9] The parameter ω_s on transport cost measures the marginal utility of log income. Parking cost, defined as the local land rent per m^2 divided by disposable income, is a useful credibility check for the value of ω_s, since the ratio of the coefficient on parking cost to ω_s must be equal to the land use for parking. This calculation yields a land use of 34 m^2 at the home location and 21 m^2 at the job location, which are reasonable numbers. The car is a land intensive mode of transport. It is therefore a less popular for consumers living in locations where land is expensive. The difference in land use at the home and the job location can either be due to more efficient land use at the job location (e.g., parking garages) or to the fact that most facilities at the job location are paid for from pre-tax income while facilities at home are paid for from after tax income.

Higher educated have a strong preference for commuting by train or bike, holding other factors constant. Since the rail infrastructure is better in cities, this contributes to an explanation of why higher educated predominantly live and/or work in cities. Out-of-vehicle time is valued more negatively than in-vehicle time for public transport. Distance to a train station is valued negatively. A high degree of urbanization leads to a higher preference for travelling by bus/tram/metro. This might be related to the higher network quality and the higher service frequency. We have tried a version where all coefficients varied by level of education. However, allowing the intercepts of each mode of transport to vary by level of education captures most of the variation.

[9] We delete irrelevant alternatives, i.e.: (i) train if the total distance to transfer (home+job) is larger than 40 km; (ii) bus/tram/metro if in-vehicle time is larger than 2 hours or out-of-vehicle time is larger than 1.5 hour; (iii) bike if commuting distance is larger than 40 km, all for a single trip.

Table 3 Estimation results for the modal split model

General variables	coef	t-val				
cost in % net wage	-0.122[a)]	(8.6)				
time (minutes/10)	-0.261	(20.0)				
parking.costs at home[b)]	-4.184	(15.8)				
parking.costs at job[b)]	-2.543	(18.0)				
Alternative specific variables	train		bus		bike	
	coef	t-val	coef	t-val	coef	t-val
intercept	-1.574	(14.7)	0.029	(0.3)	0.622	(19.2)
high educated	0.578	(11.6)	-0.003	(0.1)	0.527	(16.9)
low educated	-0.480	(6.7)	0.006	(0.1)	-0.108	(3.4)
distance home-transfer (km/10)	-0.404	(9.7)				
distance job-transfer (km/10)	-0.518	(7.8)				
urbanization at home location			0.258	(15.2)		
urbanization at job location			0.289	(17.0)		
Δ time in vehicle (minutes/10)	0.177	(15.5)	0.071	(5.6)	-0.190	(13.7)
Δ time out vehicle (minutes/10)	0.000	(0.0)	-0.146	(4.8)		
# observations	58778					

a) This implies $\omega_s = 12.2$ (since the cost variable is %

b) in % wage/m^2

The implications of these estimation results are most easily judged from the implied values of time, see Table 4. The compensatory variation required to make people indifferent can be calculated from the cost variable. The value of time is higher for higher educated workers, because they earn a higher wage. An hour spent riding a car or waiting for the train is valued at the average wage rate in our data (18 euro for high, 14 euro for middle, and 11 euro for low educated workers). Time spent in train is less costly, while time spent waiting for a bus is more costly.[10]

[10] The values of time found for car and bus are somewhat higher, and the values of time for train somewhat lower than those reported in the recent stated preferences study for the Netherlands (Significance et al., 2013). The stated preferences values of time are (averaged over education levels, and over in- and out-of-vehicle time): 9 euro/hour car, 12 euro/hour train and 8 euro/hour bus.

Table 4 The values of time (euro/hour)

education	low	middle	high
car time	12	14	19
in-vehicle time train	4	5	6
out–of-vehicle time train	12	14	19
in-vehicle time bus	9	10	14
out–of-vehicle time bus	18	22	29

5.3 Job location

Table 5 reports the estimation results for the job location logit (4).[11] Some 10% of the observations work in the same ZIP code as where they live. We have no data on these commutes. Hence, the reported c_{shh} is equal to zero. We add a dummy for the average cost of intra ZIP code commuting. Since all parameters are education level specific, the model can be estimated for each education level separately.

Table 5. Estimation results for the job location logit

education	low		middle		high	
	coef	t-val	coef	t-val	coef	t-val
μ_{Js} unrestricted						
job accessibility c_{shj}	1.261	(225.2)	1.187	(296.8)	0.992	(247.5)
dummy home=job ZIP	-0.128	(4.7)	-0.282	(11.3)	-0.373	(11.3)
$\mu_{Js} = 1$						
dummy home=job ZIP	0.567	(25.0)	0.233	(11.1)	-0.398	(13.2)
# observations	17151		26189		21999	

The estimation results show that $c_{shh} = 0$ is a good proxy for intra ZIP code commutes.[12] Theoretically, one would expect the coefficient μ_{Js} by the transport cost indicator c_{shj} to be between zero and one. In that case, $1 - \mu_{Js}^2$ is the covariance between the error terms for the various transport modes within a ZIP code. For middle and low educated workers the estimates of the coefficient of generalized transport cost are larger than one. This result

[11] In theory, standard errors in the subsequent logit model should be corrected for the fact that part of the explanatory variables is constructed using estimates from previous logit model(s). In practice, this does make much of a difference.

[12] The c_{shj} varies from –34 to 0; the estimated dummy coefficients are thus reasonably close to zero.

might reflect a non-linearity in the utility function, which does not show up in modal split model (since conditional on h and j, workers have to choose a mode of transport), but does show up in the job location choice (people dislike far away job locations more than proportional). We have experimented with different specifications of the modal split model, but by and large this does not change this outcome much. In what follows, we restrict μ_{Js} to 1, implicitly assuming a multinomial logit structure of the modal split and job location choice.

