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Does improving public transport decrease car ownership? Evidence from a residential sorting model for the Copenhagen metropolitan area

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ABSTRACT

Car ownership is lower in urban areas, where public transport is of high quality. This suggests that better public transport offers the possibility to relieve the many problems (congestion, pollution, and parking) associated with the presence of cars in urban areas. To investigate this issue, we develop a model for the simultaneous choice of residential location and car ownership by households, and estimate it on Danish data, paying special attention to accessibility of the metro network. We use the estimated model to simulate the impact of an extension of the metro network. We show that for the Greater Copenhagen Area an extension of the metro network decreases car ownership by 2–3%, while the average compensating variation is approximately 3% of household income.

1. Introduction

Public transport is, potentially, an important substitute for the car. If parking spaces are difficult to find, or if parking is expensive, as is the case in many city centres, the benefits of owning a car may still be lower (Van Ommeren, Wentink and Dekkers, 2011; Ostermeijer et al., 2019). Moreover, the availability of many amenities at walking distance in dense residential areas decreases the value of owning a car even further. It is therefore no surprise that the share of car-owners is lower in urban than in rural areas (see, for instance, Dargay, 2002).[1]

In this paper we investigate this issue by developing and estimating a choice model in which households simultaneously decide on residential location and car ownership, while taking into account the availability of public transport, and use the estimated model to simulate the effects of an extension of the public transport network. The interaction between car ownership and public transport is of considerable interest because road congestion is an important problem in many urban areas, and recent research suggests that the presence of public transport may have an important impact on urban congestion and pollution (Anderson, 2014; Bauernschuster et al., 2017). Moreover, pollution by cars associated with health problems and global warming to which CO_2 emissions of cars contribute, is perhaps the most important environmental problem of our age. Cities can be relatively green places (see e.g. Kahn, 2006) and the lower share of car owners contributes to that.

Substitution between cars and public transport presumably depends on the price and availability of both. While prices are a standard element in economic models, availability is often taken for granted. This may be problematic for public transport as the density of railroad stations, metro stations and bus stops, and hence the accessibility of employment, varies with population density and shows substantial differences over space. This suggests that availability of public transport has some of the characteristics of a local public good and is associated with Tiebout sorting (see e.g. Epple and Sieg, 1999).

The close connection between residential location and availability of public transport suggests – quite strongly – that an analysis of the substitution between car and public transport should be integrated with that of location choice. Accordingly, it is the purpose of this paper to develop a simultaneous model for residential location choice and car ownership while taking the spatial aspect of the availability of public transport properly into account. Doing so means that we fill a gap in the current

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[1] These effects are also found *within* urban areas. We will also see later that the share of car-owners is lower in the central city of Copenhagen compared with the suburbs.

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literatures in economics, planning, geography and transportation.

The interplay between public transport and car ownership, has received little attention in economics.[2] There is an older literature looking at car ownership (see, for instance, Mannering and Winston, 1985) that pays marginal attention to it. For instance de Jong (1990) develops a binomial model in which car ownership and use are modelled simultaneously and reports that living in a rural area increases the probability of owning a car.

There has been a substantial interest in the relationship between traffic and the built environment among planners (see Ewing and Cervero, 2010; Kenworthy and Laube, 1999 for reviews), but much less for car ownership and its relationship to the provision of public transport. There also exists a small geographic literature on the impact of urban form and urban amenities on car ownership. See for instance Dieleman et al. (2002); and Potoglou and Kanaroglou (2008). In this literature car ownership is estimated as a binomial choice, conditional on the characteristics of the residential area. For instance, Potoglou and Kanaroglou (2008) find that mixed land use is associated with a lower share of car owners.

It is surprising that even in transportation the impact of accessibility of public transport on car ownership does not seem to be an intensively studied topic. It has been addressed in an older literature (see for instance Goodwin, 1993), but appears to have been almost neglected in recent decades. Matas, Raymond and Roig (2009) is an exception.

In this paper we develop a structural model in which we treat the choice of car ownership and residential location as a simultaneous decision, that depends on the availability of public transport. That is, we assume that households looking for a residential location contemplate to live in a particular area while owning a car or not. More specifically, our model extends a logit-based 'horizontal' residential equilibrium sorting model (see Kuminoff et al., 2013) with car ownership. From the viewpoint of transportation economics it may be said that our model extends a standard car ownership model with residential location choice. The choice alternatives in our model are combinations of residential areas, single or multi-family housing and car ownership. Interactions between characteristics of the residential areas and car ownership are the focus of interest. The residential area characteristics include public transport related amenities as well as more traditional urban amenities. We model car ownership in a relatively simple way by focusing on the number of cars per household, while ignoring differences between car brands, makes, et cetera.

The model is estimated on administrative data for Copenhagen, the capital of Denmark. The choice of a European city appears natural, because of the availability of public transport that has sufficient quality to offer a real alternative to the car, at least in some locations. Related to this is the fact that there is a substantial share of households not owning a car, whereas in the US car ownership is the default.[3]

To get an idea of how expansion of public transport would affect car ownership and residential location choice, we use the estimated version of the model to simulate the impact of an extension of the Copenhagen metro network. The model predicts house prices, demographic composition of neighbourhoods and car ownership in this counterfactual situation. We also compute the impact on welfare of this improvement in public transport implied by our model.

The results we report provide important information for cost-benefit analyses of extending subway systems that are often neglected in practice[4]: the potential impacts of changes in demographic composition of neighbourhoods on traffic congestion, pollution of fine particles, CO_2 emissions, and the number of traffic accidents. Although the present paper makes no attempt to evaluate these externalities, it provides important ingredients for the necessary computations.

The paper is organized as follows: in the next section we briefly describe the most relevant characteristics of the data and the study area (the Greater Copenhagen Area (GCA)). In section 3 we present and discuss the theoretical model and the specification we use in our empirical work. Section 4 reports the estimation results. In Section 5 we simulate the response of an extension of the metro network. Section 6 concludes.

2. Data and descriptives

2.1. The Greater Copenhagen Area

The Greater Copenhagen Area (GCA), the Danish capital, is part of the island Zealand, see Figure Map A.1 in the Appendix A.1.[5] The GCA is the political, administrative, and educational core region of Denmark and accounts for more than 40% of Denmark's GDP, 1.6 million people (app. one third of Danish population), and 1 million workplaces (app. one half of workplaces). In the dataset, we divide the GCA into 166 smaller areas that were originally designed for detailed traffic modelling.[6] It is a fair simplification to claim that the GCA constitutes a single spatial labour market as commuting by car between any pair of locations within its boundary is possible.[7] This suggests that workers consider the whole area when looking for a job. Commuting from the GCA to other parts of Zealand is negligible, whereas commuting flows inside the GCA are relatively large.

Car ownership in Denmark is extremely expensive compared to international standards due to taxation. The purchase-tax of a car is 105% for the value of the car below app. € 10.500 and 180% of the value of the car above.[8] In addition there is an annual ownership tax of app. € 500 (300–900) depending on the characteristics of the car. Consequently, car ownership in Denmark is low relative to other comparable countries (0.81 cars per household in Denmark, 0.71 cars per household in the GCA). For many low income households car ownership is hardly affordable and even many medium income households choose not to own a car. The number of households with two cars is also quite low (8.2% of households in Denmark). The alternative travel mode to car is of course public transport but a bike is also a common mode of transport, especially in Copenhagen and other bigger cities, and among younger people.

[2] See, for instance, Anas et al. (1998), Glaeser and Kahn (2004) and Huang et al. (2019) where the impact of cars on the structure of modern cities is recognized, but the connection with public transport receives little attention.

[3] More than 90% of U.S. households in 2017 had at least one car at their disposal (McGuckin and Fucci, 2018). Moreover, there are on average 1.9 vehicles per household in the same year.

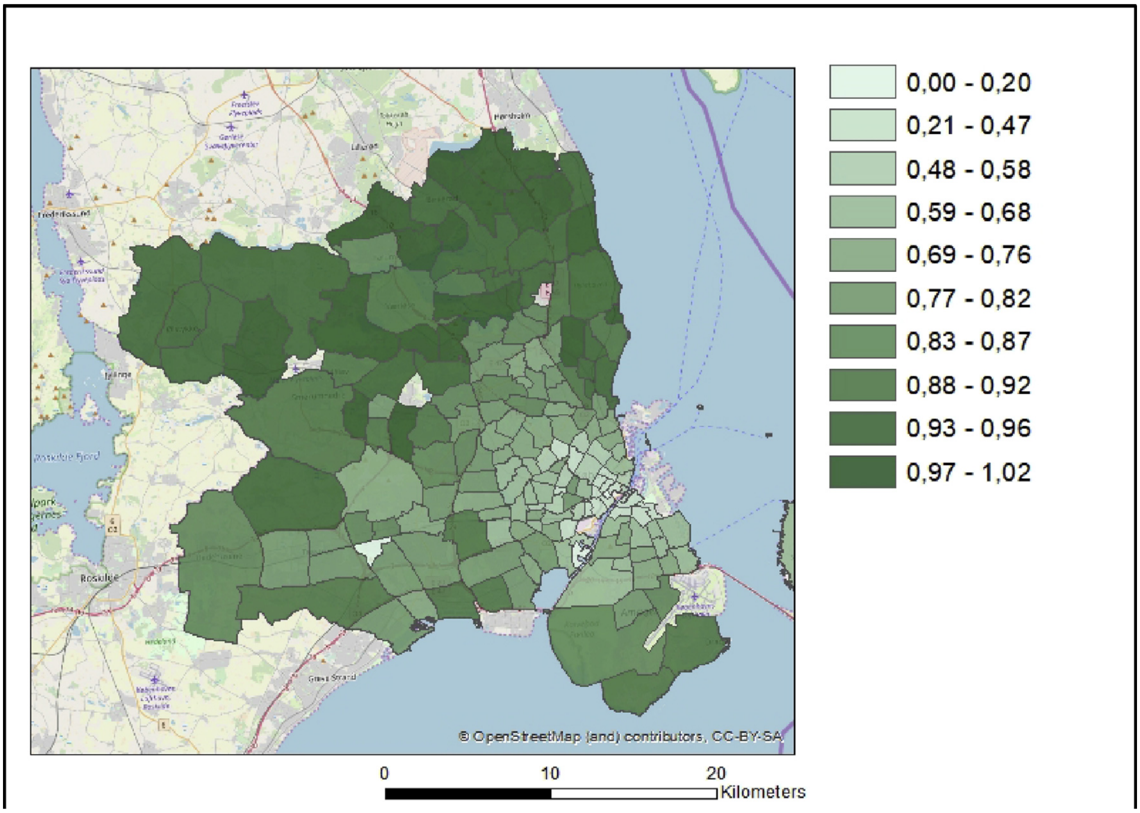
[4] See, for instance, Sieg et al. (2004) for an analysis that is similar in spirit to that of the present paper by taking into account residential sorting, although it concentrates on air pollution and uses a different analytical framework.