Table 6 Explained variance of $c_{shj} + y_{sj} + \widetilde{e}_{ihj}$

level	low		middle		high	
μ_{Js} unrestricted	variance	share[13]	variance	share	variance	share
total	17.78	1.00	15.53	1.00	12.66	1.00
c_{shj}	15.45	0.80	13.04	0.77	9.74	0.72
y_{sj}	1.29	0.07	1.32	0.08	1.25	0.09
$\widetilde{e}_{ihj}$ [b)]	1.04	0.05	1.17	0.07	1.67	0.12
$\mu_{Js} = 1$						
total	18.35	1.00	16.11	1.00	12.66	1.00
c_{shj}	15.45	0.79	13.04	0.76	9.74	0.72
y_{sj}	1.28	0.07	1.43	0.08	1.24	0.09
$\widetilde{e}_{ihj}$	1.64	0.08	1.64	0.10	1.64	0.12

[a)] Variances do not add up to unity due to the covariances between c_{shj} and y_{sj}.

[b)] The residual variance is calculated from the Type-I extreme value distribution, $\mu_{Js}^{-2}\pi^2/6 = 1.64$.

Table 6 presents the decomposition of the variance of the explanatory variables. The generalized transport cost c_{shj} explains 70 to 80 % of the job location choice. The lower the education level, the larger the share of transport cost. The job location fixed effect y_{sj} plays a minor role. The correlation between transport accessibility of a job location and the job location fixed effect is positive. This supports the notion that transport infrastructure is endogenous. More attractive job locations are, on average, better accessible. Apparently, infrastructure investment is steered towards improving the more valuable links. This

[13] The shares of explained variance are exclusive the contribution of covariances; for this reason the shares do not sum up to 1.

emphasizes the importance of explicitly accounting for job locations fixed effect. Omitting these fixed effects would lead to biased estimates of effect of commuting cost on location choice.

5.4 Land rents and home location choice

Table 7 reports the estimation results for the land rent model, equation (11). The estimation results of the first stage, the home location logit model (9) are reported in Appendix C. The parameters μ_{Hs}, which correspond to the parameter on the job availability measure g^*_{sh} are all well below one, which confirms the nesting structure. Higher educated are less sensitive to land rents. Since land rents are higher in the city, this adds to an explanation why higher educated workers predominantly live in the city. Alternatively, this result can be interpreted as saying that higher educated are prepared to pay a higher premium for amenities of the city, such as an environment with many monuments, the proximity of univerisities and the availability of restaurants.

Table 7 also reports the implied values of ρ_s, which can be backed out from the estimated values of ρ^*_s ($\equiv \mu_{Hs}\omega_s\rho_s$), μ_{Hs} and ω_s (= 12.2 (t-stat 8.6), see Table 3). Their average value is somewhat above the value of $\overline{\rho}$ estimated from the land use regressions, $\overline{\rho} = 0.058$ (t-stat 38.9), see Table 2. However, the difference seems to be within the confidence interval. This lends credibility to our interpretation of ω_s as being the marginal utility of log income.

Table 7. Estimation results for home location choice[a)]

education level	low		middle		high	
variable	coef	t-val	coef	t-val	coef	t-val
$\ln R_h^*$ (ρ_s^*)	0.645	(50.3)	0.464	(57.9)	0.311	(28.0)
job.availability[b)] g_{sh}^* (μ_{Hs})	0.637	(3.6)	0.449	(2.3)	0.434	(2.4)
# monum.1km/1000	0.491	(5.8)	0.449	(8.5)	0.485	(6.6)
# monum.1-5km/1000	0.095	(4.1)	0.107	(7.5)	0.157	(7.9)
share nature within 5km	-0.079	(1.0)	0.052	(1.1)	0.484	(7.2)
dum. university in 10km	-0.074	(3.0)	-0.023	(1.5)	0.123	(5.8)
# restaurants 1km/100	0.338	(3.4)	0.581	(9.3)	0.625	(7.2)
# restaurants 1-5km/100	0.130	(9.0)	0.074	(8.2)	0.029	(2.3)
intercept	-3.238	(60.9)	-2.602	(78.3)	-2.300	(49.9)
implied value of ρ_s	0.083		0.085		0.059	
# observations		2758		2758		2758

[a)] Standard errors are robust, assuming clustering by ZIP code.

[b)] Coefficients obtained from the estimation of the logit model (9), see Appendix C

Table 8 reports the contributions of job availability g_{sh}^* and observed $\alpha_s' a_h$ and unobserved z_h consumption amenities to the total variance of $\ln R_h^* + \ln \Pr[s|h] / \rho_s^*$. The total variance is the highest for higher educated. The job availability explains 28 to 38% of the variance, where lower educated are on the high side. For the higher education levels amenities are more important, showing the importance of consumption externalities for location choice. Figure 4 provides a graphical documentation of the importance of job availability and amenities, for high and low educated. All panels depict the value of $\ln R_h^* + \ln \Pr[s|h] / \rho_s^*$ for each ZIP code, using intervals of 0.40. The upper panels show its level, which can be interpreted as the land rent different locations would command if their population consisted exclusively of lower and higher educated respectively. The middle panels show the contribution of job availability and the lower panels show the contribution of observed amenities. The relative contribution of job availability and amenities differs widely between levels of education. For lower educated, the contribution of amenities is rather flat, with the exception of the center of Amsterdam. For higher educated, the contribution of amenities is much more spread out. However, for both education levels, Amsterdam stands out relative to the rest of the country on the amenity side, while the contribution of job availability is spread

out much more evenly among the central Western part of the country. In general, amenities contribute substantially to the popularity of cities as an area to live, in particular Amsterdam. For high educated, there is a much higher variation in the attractivity of locations, both in terms of job availability and in terms of amenities. This adds to the explanation of the spatial seggragation between high and low educated workers documented in Figure 2.

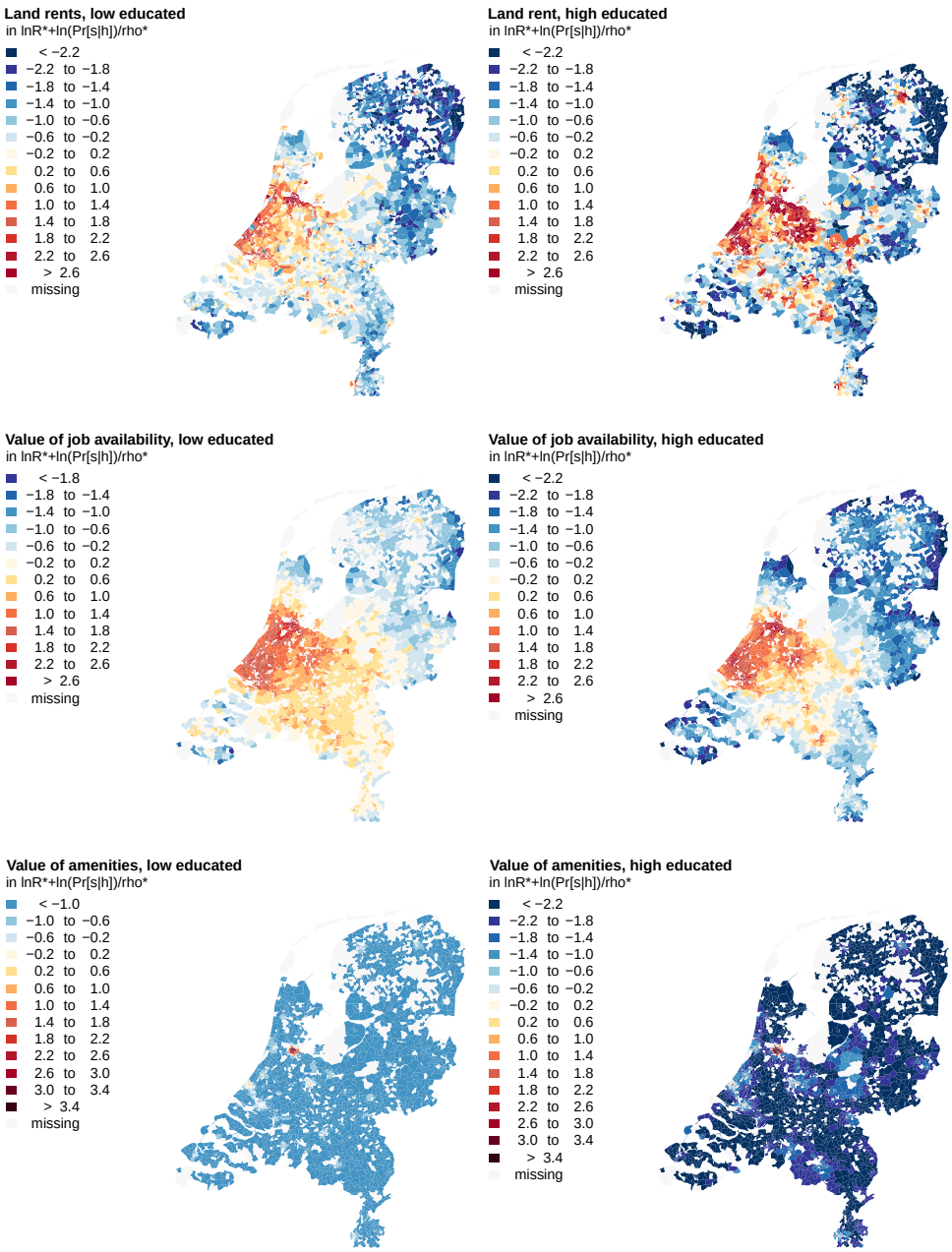
Table 8. Explained variance of $\ln R_h^* + \ln \Pr[s|h] / \rho_s^*$

level	low		middle		high	
	variance	share[14]	variance	share	variance	share
total	1.816	1.00	1.824	1.00	5.277	1.00
g_{sh}^*/ρ_s^*	0.696	0.38	0.622	0.34	1.472	0.28
$\alpha_s' a_h/\rho_s^*$	0.255	0.14	0.385	0.21	0.949	0.18
z_h/ρ_s^*	0.487	0.27	0.365	0.20	1.574	0.30

[a)] Variances do not add up to unity due to the covariances between the explanatory variables.

[14] The shares of explained variance are exclusive the contribution of covariances; for this reason the shares do not sum up to 1.

Figure 4. Value of job availability g_h^* and observed amenities a_h, expressed in terms of $\ln R_h^* + \ln \Pr[s|h] / \rho_s^*$. Low educated left, high educated right.[15]



[15] In all panels, 0 corresponds to a location in Enschede with an average land price of 109 euro/m^2.