[5] The geographical area of GCA is rather small (615.7 km^2). See the dark area in map A.1 in Appendix A.1.

[6] They consist of a few adjacent church parishes. In Denmark a parish is an administrative area consisting of several villages or localities originating from the middle ages. From 1841, the parishes were established as administrative areas and remained in use ever since. Only few alterations to the parishes were made since 1841.

[7] We have also information on travel times between the considered zones for 2008 from the Danish National Travel Model. The travel times include congestion delays and waiting and transition times for public transport. The average travel time with car within areas in the GCA is about 17 min, and the maximum is less than 1 h (51.8 min). The average travel time with public transport is about 48 min, and the maximum is almost 2 h (112.7 min).

[8] For example, the retail price of a luxury car such as e.g. VW Passat is about € 24,000, the purchase tax is about € 29,000, and the VAT is about € 6000. The list price is then € 59,000. The disposable income for an average household in Denmark in 2010 was about € 50,000. Moreover, car owners have to pay the vehicle excise duty, and annual insurance premium. Mulalic and Rouwendal (2015) show that the mean annual total expenditure associated with ownership and use of a new car purchased in 2004 and used in the period 2004–2008 is about € 11,000.



Map 1. Car ownership in the GCA (number of cars per household).

Map 1 shows that the share of car-owners is, as expected, increasing with the distance from the city centre which is the core of the regional public transport network and where many amenities are available at walking distance. The map also shows a substantial difference between car ownership in the remoter areas in the south that are populated with relatively less wealthier and educated households, where it is relatively low, and in the north on the GCA that is considered as highly attractive, where it is close to 100%. The high cost of car ownership implies that car ownership is often reconsidered when households change residence. Households thus experience an active trade-off between car ownership and housing expenditures.

2.2. Selection of sample

The equilibrium sorting model is estimated on data derived from the Danish administrative registers on the population of both households and vehicles in Denmark for all households with residence in the GCA for the year 2008. We use two main sources. The first is the vehicle license plate register, which contains the vehicle identification number, vehicle attributes, date of registration and owner identification number. The second primary data source is the household register, which contains detailed demographic data at the calendar year-level. These data include the number of members of the household, ages, genders and the highest educational levels obtained of these members, residence address, and income[9] of the household members (including transfers). We combine the data from the various sources to create a final dataset.

We use a 20% sample of the GCA population living in *owner-occupied housing*. Our model can be considered as part of a broader nested logit model in which the housing tenure choice is on the top of the utility tree and the choice of the combination of housing type (apartment or other) and the geographical area refers to the lower level.[10] The share of owner-occupied residences constitutes just over 50% of the housing stock. The model focuses strictly on the location choices of households that are active both on the labour and the housing market.[11] The households in our sample are distributed over 166 areas in which they can choose to live either in a multi-family house (apartment or flat) or a single house (covering detached villas and terraced houses). When estimating model we assume that the supply of owner-occupied residences is fixed, as seems appropriate because most of the area is already built-up and open space that is left is usually protected. However, in the simulations we explore the implications of extending the housing stock in response to market forces.

We distinguish between single earner households (66,012) and dual earner households (87,330) and estimate separate models for these two groups, because these household types are different in many respects.[12] Within these models we distinguish between owning 0 and 1 car for

[9] Information about household income is based on third-party reporting (includes both reporting from firms and banks, mortgage institutions, brokers, etc.) and is considered highly reliable.

[10] The market for rented housing in Denmark is strictly regulated in many ways. Only in the market for owned residences households have a free choice, given their budget constraint, to choose residence with respect to e.g. type and location. Since estimation on a subset of alternatives does not bias the results of a logit model (McFadden, 1978), ignoring the rental part of the housing market is not problematic.

[11] We exclude owner-occupier households when all adult members are either student, unemployed, retired or otherwise inactive on the labour market (23.8% of the population as a whole, 34.0% of the population of owner-occupiers). The majority of these inactive households are pensioners (89.93%). Note that households in which the adult members have reached retirement age or studying are included in our sample when at least one of the two persons in such a couple is still active in the labour market.

[12] For instance, Gutiérrez-i-Puigarnau et al. (2016) show that in Denmark the causal effect of household income on commuting distance is larger for single-earner than for dual-earner households.

Table 1
Household characteristics.

	Single-earner households		Dual-earner households	
	Mean	Std. dev.	Mean	Std. dev.
Household's income (1000 DKK)	393.574	470.470	630.634	435.415
Number of children in household	0.379	0.779	1.220	1.039
Single family house owner (share)	0.530	0.499	0.819	0.385
Car ownership, one or two cars (share)	0.600	0.490		
One car (share)			0.753	0.431
Two cars (share)			0.108	0.310
Age, head of the household	47.006	13.382	46.109	10.015
Low education (share), head of the household	0.565	0.496	0.501	0.500
Medium education (share), head of the household	0.244	0.429	0.242	0.429
High education (share), head of the household	0.192	0.394	0.257	0.437
Age, partner			42.733	9.626
Low education (share), partner			0.487	0.500
Medium education (share), partner			0.281	0.450
High education (share), partner			0.233	0.422
Singles	0.648	0.478		
Number of observations	66,012		87,330	

Notes: low education includes: basic school, general upper secondary school, vocational upper secondary school and vocational education; medium education includes: short-cycle higher education and medium-cycle higher education; and high education includes: bachelor, long-cycle higher education and PhD-degree.

single-earner households and between owning 0, 1 and 2 cars for the dual-earner households.[13] The total choice set includes 538 and 636 elements for single-earner households and dual-earner households, respectively.[14]

2.3. Household heterogeneity and amenities

To account for the household heterogeneity we include the following socioeconomic variables: i) age (and square of age), ii) three dummy variables indicating the highest education level obtained, iii) the number of children in the household, and iv) household income. Moreover, for single-earner households we also include a dichotomous variable indicating a one-person household (single). For dual-earner households we also include socioeconomic variables for the partner.

Table 1 shows the summary statistics of the household characteristics. Not surprisingly, household income for dual-earner households largely exceeds income for single-earner households. Dual-earner households also have more children and more of them live in single family houses. Car-ownership is also higher for dual earner households and they hold a larger share of higher educated.

We expect the different types of households to have different preferences for urban amenities. Table 2 shows the summary statistics for the considered urban amenities.[15]

Accessibility to transport facilities is of main interest. Denmark has a highly developed transport infrastructure. The accessibility to public transport is particularly highly developed in the GCA. For instance, bus stops are always close by. However, travel times by public transport can

Table 2
Descriptive statistics for area characteristics.

	Mean	Std. dev.	Min.	Max.
Employment access with public transport/1000	235.088	41.075	99.261	288.520
Proximity to the nearest metro station (km)	0.234	0.331	0.000	0.902
Standardized house price (DKK million)	2.409	0.484	1.309	3.519
Share of higher educated	0.249	0.128	0.046	0.500
Number of conserved/protected buildings per sq. m.	0.0004	0.0003	6.36E-6	0.001
Distance to the CBD. (km)	10.607	7.161	0.000	32.570
Parking charging (share)	0.133	0.340	0.000	1.000
Social housing (share)	0.243	0.235	0.000	0.950

Notes: number of observations is 166.

be considerably larger than those for cars, in particular between suburban areas. In order to account for these differences we include a measure of employment access (EA) by public transport. For area a $EA_a = \sum_{a'} J_{a'} e^{-\delta\, d_{a\,a'}}$, where the summation runs over all locations a', J is employment expressed in full time job equivalents and d denotes distance measured in travel time minutes by public transport. We set δ to 0.05.[16] This implies, for instance, that jobs 'around the corner' have a weight 1, while a job at the distance of 120 min (the max) has weight 0.0025. A job at a distance of 48 min (the mean) has weight 0.09.[17]

Because of its high frequency, greater reliability and better transportation quality, the significance of access to the metro network is unlikely to be captured completely by its impact on employment accessibility. We capture this by introducing the proximity to the nearest metro station as a separate variable. Specifically, we model proximity to the nearest metro as the average of a linearly decreasing function of the distance from each address in the area to the nearest metro station, assuming a threshold of 3 km:

$$\text{Proximity} = \begin{cases} \dfrac{3 - distance}{3} & if \quad distance\ to\ metro\ st. \leq 3\ km \\ 0 & if \quad distance\ to\ metro\ st. > 3\ km \end{cases}$$

Although the choice of the threshold is somewhat arbitrary, there is evidence that many bikers are willing to travel at most this distance for multimodal commute trips using bike and public transport.[18] Note that

[13] The share of two car owners among single-earner households is very low (2.1%).

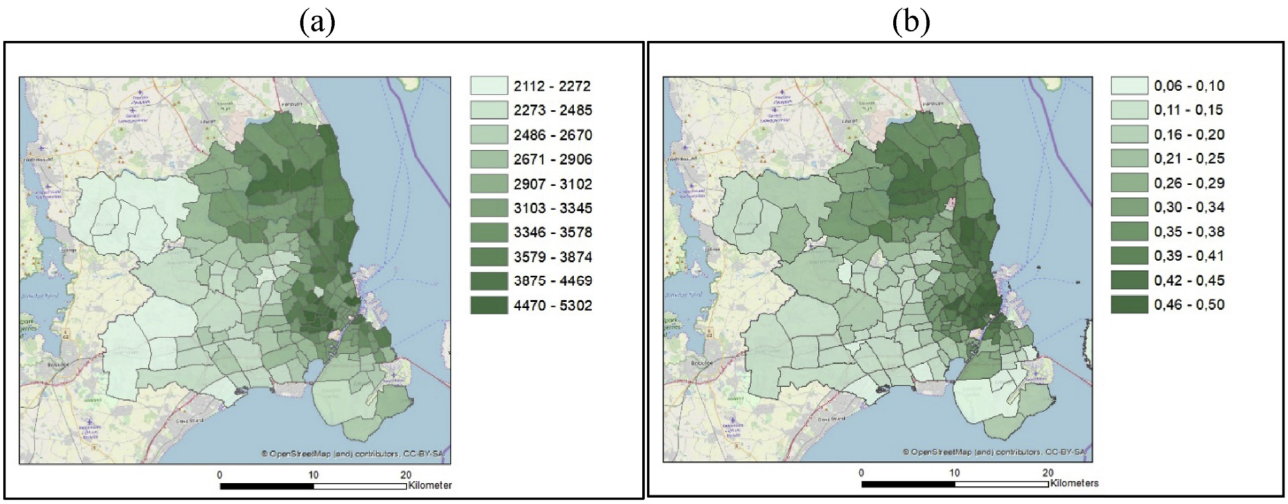
[14] In case we have no observations of a particular choice alternative we assumed it was not in the choice set of the relevant household type.