6 Comparative statics and welfare analysis

6.1 Equilibrium

An equilibrium to this economy are two vectors, of the number of houses $K = \{K_h\}$ and of land rents $R = \{R_h\}$ satisfying equation (5) for land use, $L_{shj} = R_h^{-1} \ln R_h^+ e^{-x^c_{shj}} W_{sj}$, such that supply and demand for housing at each location are equal:

$$\begin{aligned} K_h &= \sum_{s \in S} \Pr[h|s,R,K] N_s, \qquad (13) \\ K_h &= \left[\sum_{s \in S} \rho_s \Pr[h|s,R,K] N_s \sum_{j \in H} \Pr\left[j|sh,R\right] e^{-x^c_{shj}} W_{sj} \right]^{-1} \frac{R_h A_h}{\ln R_h^+}. \end{aligned}$$

The first equation measures the demand for housing, the second equation measures its supply. This is a system of $2 \times H$ equations. We cannot prove existence. The solution method is discussed in Appendix D.

6.2 Welfare analysis

There are four types of agents in our model, three types of workers differing by their level of education s and a class of absentee landlords. It is most convenient to think of workers renting the land from these landlords. Landlords might be further subdivided in local subgroups, as we will do in our empirical application. The effect on the wealth of landlords Q_l is equal to the sum of the effect on land rent across all locations:

$$Q_l = \sum_{h \in H} A_h \left(R_h^n - R_h^o \right),$$

where the superscripts n and o refer to the new and the old equilibrium respectively.

The effect on the wealth Q_s of consumers with education level s is derived from their utility. The variable q_s as defined in equation (8) is a convenient measure for the expected utility of a workers with education level s. This can be seen as follows. Let v_s be defined as $v_s \equiv \mathrm{E}_i \left[\max_{h \in H} \left(v_{ih} \right) \right]$, the expected utility for a worker with education level s. Similar to equation (17) in Appendix A, v_s satisfies:

$$v_s = \mu_{Hs}^{-1} q_s + \mathrm{E}\left[\widetilde{e}_i^* \right],$$

where $\widetilde{e}_i^*$ follows the same distribution as $\widetilde{e}_{ih} + \widetilde{e}_{ih}^*$, see Appendix A. Since $\mathrm{E}[\widetilde{e}_i^*]$ is a constant and since v_s is an increasing transformation of q_s to which a utility function is invariant, q_s

can be used as an alternative utility measure without affecting the welfare evaluation. We are looking for the equivalent variation EV_s that makes consumers of that level of education indifferent between the situation before and after the change in c_{shjm} :

$$q_s^n(R^n) = q_s^{o+}(R^o),$$

where $R^{n,o}$ is the vector of $R_h^{n,o}$, where the superfixes n and o for the utility function $q_s^{n,o}(R)$ indicate what value of c_{shjm} is applied -before or after the investment-, where the dependence of q_s on R is explicitly addressed, and where we add a superscript + to $q_s^o(R^o)$ to indicate that it is evaluated after granting the individual a money transfer EV_s to make her indifferent between the old and the new equilibrium. Technically, the money transfer is implemented by an increase in y_{sj} for all j by an amount EV_s/W_s where W_s is the average wage for education level s. A Taylor expansion of this equation implies:

$$\frac{Q_s}{N_s} = EV_s \cong \frac{q_s^n\left(R^n\right) - q_s^o(R^o)}{\sum_{j\in H} W_{sj}^{-1} \partial q_s^o(R^o)/\partial y_{sj}} \tag{14}$$

This general equilibrium effect can be decomposed in four components:

(i) the effect of the change in the transport cost for transport mode m for people who use that mode;

(ii) the effect of people changing transport modes because the relative cost of using them have changed;

(iii) the effect of people changing their job location because some jobs have become more easily accessible;

(iv) the effect of people changing their home location because locations change in their relative attractiveness for people with different levels of education and since changes in land rents induce changes in the intensive of land use of at various locations.

It is important to realize that amount of land available for residential use at each location is fixed. Hence, if the consumption of land per worker were fixed and if all workers had equal preferences, the fourth effect would not exist. The expressions for the cumulative effect of these four components are listed in Table 10. The final line is again the integral effect described in equation (14). The derivation of these expressions is relegated to Appendix D.

Table 10 Decomposition of the general equilibrium effect per person[a)]

users of mode m[b)]	$\omega_s^{-1} \sum_{h\in H} \sum_{j\in H} \Pr[hjm\|s] \left(c^n_{shjm} - c^o_{shjm}\right) W_{sj}$
idem + modal shift[c)]	$\omega_s^{-1} \sum_{h\in H} \sum_{j\in H} \Pr[hj\|s] \left(c^n_{shj} - c^o_{shj}\right) W_{sj}$
idem + job relocation	$\left[\omega_s \mu_{Js} \sum_{j\in H} \frac{\Pr[j\|sh]}{W_{sj}}\right]^{-1} \sum_{h\in H} \Pr[h\|s] \left(g^n_{sh} - g^o_{sh}\right)$
idem + home relocation	equation (14)

[a)] All probabilities are evaluated in the old equilibrium

[b)] $\Pr[hjm|s] = \Pr[hj|s] \Pr[m|shj]$

[c)] $\Pr[hj|s] = \Pr[h|s] \Pr[j|sh]$

7 Policy experiment

The model and the expression in Table 10 are applied to a policy experiment, using the parameter values reported in Table 11. The city of Amsterdam is located just south of a major canal, connecting the Amsterdam harbour to the North Sea. The main connections between Amsterdam and the area North of the canal consist of five highway tunnels and two train tunnels. Figure 5 illustrates the location of the canal and the railway network in the region. The areas North and South are indicated in dark pink respectively light pink. Since many people commute from the North to jobs in Amsterdam and the neighbouring municipality of Haarlemmermeer (the location of Schiphol airport), this connection is crucial for the Dutch economy. As a policy experiment, we consider what difference the availability of these rail tunnels makes. We calculate a counterfactual in which the rail tunnels are closed, and compare it to the present equilibrium.

Figure 5 North Sea canal area

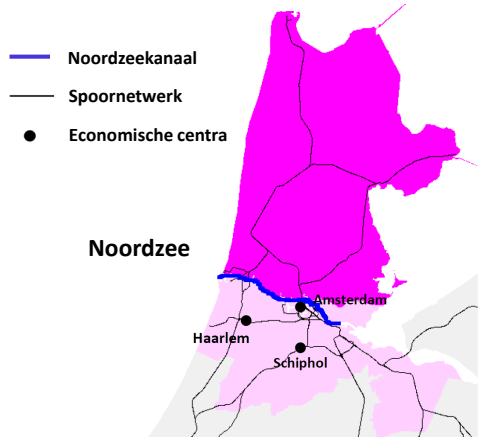


Table 11. Parameter values used in the experiment

parameter	all	low	middle	high
ω	12.24			
μ_J	1.00			
ψ	14.18			
μ_{Hs}		0.64	0.45	0.43
ρ_s [a)]		0.078	0.080	0.055
# monuments within 1km/1000		0.49	0.45	0.49
# monuments 1 to 5km/1000		0.095	0.107	0.157
share nature within 5km		-0.079	0.052	0.484
dummy university 10km		-0.074	-0.023	0.123
# restaurants within 1km/100		0.338	0.581	0.625
# restaurants 1 to 5km/100		0.130	0.074	0.029
ρ_s^0		-3.24	-2.60	-2.30

[a)] The values of ρ_s are weighted averages of $\overline{\rho}$ from Table 2 and ρ_s from Table 3

Table 12 describes the relocation of economic activity between the regions north and south of the canal due to the availability the tunnels. The better connection of the less productive region north of the canal to vibrant metropolitan area around Amsterdam leads to a relocation of jobs from the North to the South. The number of jobs in the North declines by 5%. Some 32.000 workers commute by train from the North to the South; 80%

are additional commuters. Figure 6 documents the job relocation process. However, the lower concentration of jobs in the North comes along with a higher quality of living, as can be seen from the increase in land prices in the North in particular along the railway corridors, see Figure 7. Higher land prices lead to a lower land use per worker. Hence, the total population in the North goes up. Since Amsterdam is particularly attractive as a job location for higher educated and since higher educated prefer travelling by train, the main part of the population increase are higher educated, their population being 5% higher due to the availability of the tunnels. The analysis shows that a new transportation link may lead to a flight of jobs from the periphery, but also to an increase in the price of residential land by making the region a more attractive residential area, in particular for higher educated.

Figure 6. Jobs flight to highly productive job locations south of the canal

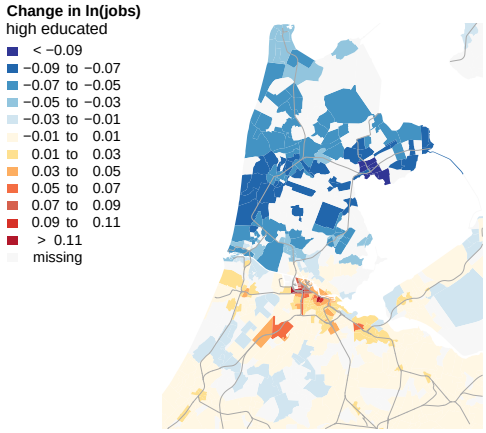


Figure 7. Higher land prices and higher population north of canal

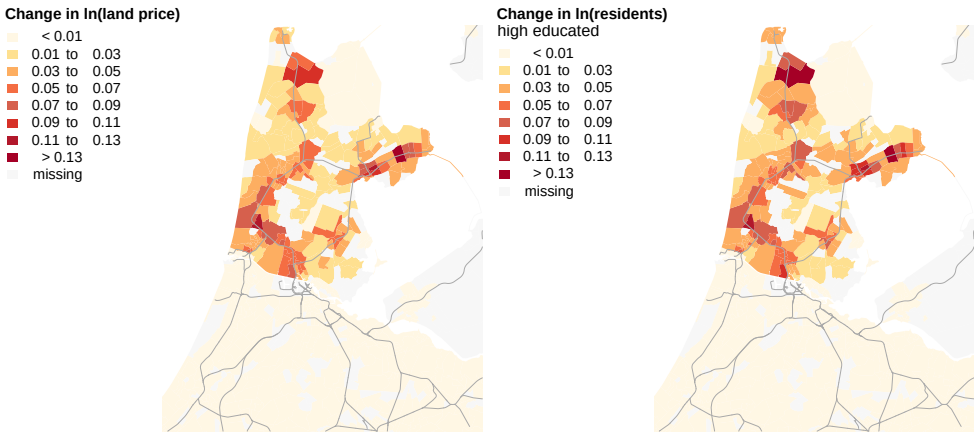


Table 12 Residents, job, and commuting North and South, in thousands

tunnels:	no				yes			
	low	middle	high	total	low	middle	high	total
residents:								
North	129	185	170	484	129	189	179	497
South	162	264	378	804	162	263	378	803
jobs:								
North	111	147	135	393	107	141	129	377
South	197	331	438	966	201	340	448	988
commuting:								
North-South	24	43	43	110	28	52	55	135
train	0	0	0	0	5	12	15	32
car	19	35	35	89	18	33	33	84
South-North	7	11	15	32	7	11	16	34
train	0	0	0	0	0.3	0.6	1	2
car	6	10	13	29	6	10	13	29
North-North	101	132	115	348	96	125	106	328
South-South	126	202	289	617	126	202	287	615