[15] All households have a universal access to childcare institutions and primary schools. Consequently, the availability of childcare and schools are not central for the residence location decision in Denmark. Moreover, there is no variation in this variable in our sample, so it is not useful in the model estimation.

[16] This decay parameter is within the range of recent estimates in the literature (Ahlfeldt and Wendland, 2016). Moreover, Ahlfeldt (2011) convincingly argues that the employment access measures are successful in empirically establishing a relationship between housing prices and the spatial distribution of employment. Jacob et al. (2019) shows that it is important to consider heterogeneity in measures that include commuting. For a discussion of accessibility measures, see for instance, Spiekermann et al. (2015).

[17] Using this accessibility measure implies that we do not pay specific attention to the location of the current job of the workers. The reason is that household members more frequently change job than house, which makes it likely that they do not only take into account their present commute when choosing residential location. Job mobility is extremely high and even the highest in Europe. This applies to most categories of workers and is not caused by a minor share of (unskilled) workers (Mulalic et al., 2014). Moreover, due to steep housing transaction taxes and rent control, residential mobility rates are moderate and substantially less than for example in the UK and the US. Note also that the choice of the work location is likely endogenous – e.g. Paetzold (2019) shows that commuting subsidies increase the length of commute –, which would imply an endogeneity problem that can perhaps best be solved by developing a simultaneous model for residential and location choice, which is outside the scope of the present paper.

[18] The majority of bike-and-ride users travel up to 3 km to a public transport stop (Martens, 2004). We have also as an additional sensitivity analysis estimated a model with a threshold of 2 km; see section 4.4.



Notes: standardized house price has been compiled from the two separated hedonic models with area fixed effect, i.e. one for the single family houses and one for the multi-family houses. Estimation results of these hedonic price functions are reported in the online appendix.

Map 2. Weighted average standardized housing price in the GCA (1000 DKK) (panel a) and the share of higher educated (panel b).

biking is very popular in Denmark. Most of the Danes are able to bike and there are facilities for parking bikes at most metro stations.

We model the housing market by including an area price index for a standard house (see section 3.1), which we interpret as the price of housing services. Standardized house price has been compiled from two separate hedonic models with area fixed effects, one for single family houses and the other for multifamily houses.[19] Map 2a shows the weighted average standardized house and apartment price in the GCA. The map shows the expected pattern of high house prices in the northern part of the GCA that is considered as highly attractive by Copenhagen households.

We also include the share of higher educated people as an indicator of endogenous amenities. It is often argued in the literature that the attractiveness of living in a particular area is partly determined by the demographic composition of that neighbourhood.[20] Map 2.b shows the share of higher educated in the sample distributed over the considered areas. It is interesting to notice the similarity over Maps 2.a and 2.b. Map 2.b shows a higher share of the higher educated in the northern part of the GCA, the same part that is considered as highly attractive by Danish households. It is however not necessarily the share of higher educated households *per se* that is important. It may well be the case that the presence of such households has an impact on the attractiveness through shops, restaurants and other facilities that are offered in the vicinity. We include for similar reasons the share of social housing relative to the total number of houses in the neighbourhood: households may have preferences for (or against) living in the proximity of social housing. It has been shown in the literature that the concentration of historical buildings is important for household location choice (Van Duijn and Rouwendal, 2013) either because this cultural heritage is appreciated itself or because it helps to attract shops, restaurants, cinema's and other endogenous amenities. Since there is not a generally accepted measure of cultural heritage that reflects differences in its quality, we use the number of conserved and/or protected buildings per sq.km. as an indicator for it.

We also include the distance to the CBD. Distance to the CBD has been compiled as the distance from an area to the area representing the city centre in Copenhagen (the city hall). Finally, we include a dichotomous variable indicating whether curb side parking in the area is subject to charges because they may reduce the benefits of owning a car while living in that area (Van Ommeren, Wentink and Dekkers, 2011).[21]

3. The model

This section presents the theoretical model that underlies the empirical analyses. We introduce the model for single-earner households. The setup for dual-earner households is similar, as we discuss in subsection 3.6 below.

3.1. Choice alternatives

The model we use in this paper considers car ownership and residential location as a joint decision. Households choosing a residential area know about the availability of public transport in that area, about the parking possibilities and the presence of other urban amenities. These characteristics of the area determine the value of having a car while living there. Following this reasoning we develop a discrete choice model in which the choice alternatives are combinations of car ownership and residential areas. A household thus considers living in a residential area with and without having a car and chooses the alternative that offers the highest utility. Car ownership is included as a simple indicator that takes on the values of 0 and 1.[22]

We model the demand for housing using the concept of housing services. Housing services are available at a given price per unit that is specific for the residential area. Households determine their optimal number of units consumed by choosing from the housing stock and, if necessary, adjust to the desired number of housing services (see Muth,

[19] Estimation results of these hedonic price functions are provided in the online appendix.

[20] For instance, in sociology the phenomenon of homophily which holds that households interact preferably with other households that are similar, is well-known. In the urban economics literature, the importance of this factor for location choice within the San Francisco Bay area was documented by Bayer et al. (2007).

[21] Curb side parking charges are especially found in the centre of Copenhagen and gets less frequent the further you get from the centre. Areas with parking charging are typically also areas where parking spaces are scarce and where a lot of cruising for parking potentially takes place. In neighbourhoods with parking charges it is typically possible for residents to buy a yearly parking permit at a low cost.

[22] This means that we ignore heterogeneity in car types and makes, car sharing and carpooling. We also do not model car use for commuting or other purposes.

1969; Rouwendal, 1998; Epple and Platt, 1998).[23] However, the neglect of the durable aspects of housing that are difficult to change may be problematic if quality differences are substantial. In particular the distinction between single and multifamily housing seems to be a fundamental one. We have therefore decided to distinguish between these two types of houses, while maintaining the "Muth-framework" for each of the separate stocks of these two types of housing.

In summary, we have for each area in principle four choice alternatives that are determined by the car ownership (yes or no) and housing type (single vs multifamily) decisions. Choice alternatives are therefore defined by three dimensions: area ($a = 1 \ldots n$), house type ($h = s, m$), and car ownership ($c = 0, 1$).

3.2. Utility

Indirect utility depends on the characteristics of the choice alternative and of the household. The former set includes accessibility of public transport and the metro system apt_a and amt_a, car ownership for which we use a dummy d_c, the housing type for which we use a second dummy d_h representing a single house, the natural logarithm of the housing price, which depends on the housing type as well as the area and will be denoted as $P_{h,a}$ and other area characteristics X_a (e.g. distance from the CBD, number of protected or conserved buildings, etc.). Household characteristics include the (natural) log of income y^i and other characteristics Z^i (e.g. age and education of the head of the household, the number of children in the households, etc.). All household characteristics are used in demeaned form.

The deterministic part of the utility of a choice alternative for household i is:

$$v^i_{a,h,c}(apt_a, amt_a, d_c, d_h, P_{h,a}, X_a; y^i, Z^i) = \alpha^i_1 apt_a + \alpha^i_2 amt_a + \alpha^i_3 d_c + \beta^i_1 d_h + \beta^i_2 P_{h,a} + \beta^i_3 X_a + \left(\gamma^i_1 apt_a + \gamma^i_2 amt_a + \gamma^i_3 d_h + \gamma^i_4 X_a\right) d_c + \xi_{a,h,c} \tag{1}$$

Utility is thus the sum of three parts, indicated by coefficients α, β and γ, respectively and an alternative-specific variable ξ that reflects unobserved (by the researcher) characteristics of the alternative. The superscript indicates that the coefficients are functions of household characteristics, as will be discussed below. Equation (1) gives the most extensive specification considered; in the empirical work we decided to leave some variables out.

The first part of the utility refers to transport variables: availability of public transport and car ownership; the second part refers to area characteristics as they are included in equilibrium sorting models as used by Bayer et al. (2007); the third part refers to interactions of car ownership with the availability of public transport and with other neighbourhood characteristics. These interactions are key in our model. We indicated in the previous subsection that we expect car ownership to be less valuable for a household if there is better public transport. Hence we expect γ^i_1 and γ^i_2 to be negative. Since single family houses often have more parking space either on their own plot or on the street (density is usually lower in areas with single family housing) one may expect γ^i_3 to be positive. The signs of the elements of γ^i_4 depend on the nature of the area characteristic. For instance, if it is an indicator for the presence of parking charges, we expect the sign to be negative as this makes car ownership more expensive.[24] The final term was originally proposed in Berry et al. (1995) in the context of discrete choice models for car type choice. Bayer, Ferreira and McMillan (2007) used it in the context of residential sorting behaviour and we follow them here. Incorporating this term is helpful in fitting the model[25] and in the analysis of potential endogeneity problems associated with the housing price and other potentially endogenous variables.

The coefficients α, β and γ all depend on household characteristics and we specify them further as:

$$\alpha^i_j = \tilde{\alpha}^0_j + \tilde{\alpha}^1_j \ln y^i + \sum_{l=1}^{L} \tilde{\alpha}^{l+1}_j Z^i_l \tag{2}$$

and analogous expressions for the βs and γs. Note that for the coefficients with a tilde, the superscript refers to the associated household characteristic. Since we have demeaned the household characteristics, $\tilde{\alpha}^0_j$ is the average value of the coefficients α^i_j in the population.

The total utility attached to a choice alternative is the sum of the deterministic part, discussed thus far, and a random part ε^i_j. The assumption that these random parts are independent and identically Extreme Value Type I distributed leads to the multinomial logit model (McFadden, 1973).