Table 13 reports the welfare gains from the tunnels. The net welfare benefits for landowners are relatively small: landowners in North and South gain, landowners elsewhere loose. This is due to the greater attractivity of the North for living. This reduces the demand for land elsewhere in the country. In this example, the negative and positive effect for land rents largely cancel. In other applications, either land rents went down or they went up, depending on the land rent in the area that benefits most of the investment. If land rents in this area are initially above average, the share of land rents increase because land rents go up for individuals with a high land share in their consumption and down for individuals with a low land share, and the reverse if land rents are initially low in the most affected area. This is due to the fact that the land rent elasticity of individual land use is less than one. Agglomeration of economic activity at a small number of hot spots will therefore favor the class of land owners as a whole, though in fact only the land owners in big cities will benefit.

Table 13 also show that the benefits of the tunnels are distributed unevenly among

education levels: highly educated individuals benefit more, since they have the highest preference for commuting by train and the most to gain from being able to commute to the vibrant Amsterdam economy with its wide availability of high paying jobs. Their benefits are twice as high as the benefits of middle educated and eight times higher than the gains of low-educated individuals. This is in line with Kuminoff and Pope (2013) and Bayer et al. (2007) who report a wedge between the capitalisation effect and the total welfare effect of a policy measure. This effect arises due to changes in hedonic schedule caused by relocation of people and can be very substantial, as illustrated by our counterfactual example.

Table 13 Decomposition welfare effects, in mln euros

effect	education level			land owners			total
	low	middle	high	North	South	Else	
modal split	203	595	1149				1947
job relocation	67	195	464				726
home relocation	-50	-65	57				-58
land owners				1755	-166	-1477	113
total	220	725	1670	1755	-166	-1477	2615

The direct gain via the modal split makes up for about two thirds of the total welfare gain, while job relocation mainly be commuting more attractive jobs acounts for another third. Though the home relocation effect and the effect for landowners are relatively small in total, they are very important for the distribution of the gains. The home relocation effect is negative. At the first sight it seems counter-intuitive that a relaxation of the constraint on changing the home location can decrease welfare. The reason is that part of the benefits is transferred to land owners by an increase in local land rents. Low and middle educated lose because they derive little benefit from the new infrastructure while they face higher land rents due high educated workers driving up land rents at locations close to stations.

8 Conclusion

Land rents provide a useful tool for the welfare impact of changes in the supply of public goods. However, ignoring the relocation of people with different education levels due to selection effects and changes in the intensity of land use miss important aspects of the distribution of the gains from infrastructure. Since the valuation of public goods differs widely

across education levels, their benefits of invetments in this infrastructure are distributed unequally between them. The application to a policy experiment, closing down the railway tunnels connecting Amsterdam to the region North of the city, shows that the direct effect on the modal splitt ignores indeed substantial indirect effects, up to 30% of the total effect. Moreover, the benefits of the railway tunnels are distributed highly unequally across education levels indeed, the gains for higher educated being ten times larger than for lower educated. This unequal distribution of benefits poses a challenge for the political economy of investment in transport infrastructure.

Like any model, our analysis has its limitations. We mention three. First, there is no feedback of changes in modal split on travel times. For example, if the closure of the railway tunnels were to lead to a massive increase in car traffic, that would increase travel times for these trips. However, travel times are treated as exogenous in our application. This leads to an underestimation of the benefits. Luckily, travel by car did not massively increase in our policy experiment, so this does not affect our conclusions much.[16] Second, we allow for changes in land intensity within the area available for residential use, but we do not allow for transferring land from agricultural to residential use. Similarly, we do not allow for agglomeration benefits and the local supply of amenities to be adjusted to changes in the structure of the economy. Again, ignoring this margin of adjustment leads to an underestimation of the benefits of public goods. Our research does not provide information about the magnitude of this effect. Getting a better feel for the magnitude of these additional effects is a challenge for future research.

[16] This is in line with various existing studies (see e.g. Parry and Small, 2009, Duranton and Turner, 2011) suggesting that public transit is unlikely to generate large reductions in traffic congestion. Duranton and Turner's "fundamental law of road congestion" implies that in the long run individuals react to increases in congestion levels by reducing travel to some degree or by migrating. Anderson (2014) argues however that ceasing public transit service on highly congested routes would result in a marked increase in traffic delays, also in the long run.

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Online appendices
Appendix A Derivation of the logit models

Workers choose the transport mode maximizing v_{ihjm}. Hence, by equation (1)

$$\begin{aligned}\Pr[m|ihj] &= \Pr[v_{ihjm} > v_{ihjk}|\forall k \in M] \\ &= \Pr[c_{shjm} + \widetilde{e}_{ihjm} > c_{shjk} + \widetilde{e}_{ihjk}|\forall k \in M].\end{aligned}$$

This is a standard logit model, see equation (3). Applying the formula for a maximum of a number of type I extreme value stochasts with equal variance yields

$$\begin{aligned}\max_{m\in M}[c_{shjm} + \widetilde{e}_{ihjm}] &= c_{shj} + \widetilde{e}^*_{ihj}, \\ c_{shj} &\equiv \ln\left(\Sigma_{m\in M} c_{shjm}\right).\end{aligned} \tag{15}$$

$\widetilde{e}^*_{ihj}$ follows the same distribution as $\widetilde{e}_{ihjm}$. Define $v_{ihj} \equiv \max_{m\in M}(v_{ihjm})$. Substitution of equation (15) in (1) yields

$$\begin{aligned}v_{ihj} &= \mu_{Hs}^{-1}\left(z_h + \alpha_s' a_h + \ln K_h\right) + \mu_{Js}^{-1} g_{shj} - \omega_s \rho_s \ln R_h^* \\ &\quad + \widetilde{e}_{ih} + \widetilde{e}_{ihj} + \widetilde{e}^*_{ihj}, \\ g_{shj} &\equiv \mu_{Js}\left(c_{shj} + y^*_{sj}\right).\end{aligned} \tag{16}$$

Workers choose the job location maximizing v_{ihj}. Hence, by equation (16)

$$\begin{aligned}\Pr[j|ih] &= \Pr[v_{ihj} > v_{ihk}|\forall k \in H] \\ &= \Pr[\mu_{Js}^{-1} g_{shj} + \widetilde{e}_{ihj} + \widetilde{e}^*_{ihj} > \mu_{Js}^{-1} g_{shk} + \widetilde{e}_{ihk} + \widetilde{e}^*_{ihk}|\forall k \in H].\end{aligned}$$

$\widetilde{e}_{ihj} + \widetilde{e}^*_{ihj}$ follows the same distribution as $\widetilde{e}_{ihj} + \widetilde{e}_{ihjm}$. Hence, $\Pr[j|ih]$ satisfies equation (4). Similar to equation (15)

$$\begin{aligned}\max_{j\in H}\left[\mu_{Js}^{-1} g_{shj} + \widetilde{e}_{ihj} + \widetilde{e}^*_{ihj}\right] &= \mu_{Js}^{-1} g_{sh} + \widetilde{e}^*_{ih}, \\ g_{sh} &\equiv \ln\left(\Sigma_{j\in H} g_{shj}\right).\end{aligned} \tag{17}$$

$\widetilde{e}^*_{ih}$ follows the same distribution as $\widetilde{e}_{ihj} + \widetilde{e}^*_{ihj}$.

Substitution of equation (17) in (16) yields

$$\begin{aligned}v_{ih} &= \mu_{Hs}^{-1}\left(z_h + q_{sh} + \ln K_h\right) + \widetilde{e}_{ih} + \widetilde{e}^*_{ih}, \\ q_{sh} &\equiv \alpha_s' a_h + \mu_{Hs}\mu_{Js}^{-1} g_{sh} - \mu_{Hs}\omega_s\rho_s \ln R_h^*.\end{aligned} \tag{18}$$

Hence

$$v_{ih} = \mu_{Hs}^{-1}\left(z_h + q_{sh} + \ln K_h\right) + \widetilde{e}_{ih} + \widetilde{e}_{ih}^{*} \tag{19}$$

Workers choose the home location maximizing v_{ih}. Hence, by equation (19)

$$\begin{aligned}\Pr\left[h|i\right] &= \Pr\left[v_{ih} > v_{ik}|\forall k \in H\right] \\ &= \Pr[\mu_{Hs}^{-1}\left(z_h + q_{sh} + \ln K_h\right) + \widetilde{e}_{ih} + \widetilde{e}_{ih}^{*} > \mu_{Hs}^{-1}\left(z_k + q_{sk} + \ln K_k\right) + \widetilde{e}_{ik} + \widetilde{e}_{ik}^{*}|\forall k \in H].\end{aligned}$$

Hence, $\Pr\left[h|i\right]$ satisfies equation (8).

Appendix B Data

Travel times by car are reported for the morning peak hour between 7 and 9 a.m. When multiple routes are possible, travel times, costs and distances are calculated as averages over all possible routes, weighted by the number of commuters using each route. The cost of car travel has been set at 0.3 euro for every kilometre traveled plus toll costs.[17] Travel times by train and bus/tram/metro are split up between in- and out-of-vehicle times. Travel costs for the train have been provided by the Ministry of Transportation; travel cost for bus/tram/metro is calculated from the number of urban transit zones traveled.[18] Biking and walking travel times are calculated by using the travel distances calculated for car trips, assuming an average speed of 16 km/hr. The cost of these trips is set equal to zero. We deleted implausible observations, e.g. for which the actually chosen travel mode is characterized by very large or very small travel times and/or distances (below the 2.5 or above the 97.5 percentile for the mode concerned; home-work distances smaller than the home-work straight line).

Table 14 presents the descriptive statistics of the mode choice by education level. Table 15 presents the number of ZIP codes with positive number of workers and people living there. Summary statistics for the amenity variables, for land prices, and for ZIP code fixed effects in wages are presented in Table 16.

[17] This includes fuel, amortization, insurance, maintenance, and taxes for a car in a medium-price range, using http://www.autoweek.nl/kostenberekening.php?id=35685&jaar=2005) using a gasoline price of €1.25 per litre or €0.10 per kilometre for 2005 and of €1.78 per litre or €0.15 per kilometre for 2012.

[18] Cost = €0.43 times the number of urban transit zones plus one.