3.3. Estimation

To estimate the model we use a two-step procedure adapted from Berry et al. (1995) and Bayer et al. (2007). We substitute (2) and the analogous expressions for the βs and γs into (1) and write the result as the sum of the average utility $\delta^0_{a,h,c}$ of the alternative (that only includes the coefficients $\tilde{\alpha}^0_j$ $\tilde{\beta}^0_j$ $\tilde{\gamma}^0_j$ and $\xi_{a,h,c}$) and a household-specific deviation from that average. The average is then viewed as a single alternative specific constant which is, in the first step estimated as a single coefficient, jointly with the remaining parameters. This first step thus involves estimation of a multinomial logit (MNL) model.

In the second step the alternative-specific constants are again written as a function of the coefficients $\tilde{\alpha}^0_j$, $\tilde{\beta}^0_j$ and $\tilde{\gamma}^0_j$:

$$\delta^0_{a,h,c}(apt_a, amt_a, d_c, d_h, P_{h,a}, X_a) = \tilde{\alpha}^0_1 apt_a + \tilde{\alpha}^0_2 amt_a + \tilde{\alpha}^0_3 d_c + \tilde{\beta}^0_1 d_h + \tilde{\beta}^0_2 P_{h,a} + \tilde{\beta}^0_3 X_a + \left(\tilde{\gamma}^0_1 apt_a + \tilde{\gamma}^0_2 amt_a + \tilde{\gamma}^0_3 d_h + \tilde{\gamma}^0_4 X_a\right) d_c + \xi_{a,h,c}. \tag{3}$$

Eq. (3) can be estimated using methods for linear equations. In the context of the present paper OLS is not appropriate, since the housing price, which equilibrates supply and demand, should be expected to reflect the impact of the unobserved neighbourhood characteristics $\xi_{a,h,c}$. We therefore use an instrumental variables approach.

[23] Using a neighbourhood, instead of single house as the unit of choice overcomes a problem associated with treating individual houses as choice alternatives, viz. that not every household can afford to live in every house. We assume here that every household can find affordable (single- or multi-family) housing in every area. This allows for the possibility that a (large) part of the housing stock that is available in an area may not be affordable for specific (low income) households.

[24] Although one could perhaps argue that the presence of such charges makes parking space less scarce, which makes car ownership more valuable. Moreover, parking charges may reduce cruising for parking (Van Ommeren et al., 2011).

[25] It implies the use of an alternative specific constant and this guarantees that the share of households choosing a particular alternative as predicted by the estimated model equals the observed share of households doing so in the data. See Berry et al. (1995).

3.4. The implied model for car ownership

In the model developed above the consumer will own a car if the maximum utility of the alternatives in which a car is owned exceeds the maximum utility of the alternatives in which no car is owned. The former maximum utility, which we denote as U_1^i $(= max\{v_{a,h,c}^i + \varepsilon_{a,h,c}^i | c = 1\})$ with the εs denoting the random parts of the utilities, is:

$$U_1^i = \ln\left(\sum_a\sum_h e^{v_{a,h,1}^i}\right) + \varepsilon_{c=1}^i. \quad (4)$$

For the utility U_0^i of not having a car we have similarly:

$$U_0^i = \ln\left(\sum_a\sum_h e^{v_{a,h,0}^i}\right) + \varepsilon_{c=0}^i \quad (5)$$

The first terms on the right-hand side of (4) and (5) are the expected values of the maximum utility a household will be able to reach when owning a car, or not owning one, respectively. The random terms $\varepsilon_{c=1}^i$ and $\varepsilon_{c=0}^i$ are also independent and Extreme Value Type I distributed. The choice whether or not to own a car can therefore be described as a binomial logit model in which the expected values in (4) and (5) are the deterministic parts of the utilities. Denoting the probability of car ownership as $\pi_{c=1}^i$ we thus have[26]:

$$\pi_{c=1}^i = \frac{e^{\ln\left(\sum_a\sum_h e^{v_{a,h,1}^i}\right)}}{e^{\ln\left(\sum_a\sum_h e^{v_{a,h,1}^i}\right)} + e^{\ln\left(\sum_a\sum_h e^{v_{a,h,0}^i}\right)}} \quad (6)$$

The expression reflects that households can choose any location and housing type when owning or not owning a car. This model differs from the one typically used in the literatures discussed above that concentrates on binomial models that take location as given. When a logit model is used, its formulation would be:

$$\pi_{c=1|a,h}^i = \frac{e^{v_{a,h,1}^i}}{e^{v_{a,h,1}^i} + e^{v_{a,h,0}^i}} \quad (7)$$

This equation results from (6) if the choice set for location and housing types is restricted to a single alternative. While model (6) allows the consumer to choose a different neighbourhood and housing type depending on whether or not a car will be owned, (7) only compares the utility a household would be able to reach with and without owning a car in a given neighbourhood and housing type. This implies, among other things, that the model of (6) is able to explain household's relocation decisions in response to improvements in public transport such as the introduction of a metro network, whereas (7) is not. Summarizing, the model of the present paper does not only generalize existing Tiebout-sorting models to incorporate public transport and car ownership, but it also generalizes existing car ownership models to include the choice of the residential location.[27]

3.5. The effects of better public transport

In our model the availability of public transport is an amenity that increases the utility of living in a particular zone.[28] If estimation results confirm our conjecture that the impact of the availability of public transport is larger for the choice alternatives in which no car is owned, improving public transport will have a nonpositive impact on car ownership.[29]

To see how this works in the model discussed above, observe that the immediate effect of the opening of a metro network will be an increase in the attractiveness of areas close to its stops. This effect will be different for choice alternatives with and without car-ownership. Not owning a car will become more attractive in a relative sense. This will induce some households to abandon their car or to change their residential location to benefit from improved public transport, or both.[30] As a result, demand for cars will decrease while demand for housing will increase in areas close to metro stations and decrease elsewhere. Housing supply or housing prices will react in response to this to restore equilibrium. These effects, as implied by our estimated model will be discussed in the simulation exercises reported below.

Since public transport is an amenity, its improvement increases utility and the associated compensating variation is expected to be positive. The welfare analysis of public transport improvement follows De Palma and Kilani (2003).[31]

3.6. Extension to dual-earner households

The setup of our model for dual earner households is entirely similar to that of single earner households discussed above, so we can be brief. The main differences are the extension of the choice set by now have to consider the choice of one residential location and housing type, but two job locations and by including ownership of 2 cars for each of these combinations. We used the same structure of the household utility function (see eq. (3)), but now make the parameters functions of the characteristics of both partners. We distinguish between head and partner based on the definition of Statistics Denmark and allow the parameters for both spouses to be different. This gives reasonably flexible specification of the model that allows for comparison with single earners. Unfortunately, we have no information about the use of the car for commuting purposes in dual earner households owning a single car.

Just like in the case of single earner households, the model allows for substitution between all choice alternatives in response to, for instance, the opening of the metro network. So households may – for instance - switch from owning two cars to owning one car while simultaneously moving to a neighbourhood with a metro station in response to the realisation of this network.

4. Estimation results

We estimate two models: one for single-earner households and another for dual-earner households. For both samples we first estimate a multinomial logit model with alternative-specific constants, while in the second stage we use methods for linear regressions to link these constants to the characteristics of the choice alternatives.

4.1. Endogeneity and the selection of instruments

Several variables in our models can be considered as endogenous. That is, it may be argued that the values of these variables are correlated with the error term $\xi_{a,h,c}$ in the second stage regression (3). In this subsection we discuss these variables as well as the instruments we use to

[26] This equations can also be rewritten to $\pi_{c=1}^i = \frac{\sum_a\sum_h e^{v_{a,h,1}^i}}{\sum_a\sum_h e^{v_{a,h,1}^i} + \sum_a\sum_h e^{v_{a,h,0}^i}}$.

[27] We also compared our model with the conventional car ownership models. Notice that the traditional car ownership models are silent about the choice of neighbourhood or housing type. Estimation results for a number of such traditional car ownership morels are provided in the online appendix.

[28] In our empirical work we measure the impact of car ownership and public transport on the utility of the choice alternatives without imposing a priori restrictions on the signs or relative magnitudes.

[29] Under ceteris paribus conditions. It is possible that adjustments on the housing market following the improvement of public transport have an impact on car ownership that partly counteracts the initial effect.

[30] Recall here that we treat car ownership similarly to house ownership. That is, we treat car owners as if they lease their vehicles and pay an annualized price of car ownership to an absentee car dealer.

[31] See also McFadden (1999) and Dagsvik and Karlström (2005).

deal with these endogeneity concerns.

Since the unobserved characteristics $\xi_{a,h,c}$ affect the attractiveness of a choice alternative directly, it must be expected that they have an impact on the equilibrium price of housing. This problem was observed by Berry et al. (1995) in their study of the automobile market and they proposed the use of the sums of car characteristics as instruments.[32] In the context of residential sorting some researchers have used characteristics of alternatives that are geographically close (see Klaiber and Phaneuf, 2010). A potential drawback of this practice is that characteristics of residential areas that are physically close may well have a direct impact on the utility of the choice alternative considered as residents may easily cross the borders of their area of residence to visit areas in the vicinity that have attractive amenities.[33] Bayer et al. (2007) adopted a different approach. They construct an instrument that intends to summarize the relative position of a choice alternative on the housing market on the basis of all available exogenous information. Their proposed instrument is the counterfactual equilibrium price predicted by the model when the term $\xi_{a,h,c}$ that reflects the unobserved characteristics is absent. This instrument is by construction independent of the unobserved heterogeneity terms ξ and most likely strongly correlated with the observed housing prices.[34]

Van Duijn and Rouwendal (2018) have shown that the equilibrium housing price depends on an entropy-based measure of inequality of the choice probabilities. The variation in choice probabilities is caused by the differences in actor characteristics which is exogenous information that is not employed in the second stage of the estimation procedure and thus can be exploited to construct an instrument. Bayer et al. (2007)'s instrument are the equilibrium prices that are predicted by the model if the unobserved heterogeneity is removed from it. These counterfactual prices depend on counterfactual choice probabilities that transform the distribution of actor characteristics to alternative-specific variables by interacting it in a nonlinear way with the characteristics of the choice alternatives.[35]

Van Duijn and Rouwendal (2018) employ the methodology of Belloni et al. (2012) to choose the preferred instrument among a large number of nonlinear transformations of the exogenous characteristics of the choice alternatives. They find that Bayer et al.'s instrument for the price is selected whenever it is included in the set of candidate instruments. We have here used the same procedure and obtained the same result.[36] Our interpretation is that the superior performance of Bayer's instrument is due to the use of the additional exogenous information about the heterogeneity of the population that is not employed in the other candidate instruments.

A second variable that may be considered endogenous is the share of higher educated. To instrument for this variable we use information about the location of private schools before 1890 in the GCA. At that time only the rich could afford to send their children to such schools and the location of these schools was related to the preferred residential locations of the upper class. In 1890 there were 12 such schools, only a few of them located in – what is now – the centre of Copenhagen. The idea behind this instrument is that unobserved characteristics that make a location currently (un)attractive for the average Danish household are unrelated to those that determined the location of the private schools more than a century ago, while the clustering of high income people in the early 21st century is correlated with that in the 19th century. Our instrument is the distance to the private school that is closest to the area of the choice alternative.

Thirdly it can be argued that accessibility to employment could also be endogenous as many firms nowadays are 'footloose' with respect to inputs and outputs, and may tend to locate close to where their potential workers live, while other firms – for instance shops – want to locate close to the households to which they sell their goods. The instrument we use for this variable is the train stations that were founded before World War II. Many of these stations were constructed in the 1930s for the purpose of serving local industries and incidental trips from rural areas to the capital and vice versa. At the time commuting by train was exceptional, but when it became more common in the 1960s the lines connecting these stations served as the starting point for the extensive rail network constructed later on. For this reason the distance to the nearest of these older stations (which we use as our instrument) must be expected to be still correlated with accessibility to employment by public transport. Moreover, the unobserved characteristics that make an area attractive as a place of residence for the average Danish household are unrelated to the factors that determined the location of these stations.

4.2. The average household

Table 3a and 3b show the results of the second stage, which refers to the utility attached by the average household to the various choice alternatives. Table 3a refers to the single-earner households and 3b to the

Table 3a
Second step estimation results for single-earner households: decomposition of the household's mean indirect utilities.

		[1] OLS	[2] IV (2SLS)
α's	Employment access with public transport/1000 * dummy variable indicating no car[1]	0.008***	0.007*
		(0.003)	(0.004)
	Proximity to the nearest metro station (km) * dummy variable indicating no car[1]	0.454**	0.547**
		(0.207)	(0.230)
	Dummy variable indicating one car	0.960***	0.889***
		(0.227)	(0.304)
β's	Dummy variable indicating non-apartment	1.432***	1.980***
		(0.235)	(0.353)
	Log (standardized house price)	−2.178***	−3.032***
		(0.324)	(0.517)
	Share of higher educated	1.874***	3.130***
		(0.532)	(1.043)
	Number of conserved and protected buildings per sq.m.	0.937***	0.903***
		(0.167)	(0.167)
	Distance to the CBD.	0.020**	0.016*
		(0.008)	(0.009)
	Social housing (share)	−0.418**	−0.410*
		(0.206)	(0.219)
γ's	Dummy variable indicating non-apartment * dummy variable indicating one car	0.128	0.126
		(0.151)	(0.152)
	Dummy variable indicating parking charging * dummy variable indicating one car	−0.168	−0.179
		(0.194)	(0.196)
	Constant	−1.189***	−0.937**
		(0.324)	(0.392)
	Anderson canon. corr. LM statistic		137.887
	Cragg-Donald Wald F statistic		60.423
	R-squared	0.214	
	No. of observations	538	538

Notes: standard errors are in parentheses; standardized house price, share of higher educated and employment access with public transport are instrumented; see Table A2.1 in Appendix A.2 for first-stage regression estimates of the 2SLS; ***, **, * indicate that estimates are significantly different from zero at the 0.01, 0.05 and 0.10 levels, respectively.

[1] Note that the multiplication with the no-car dummy $(1-d_c)$ implies that we have in fact specified the term as $\alpha X + X d_c$, where X is employment access or proximity to metro, while imposing the restriction $\gamma = -\alpha$.

[32] They use sums over all car makes as well as over the makes offered by a given producer. This choice was inspired by the literature on optimal instruments (see Chamberlain, 1987).

[33] Van Duijn and Rouwendal (2018) develop a model in which this is explicitly taken into account.

[34] This instrument is thus a function of all exogenous area characteristics (urban amenities). It may be observed that this requires area characteristics to be excluded from the equation for the average utility (3).

[35] See Bernasco, de Graaff, Rouwendal and Steenbeek (2017) for the use of a similar instrument in a different setting.

[36] A detailed description of the construction of the instrument variable candidates is provided in the online appendix.

Table 3b
Second step estimation results for dual-earner households: decomposition of the household's mean indirect utilities.

		[1] OLS	[2] IV (2SLS)
α's	Employment access with public transport/1000	0.012***	0.010*
	* dummy variable indicating no car[1]	(0.003)	(0.005)
	Proximity to the nearest metro station (km) *	0.712***	0.800***
	dummy variable indicating no car[1]	(0.215)	(0.236)
	Dummy variable indicating one car	1.728***	1.770***
		(0.298)	(0.392)
	Dummy variable indicating two cars	1.033***	0.912**
		(0.327)	(0.444)
β's	Dummy variable indicating non-apartment	2.743***	3.428***
		(0.277)	(0.463)
	Log (standardized house price)	−2.321***	−3.357***
		(0.361)	(0.651)
	Share of higher educated	2.644***	3.880***
		(0.586)	(1.255)
	Number of conserved/protected buildings per	0.897***	0.848***
	sq.m.	(0.159)	(0.161)
	Distance to the CBD.	0.039***	0.027**
		(0.009)	(0.012)
	Social housing (share)	−0.370*	−0.443**
		(0.199)	(0.215)
γ's	Employment access with public transport/1000	0.004	0.002
	* dummy variable indicating one car	(0.003)	(0.005)
	Proximity to the nearest metro station (km) *	0.243	0.300
	dummy variable indicating one car	(0.217)	(0.235)
	Dummy variable indicating non-apartment *	0.495***	0.471***
	dummy variable indicating one car	(0.168)	(0.174)
	Dummy variable indicating non-apartment *	−0.147	−0.142
	dummy variable indicating two cars	(0.236)	(0.245)
	Dummy variable indicating parking charging *	−0.130	−0.122
	dummy variable indicating one car	(0.212)	(0.214)
	Dummy variable indicating parking charging *	−0.072	−0.143
	dummy variable indicating two cars	(0.424)	(0.431)
	Constant	−2.854***	−2.370***
		(0.368)	(0.498)
	Anderson canon. corr. LM statistic		131.118
	Cragg-Donald Wald F statistic		40.188
	R-squared	0.570	
	No. of observations	636	636

Notes: standard errors are in parentheses; standardized house price, share of higher educated and employment access with public transport are instrumented; see Table A2.2 in Appendix A.2 for first-stage regression estimates of the 2SLS; ***, **, * indicate that estimates are significantly different from zero at the 0.01, 0.05 and 0.10 levels, respectively.

[1] Note that the multiplication with the no-car dummy $(1-d_c)$ implies that we have in fact specified the term as $\alpha X + Xd_c$, where X is employment access or proximity to metro, while imposing the restriction $\gamma = -\alpha$.

dual-earner households. Table 4a and 4b report the coefficients that show deviations from the average utilities related to household characteristics, for the same groups of households.

Table 3a and 3b show the results of the second step of the estimation procedure based on (3). The dependent variable is the vector of mean indirect utilities that were estimated as alternative specific constants in the first (logit) step of the estimation procedure. These $\delta_{a,h,c}$'s represent the part of the utility that is equal for all single-earner households or dual-earner households. Table 3a gives the results for single-earner households. For the alternatives in which no car is owned, accessibility to employment by public transport and proximity to a metro station are important. Ownership of a car always makes a choice alternative more attractive. Single family houses are preferred to multi family houses and a higher housing price makes an alternative less attractive. The presence of higher educated households and monuments make an area more attractive. Distance to the CBD is valued positively, perhaps because of the crowding and congestion effects, while the attractive features of city life are already reflected in the share of higher educated and the monuments. The presence of social housing has a negative impact. The interactions of car and neighbourhood characteristics have no significant impact on the average household.

Dealing with the endogeneity issues through IV makes a substantial difference for the estimation results. The larger (in absolute value) size of the price coefficient is a well-known phenomenon that is caused by attributing the impact of unobserved heterogeneity to limited price sensitivity when this is not properly taken into account. The coefficient of the share of higher educated almost doubles, which may have similar reasons. The coefficient for the accessibility of employment by public transport hardly changes.

The results for the dual-earner households, presented in Table 3b, are qualitatively similar. Having one or two cars is better than having none, but given that cars are costly, ownership of one car is clearly the situation that is on average most preferred. This reflects the high costs of car ownership and use in Denmark and the diminishing returns to ownership of an additional car. The interaction term for having one car and living in a single family house is now significantly positive, which may be related to better parking possibilities (on one's own plot) that are often present with such housing.

4.3. Deviations from the average

Table 4a and 4b show the coefficients that relate deviations from average utility to household characteristics. Income is clearly important in this respect. Let us first look at the single-earner households. Having a higher income makes one less sensitive to the availability of public transport if no car is owned, but owning a car becomes much more attractive. The sensitivity to the housing price decreases, but the presence of higher educated is appreciated more. And the combination of a single family house and a car gets more important with income. The interactions with other household characteristics show that accessibility to public transport as well as owning a car become less important with age although at a decreasing rate, while households with children have stronger preferences for cars and single family houses. The combination of children and living in an area with parking charges is unattractive. Singles are less sensitive to the availability of public transport if no car is owned. Moreover, owning a car is much less attractive for singles but the presence of higher educated and access to monuments are appreciated more. The combination of car ownership and living in an area with parking charges and the combination of car ownership and single family houses are less attractive for singles.

The results for dual-earner households presented in Table 4b confirm the importance of household income. We have included age and education of both workers, which are in many households similar. The estimation results confirm the picture that arises from Table 4a for the single-earner households.

4.4. Sensitivity analyses

We *have* performed a number of sensitivity analyses. Most of the robustness checks focus on the model specification. It may be observed that some of the choice alternatives that we use share important characteristics: owning one or two cars, living in a single family house or in a particular area. The idiosyncratic utilities of these alternatives may reflect these similarities.[37] We have therefore also estimated a mixed logit model. The results of the mixed logit model are very similar to the ones with the MNL. We conclude that, despite the apparently plausible a priori arguments for correlation between the random parts of the utilities that are similar in number of cars, housing type or geographical area, the empirical importance of this phenomenon appears to be limited. We have also estimated a model in which we have replaced the variable representing "proximity to the nearest metro station" with "proximity to the

[37] That is, the $\varepsilon^i_{a,h,c}$'s may be statistically dependent for alternatives sharing the same *a, h* or *c*.