Table 14 Descriptive statistics for commuting data

mode	car		train		bus		bike, walk	
	mean	st.dev.	mean	st.dev.	mean	st.dev.	mean	st.dev.
modal share	0.71		0.05		0.03		0.21	
distance, km	44.7	(36.9)	87.9	(47.4)	29.9	(19.2)	11.6	(7.2)
duration, min	48.9	(30.0)	143.6	(42.4)	85.9	(34.4)	43.4	(27.0)
cost, euro	6.8	(5.4)	6.8	(3.3)	3.7	(1.5)	0	

Table 15 Coverage of the population data commuters

	our dataset	The Netherlands
# home ZIP codes	3520	4019
# work ZIP codes	3247	4015
working population (mln)	7.40	7.50
mean # residents by ZIP code	2103	1867
mean # jobs by ZIP code	2384	1951
fraction males	0.56	0.56
fraction per education level:		
- low	0.25	0.27
- middle	0.36	0.44
- high	0.38	0.30

Table 16 Descriptive statistics on wages, land prices, and amenities by ZIP code

variable	unweighted		weighted by # residents/workers		# ZIP codes
	mean	st.dev.	mean	st.dev.	
ln net daily wage low	4.514	0.039	4.515	0.038	2729
ln net daily wage middle	4.668	0.054	4.678	0.053	2834
ln net daily wage high	4.961	0.044	4.976	0.039	2510
ln daily land rent	-3.689	0.901	-3.329	0.891	2758
# monum.1km/1000	0.032	0.161	0.051	0.238	2758
# monum.1 to 5km/1000	0.284	0.779	0.463	1.161	2758
share nature within 5km	0.127	0.114	0.132	0.109	2758
dummy uni.10km	0.269	0.444	0.380	0.485	2758
# rest. 1km/100	0.054	0.159	0.086	0.224	2758
# rest.1 to 5km/100	0.634	1.507	1.055	2.242	2758
share social housing	0.256	0.157	0.298	0.155	2754

Appendix C Estimation results first-stage transpose logit

Table 17 Estimation results home location logit

education level	low		middle		high	
variable	coef	t-val	coef	t-val	coef	t-val
job availability g^*_{rh}	0.637	(3.6)	0.449	(1.6)	0.434	(2.4)
$\ln R^*_h$	-0.177	(2.9)			0.138	(2.3)
# mon.1km/1000	-0.131	(0.4)			-0.062	(0.2)
# mon.1-5km/1000	-0.017	(0.2)			0.020	(0.3)
share nature 5km	0.089	(0.3)			0.409	(1.3)
dummy.uni.10km	-0.001	(0.0)			0.138	(1.5)
# rest. 1km/100	-0.331	(1.0)			0.097	(0.3)
# rest.1 to 5km/100	0.062	(1.1)			-0.020	(0.4)
intercept	-0.587	(2.5)			0.276	(1.3)
# observations	2.75 mln					

Appendix D Solution method and welfare analysis

Equilibrium is described by a system of supply and demand for housing:

$$\begin{aligned} K^d_h &= \sum_{s\in S} \Pr[h|s,R,K^s]N_s, \\ K^s_h &= \left[\sum_{s\in S}\sum_{j\in H} \rho_s \Pr[h|s,R,K^d]\Pr[j|sh,R]\, e^{-x^c_{shj}} W_{sj} N_s\right]^{-1} \frac{R_h A_h}{\ln R^+_h}. \end{aligned}$$

where the superscripts s and d for K denote supply and demand. The task is to adjust R to set equal demand and supply at each location. The land rent elasticity of demand is approximately equal to:

$$d\ln K^d_h \cong -\rho^*_s d\ln R^*_h \cong -\rho^*_s \ln R^+_h d\ln R_h,$$

see equation (8). This elasticity is used to calculate an update for land rents $\Delta \ln R_h$:

$$\Delta \ln R_h = \xi(\ln K^d_h - \ln K^s_n),$$

where ξ is a smoothing parameter.[19] This new value of land rents is used to repeat this calculation.

[19] ξ is set equal to 0.2. This procedure for updating R ignores the price elasticity of supply, but that does

For yhe welfare analysis we need the partial derivatives of the utility with respect to income. By equation (16) and (18), we have:

$$\begin{aligned} g_{shj} &= \mu_{Js}\left(c_{shj} + \omega_s y_{sj}\right), \\ q_{sh} &= \alpha_s' a_h + \mu_{Hs}\mu_{Js}^{-1} g_{sh} - \rho_s^* \ln R_h^*. \end{aligned}$$

Hence, by equation (4) and (8):

$$\begin{aligned} \frac{\partial g_{shj}}{\partial y_{sj}} &= \mu_{Js}\omega_s, \\ \frac{\partial g_{sh}}{\partial y_{sj}} &= \exp(g_{shj} - g_{sh})\frac{\partial g_{shj}}{\partial y_{sj}} = \mu_{Js}\omega_s \Pr[j|sh], \\ \frac{\partial q_{sh}}{\partial y_{sj}} &= \mu_{Hs}\mu_{Js}^{-1}\frac{\partial g_{sh}}{\partial y_{sj}} = \mu_{Hs}\omega_s \Pr[j|sh, W_s], \\ \frac{\partial q_s}{\partial y_{sj}} &= \sum_{h\in H} \exp(z_h + q_{sh} + \ln K_h - q_s)\frac{\partial q_{sh}}{\partial y_{sj}} = \sum_{h\in H} \Pr\left[h|s, R, W_s\right]\frac{\partial q_{sh}}{\partial y_{sj}}. \end{aligned}$$

not hamper our ability to find a solution. In the empirical application in Section 7, the system converges to an equilibrium in about 110 iterations.