Table 4a
First step estimation procedure (MNL) for single-earner households: interaction parameter estimates.

	Amenities	Households characteristics						Singles
		Log (hous. income)	Age	Age sq./1000	Number of children	Education (medium)	Education (high)	
α's	Employment access with public transport/1000 * dummy variable indicating no car[1]	−0.005*** (0.001)	−0.001*** (0.0001)	0.007*** (0.001)	−0.001*** (0.001)	0.002* (0.001)	0.001 (0.001)	−0.003*** (0.001)
	Proximity to the nearest metro station (km) * dummy variable indicating no car[1]	−0.062 (0.062)	0.019* (0.009)	−0.243** (0.096)	−0.054 (0.042)	−0.069 (0.057)	0.016 (0.059)	−0.109 (0.068)
	Dummy variable indicating one car	0.501*** (0.082)	−0.033*** (0.011)	0.329** (0.120)	0.155*** (0.053)	0.211** (0.078)	0.030 (0.087)	−0.830*** (0.088)
β's	Dummy variable indicating non-apartment	−0.693*** (0.084)	−0.053*** (0.012)	0.460*** (0.125)	0.404*** (0.054)	0.152 (0.086)	0.001 (0.096)	−1.159*** (0.092)
	Log (standardized house price)	2.230*** (0.111)	0.052*** (0.016)	0.109 (0.168)	0.195** (0.070)	−0.283** (0.116)	−0.017 (0.126)	1.030*** (0.122)
	Share of higher educated	2.420*** (0.182)	−0.087*** (0.025)	1.082*** (0.261)	0.178** (0.109)	2.968*** (0.177)	5.582*** (0.201)	0.732*** (0.186)
	Number of conserved/ protected buildings per sq.m.	−0.262*** (0.052)	0.005 (0.007)	0.071 (0.071)	0.270*** (0.029)	0.021 (0.048)	−0.129* (0.055)	0.161*** (0.050)
	Distance to the CBD.	0.013*** (0.002)	0.001** (0.0003)	0.006** (0.003)	0.011*** (0.001)	−0.008** (0.002)	−0.024*** (0.003)	0.019*** (0.002)
	Social housing (share)	−0.528*** (0.069)	0.018** (0.008)	−0.072 (0.085)	0.108*** (0.035)	0.096 (0.062)	0.084 (0.078)	−0.189*** (0.062)
γ's	Dummy variable indicating non-apartment * dummy variable indicating one car	0.285*** (0.052)	0.052*** (0.007)	−0.308*** (0.072)	−0.075*** (0.031)	0.081 (0.048)	0.218*** (0.055)	−0.313*** (0.053)
	Dummy variable indicating parking charging * dummy variable indicating one car	−0.058 (0.054)	−0.007 (0.008)	−0.057 (0.083)	−0.291*** (0.039)	−0.138** (0.061)	0.004 (0.057)	−0.287*** (0.059)

Notes: standard errors are in parentheses; ***, **, * indicate that estimates are significantly different from zero at the 0.01, 0.05 and 0.10 levels, respectively.
[1] Note that the multiplication with the no-car dummy $(1 - d_c)$ implies that we have in fact specified the term as $\alpha X + \gamma X d_c$, where X is employment access or proximity to metro, while imposing the restriction $\gamma = -\alpha$.

nearest bus stop". This can be considered as a placebo test. We find that, conditional on the measure of employment access (EA) by public transport that also includes bus connectivity, proximity to the nearest bus stop does not have significant effect on the household utility. Then we have estimated a model when the threshold for the distance to the nearest metro station is not 3 km, but 2 km as in e.g. Gibbons and Machin (2005). The results of this model are very similar to the basic model. Moreover, when we use an alternative instrument for the housing price, the share of house sales following a divorce in the year before the sale in the total number of house sales in the area, it appears that the estimates are qualitatively similar to those in the basic model.[38] Finally, we have also tested an alternative instrument for the share of higher educated based on the methodology proposed by Bayer et al. (2007). It is the counterfactual equilibrium share of higher educated predicted by the model when the term that reflects the unobserved characteristics is absent. This instrument is by construction independent of the unobserved heterogeneity terms and most likely strongly correlated with the observed share of higher educated. Estimation results with this alternative instrument are also qualitatively similar to those in the basic model. Results of the sensitivity analyses are available in the online appendix.

5. The impact of an improved metro network

The metro system in Copenhagen is relatively new. The first stations opened in 2002, a second set of stations followed in 2003 while the third phase (extending an existing line to the airport) was opened in 2007. The metro represented a significant upgrading of public transport with respect to quality and has been quite popular (almost) from the start. It is used daily by many people and has more than 63 mio. passengers yearly (in 2017). The metro has at present 22 stations; see the black dots in Map 3.

The extension of the metro opened in 2019 implies a significant expansion of the network with a city-circle and 18 new stations, most of them in central Copenhagen (see the red dots in Map 3). This contrasts with many extensions of metro networks in other metropolitan areas that aim to link suburbs with the central city.

We use the estimated model to simulate the impact of the extension of the metro network. The primary effect of the extended public transport is a change in neighbourhood characteristics: the distance to the nearest metro station reduces for many areas in the city of Copenhagen and job accessibility by public transport (travel times by public transport) improves as well. The changes in these variables are available from the Danish National Traffic Model. These changes will affect the utility attached to the choice alternatives concerned and through this on household location behaviour.

We compute the counterfactual equilibria implied by our model after the extension of the metro network under two different assumptions with respect to housing supply and compare them with the original situation.[39] This comparison is facilitated by the fact that estimated logit models with alternative-specific constants predict exactly the observed number of households choosing a particular alternative in the sample. It is well-known that without 'social interaction' effects the price

[38] The idea behind this instrument is that a larger share of divorces will lead to an increase in the number of houses for sale and hence, along with the limited time-window acceptable for a house sale, will have a negative effect on the price. A more detailed discussion of this instrument is provided in the online appendix.

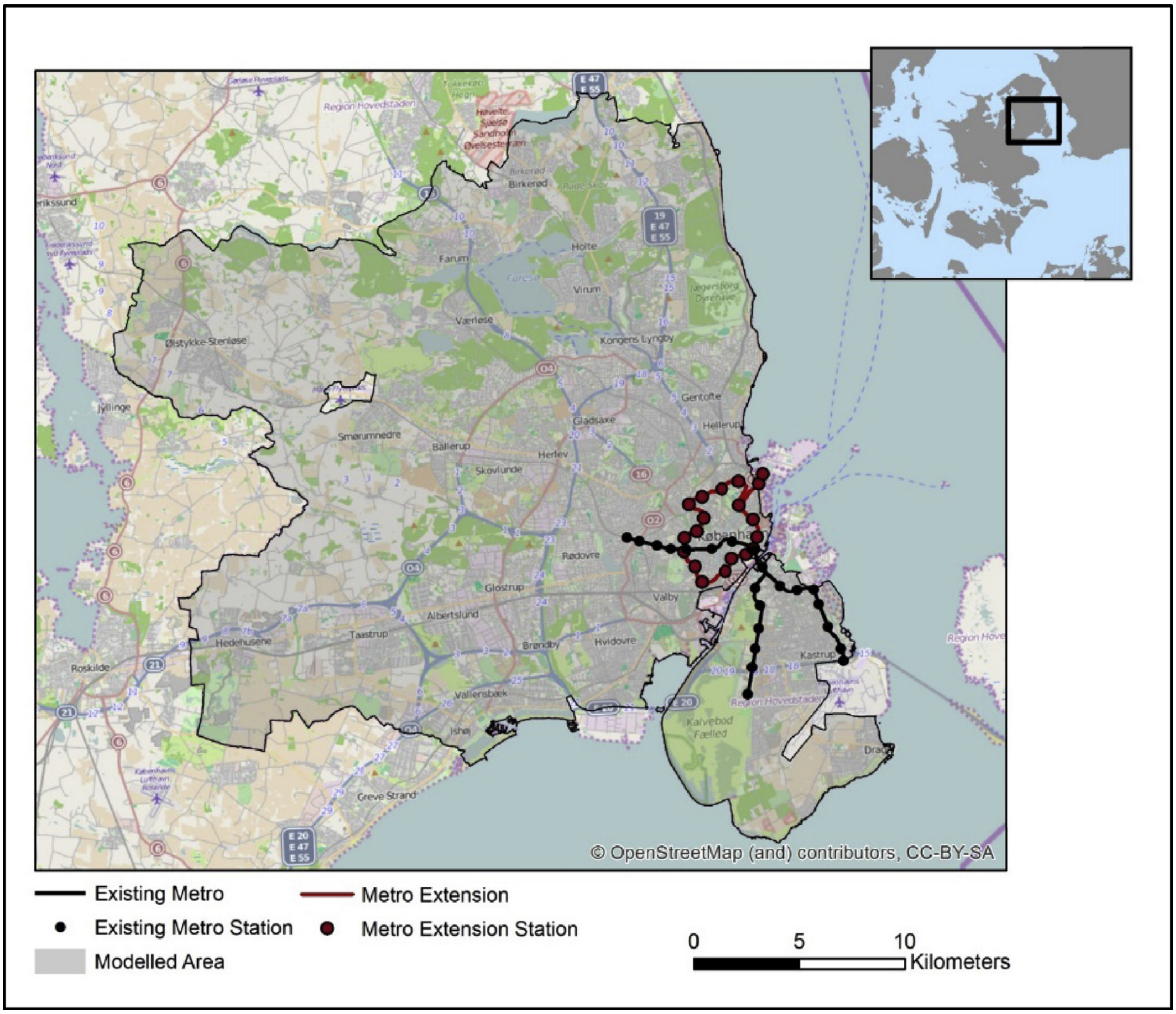
[39] Since the allocation system on the rental part of the Copenhagen housing market differs substantially from the price system, our simulations refer only to the owner-occupied part of the market. That is, we assume that the population of owner-occupying households does not change because of the metro and compute counterfactual equilibria for that part of the market.

Table 4b
First step estimation procedure (MNL) for dual-earner households: interaction parameter estimates.

	Amenities	Households characteristics									
		Log (hous. income)	Age, head	Age sq./ 1000, head	Number of children	Education (medium), head	Education (high), head	Age, partner	Age sq./ 1000, partner	Education (medium), partner	Education (high), partner
α′s	Empl. access with public transport/1000 * dummy indicating no car[a]	−0.006***	0.0004	0.002	0.002***	0.003**	0.003*	−0.0002	0.004	0.004**	0.006***
		(0.002)	(0.001)	(0.008)	(0.001)	(0.001)	(0.002)	(0.001)	(0.009)	(0.001)	(0.002)
	Proximity to the nearest metro station (km) * dummy indicating no car[a]	−0.561***	0.043	−0.439	−0.185***	0.139	0.317***	0.039	−0.668	0.295***	0.273***
		(0.106)	(0.049)	(0.518)	(0.039)	(0.091)	(0.095)	(0.052)	(0.588)	(0.088)	(0.097)
	Dummy variable indicating one car	0.274*	0.036	−0.659	0.485***	0.224*	0.201	0.001	0.436	0.405***	0.162
		(0.144)	(0.071)	(0.728)	(0.054)	(0.132)	(0.142)	(0.074)	(0.820)	(0.128)	(0.148)
	Dummy variable indicating two cars	1.268***	0.005	−0.065	0.301***	0.413*	0.218	0.143	−1.331	0.410**	0.335*
		(0.184)	(0.098)	(0.999)	(0.073)	(0.177)	(0.186)	(0.103)	(1.126)	(0.173)	(0.190)
β′s	Dummy variable indicating non-apartment	0.089	0.028	−0.859	0.701***	0.294***	0.337***	0.247***	−1.695***	0.631***	0.097
		(0.120)	(0.063)	(0.645)	(0.050)	(0.114)	(0.118)	(0.067)	(0.729)	(0.110)	(0.123)
	Log (standardized housing price)	3.656***	0.153**	−0.457	0.048	−0.350***	−0.434**	−0.173**	1.373	−0.524***	−0.112
		(0.136)	(0.077)	(0.775)	(0.059)	(0.131)	(0.132)	(0.081)	(0.870)	(0.126)	(0.137)
	Share of higher educated	3.932***	−0.142	1.574	0.350***	2.680***	5.566***	0.298	−2.441*	2.579***	4.165***
		(0.222)	(0.118)	(1.193)	(0.090)	(0.169)	(0.203)	(0.123)	(1.343)	(0.188)	(0.213)
	Number of conserved and protected buildings per sq.m.	−0.772***	0.075**	−0.912***	0.126***	0.029	0.100*	0.055*	−0.456	0.037	0.028
		(0.062)	(0.029)	(0.303)	(0.021)	(0.046)	(0.052)	(0.031)	(0.340)	(0.044)	(0.053)
	Distance to the CBD.	0.010***	0.002	−0.022	0.006***	0.006**	0.002	−0.005***	0.056***	−0.003	−0.003
		(0.003)	(0.002)	(0.017)	(0.001)	(0.003)	(0.003)	(0.002)	(0.019)	(0.002)	(0.003)
	Social housing (share)	−0.923***	0.101***	−1.166***	0.001	0.283***	0.304***	0.007	0.137	0.154***	0.252***
		(0.073)	(0.035)	(0.362)	(0.025)	(0.054)	(0.064)	(0.036)	(0.400)	(0.052)	(0.066)
γ′s	Empl. access with public transport/1000 * dummy indicating one car	−0.0004	−0.0001	0.003	−0.0002	0.002***	0.002**	−0.001	0.008	0.002**	0.004***
		(0.001)	(0.001)	(0.005)	(0.0004)	(0.001)	(0.001)	(0.001)	(0.006)	(0.001)	(0.001)
	Proximity to the nearest metro station (km) * dummy indicating one car	−0.368***	−0.002	−0.019	−0.112***	0.113**	0.134**	0.076	−0.889**	0.105**	0.276***
		(0.068)	(0.032)	(0.332)	(0.024)	(0.052)	(0.056)	(0.033)	(0.370)	(0.051)	(0.057)
	Dummy variable indicating non-apartment * dummy indicating one car	−0.633***	−0.059	0.602	−0.205***	0.004	0.056	0.074*	−0.891*	−0.192***	0.056
		(0.086)	(0.040)	(0.418)	(0.032)	(0.075)	(0.079)	(0.043)	(0.479)	(0.073)	(0.082)
	Dummy variable indicating non-apartment * dummy indicating two cars	−1.052***	−0.057	0.448	−0.098	−0.061	0.116	−0.034	0.378	−0.189	0.131
		(0.147)	(0.082)	(0.830)	(0.060)	(0.143)	(0.147)	(0.087)	(0.938)	(0.141)	(0.149)
	Dummy variable indicating parking charging * dummy indicating one car	−0.298***	−0.038	0.454	−0.143***	−0.176***	−0.057	0.004	−0.227	−0.053	−0.027
		(0.077)	(0.034)	(0.359)	(0.028)	(0.067)	(0.061)	(0.037)	(0.419)	(0.065)	(0.062)
	Dummy variable indicating parking charging * dummy indicating two cars	0.493**	0.077	−1.000	−0.277**	0.061	−0.095	−0.338	3.870	−0.128	−0.397
		(0.225)	(0.226)	(2.251)	(0.136)	(0.333)	(0.338)	(0.222)	(2.301)	(0.320)	(0.343)

Notes: standard errors in parentheses; ***, **, * indicate that estimates are significantly different from zero at the 0.01, 0.05 and 0.10 levels, respectively.

[a] Note that the multiplication with the no-car dummy $(1-d_c)$ implies that we have in fact specified the term as $\alpha X+\gamma X d_c$, where X is employment access or proximity to metro, while imposing the restriction $\gamma=-\alpha$.



Map 3. Metro system extension.

equilibrium of a logit model of the kind discussed here is unique (see, for instance, Rouwendal, 1990). However, the fact that the attractiveness of neighbourhoods is determined partly by the demographic composition of the households living there causes complications. Bayer and Timmins (2005) show that if the presence of one group of households – the higher educated in our model – makes a neighbourhood more attractive, multiple equilibria may occur. Although we cannot completely exclude this possibility for our particular application, in our simulations the model always converged to the same equilibrium.[40]

5.1. *Excess demand*

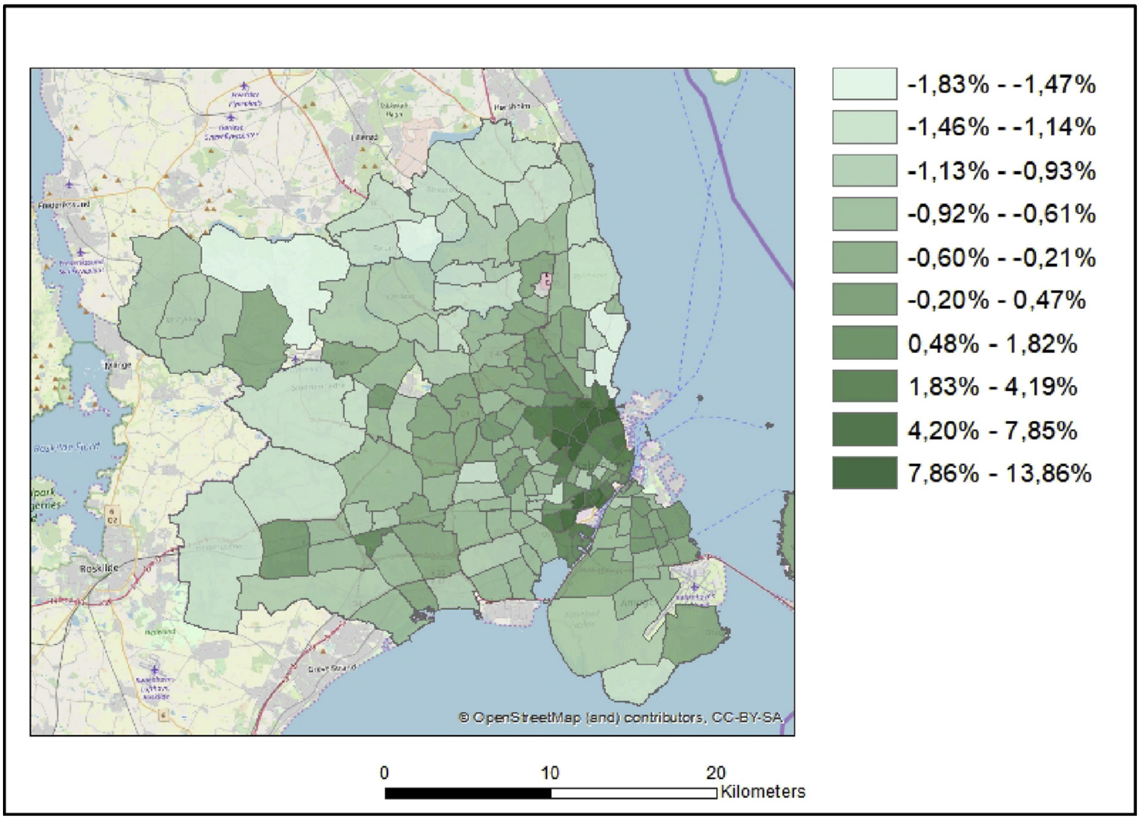
Our first investigation concerns the changes in housing demand that would occur because of the extension of the metro network if house prices would remain unchanged. These changes in demand can only be realized if housing supply is infinitely elastic, which is obviously not the case in the Copenhagen area, if only because of the fact that so much land is already used for houses and other buildings. The exercise is nevertheless interesting because it shows how people would react to the change in public transport *per se*.

The simulation results suggests that extension of the metro system will have a substantial impact on housing demand, especially in the centre of the area along the new metro line. The increase in demand for these areas implies, of course, a decrease elsewhere in the region but since the improvement in accessibility is concentrated in a few areas, the decrease is spread over a much larger area. The extension of the metro will have more or less identical impact on single-earner households and dual-earner households. Moreover, especially households with higher incomes and more education will be attracted by the extension of the metro system (see the maps A.2. and A.3. in Appendix A.1).

5.2. *Housing price adjustments*

Next, we investigate the housing market equilibrium that would realize after the extension of the metro network has been realized under the assumption that housing supply remains unchanged. This assumption is also unlikely to be completely true, but the possibilities to increase housing supply in the centre of the GCA are clearly limited and a decrease in the housing stock in the suburban regions because of lower house

[40] To compute the equilibrium we started by computing the demand for each choice alternative in the new situation (i.e. after the extension of the metro network). Then we adjusted the price (in the direction of reduced excess demand, only if housing supply is inelastic) and share of higher educated (using their share in the predicted demand for each alternative). We recomputed demand with the new values of the local prices and amenities, and so on. This procedure seems reasonably close to what one could expect of the actual adjustment process. See the online appendix for a detailed description of the different transition path algorithms that we used to test for the presence of multiple equilibria.



Map 4. Change in relative house prices caused by the metro extension.

prices also seems very unlikely. Hence, the assumption of a zero elasticity of supply should be expected to be much closer to reality than that of an infinitely inelastic supply.

The reaction of the housing prices to the metro extension is shown on Map 4. Since our model can only deal with relative prices, we assumed that the average price level remains constant in the Greater Copenhagen Area.[41] The housing prices increase in the areas closer to the new metro line and decrease in other areas that become relatively less attractive. The reaction of house prices thus counteracts that of the extension of the metro network. The return to housing market equilibrium with fixed housing supply thus acts partly as a redistribution of the benefits of the metro extension.[42]

Our results suggest also a substantial increase in the interest for living in areas close to the metro network. Moreover, the simulation results show the impact of the extension of the metro-network on the location choices of high income households, i.e. households from the northern part of the GCA who are on average more well-to-do are in particular attracted by the improved access to high quality public transport (see map A.4 in Appendix A.2). Higher educated workers and households with children are attracted by the extended metro-network as well. Our simulation results suggest that improving high quality public transport significantly affects the demographic composition of neighbourhoods.[43]

[41] Since our model does only refer to the Copenhagen area, it cannot predict the possible effect of the metro on migration from other parts of Denmark that could change the price level.

[42] Note, however, that we do not consider the wealth effects of the housing price changes. Although these are redistribution effects, they may have an impact on the behaviour of the actors involved that we do not take into account.

[43] See online appendix for additional maps of the impact of the extension of the metro network.

Table 5
Car ownership.

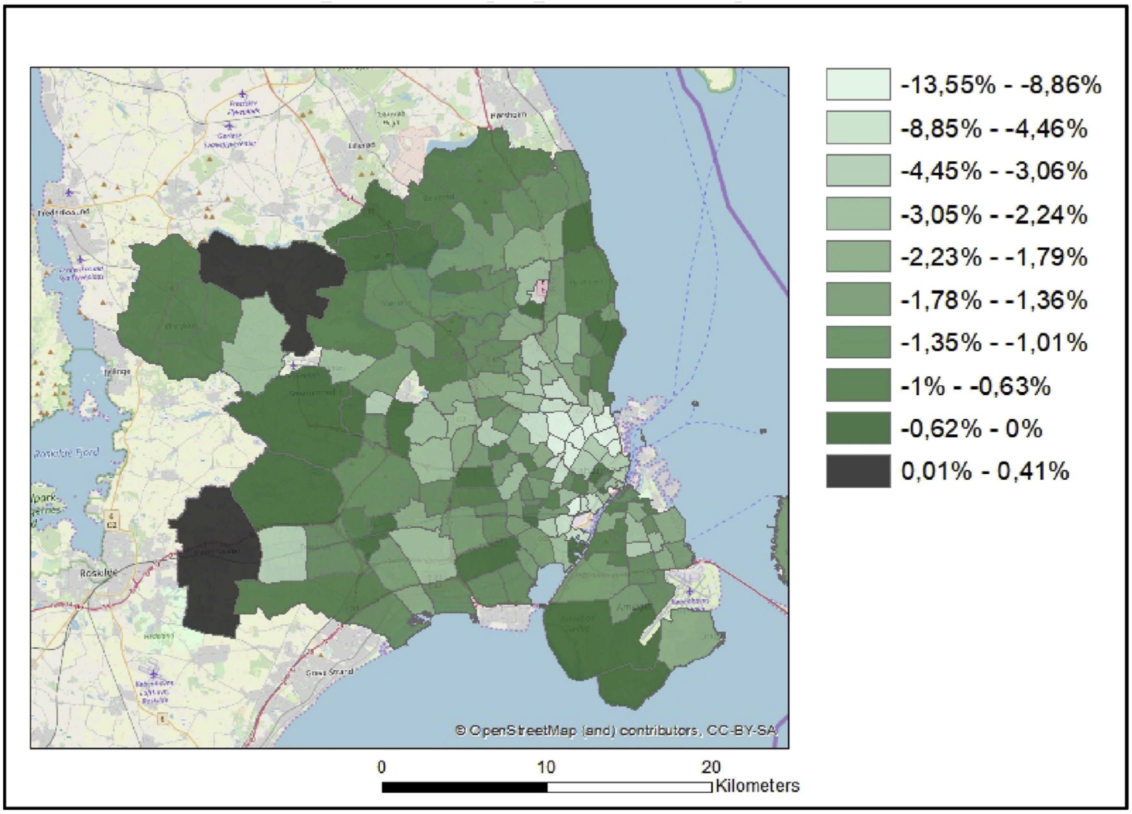
	Reference scenario	Scenario 1	Scenario 2
		Fixed prices	Fixed supply
One car households	85,388	82,906 (−2.9%)	83,389 (−2.3%)
Two cars households	17,495	16,695 (−4.6%)	16,949 (−3.1%)
Total number of cars	120,378	116,295 (−3.4%)	117,287 (−2.6%)

Notes: percent changes of number of car owners are in parentheses.

5.3. Car ownership

We argued in section 3 that we expect that improving public transport will have a nonpositive impact on car ownership. This is confirmed by the simulation study. The model suggests that the number of car owners will be reduced as a result of the metro extension. Table 5 shows that number of one car owners will decrease by 2.9% if housing supply would be elastic and by 2.3% with inelastic supply (house prices adjust). For two car owners the corresponding figures are 4.6% and 3.1%, respectively. Clearly some households that would give up their car (or one of their cars) if they could move to the areas where metro accessibility improved will change this intention when house prices adjust.[44] When interpreting these figures, it should be noted that they refer to the whole GCA. Changes in the shares of car owners are much larger in the neighbourhoods that are directly affected by the extension, see Map 5. In some areas further away from the city centre the car ownership rates even increase slightly. The reason is that the composition of the population shifts towards households that attach a relatively small value access to the metro network and are more inclined to own a car.

[44] We have also estimated the model with Bayer et al. (2007)'s instrument. The simulation results based on this version of the model are similar to those in Table 5, see the online appendix.



Map 5. Change in car ownership in the GCA caused by the metro extension (percentage point change).

5.4. Welfare change

To compute the welfare implication of the change in the metro network, we assume that the random parts of the utilities - the $\varepsilon^{i}_{a,h,c}$'s – are individual-specific constants. Our utility function is nonlinear in income, which complicates the computation of the compensating variation (McFadden, 1999). We use the approach of De Palma and Kilani (2003) who show that the compensating variation can be expressed as a single-dimensional integral (see online appendix for a detailed description of our application).

There are various ways to assess the impact of the extension of the Copenhagen metro network. The first possibility is to look at what its impact will be on the welfare of those involved if choice behaviour would remain unchanged. All households therefore stay in their initially chosen alternative, house prices do not change. We can thus compute the compensating variation of the households that results directly from the change in the quality of public transport.

It is, of course, likely that households will react. In our second assessment we assume this to happen, while housing supply is infinitely elastic. Note that households do not only switch to other areas, but also to other positions with respect to car ownership, and with respect to this change, the assumption of elastic supply is clearly more realistic.

Third we assess the welfare implications of the extended metro network under the contrary assumption that housing supply is completely inelastic and prices adjust so as to re-establish the equality between supply and demand. We take into account that single-earner households and dual-earner households are active on the same housing market when computing the new equilibrium prices. Prices increase in areas that become more attractive because of the extended metro network, which compensates for the initial increase in attractiveness. Similarly, areas that became initially less attractive because of increased public transport now get lower housing prices.

Note that our computations ignore the wealth effects of the house price changes. In our model higher house prices translate in higher user costs that make a neighbourhood less attractive. This seems realistic for explaining (re)location choices of households. For incumbents the increase in house prices implies an additional welfare benefit that should ideally be taken into account in a full cost-benefit analysis. Since wealth is not included in our model, we do not present such calculations in this paper.[45]

The results for the average single (top panel) and dual earner households (bottom panel) are presented in Table 6. The figures are averages of the compensating variation for households with average characteristics that initially have chosen a particular choice alternative. For both types of households we first present the average compensating variations over all choice alternatives. Column 1 gives the compensating variation if house prices do not change and all households stay where they are. It equals slightly more than 11,000 DKK for single-earner households and 2000 DKK more for two-earner households.[46] If we allow households to move, but still keep house prices constant the figures in column 2 result. The possibility to move to a choice alternative that has become more attractive than the one currently chosen (e.g by abandoning the car) causes the moderately larger welfare effect. Column 3 shows the welfare effects if house prices adjust to their new equilibrium values. This implies an additional gain for single-earner households but a lower average welfare effect for the dual-earner households as prices increase most in the areas that are popular among this group.

The second line in the panel referring to the single earner households concerns only those choice alternatives that benefit directly from the metro extension, that is, those alternatives in which no car is owned and a new metro station is closer than 3 km. There are 89 such alternatives. The

[45] It may be argued that the wealth effect of the metro has potentially an impact on neighbourhood choice and the demand for housing types, housing services and cars. Assessing this would require a separate study.

[46] 1 DKK is appr. € 0.13.

Table 6
Compensating variations of the extension of the metro network.

			[1] No mobility	[2] Elastic supply	[3] House prices adjust
Single-earner households	All households	Average CV (DKK)	11,062	12,026	11,899
		Share of income (%)	*2.8*	*3.1*	*3.0*
	Dir. affected alt. (no car)	Average CV (DKK)	33,753	34,386	24,324
		Share of income (%)	*8.6*	*8.7*	*6.2*
Dual-earners households	All households	Average CV (DKK)	13,271	13,669	13,012
		Share of income (%)	2.1	2.2	2.1
	Dir. affected alt. (no car)	Average CV (DKK)	53,156	53,413	38,641
		Share of income (%)	*8.4*	*8.4*	*6.1*
	Dir. affected alt. (one car)	Average CV (DKK)	12,019	12,412	3,518
		Share of income (%)	*1.9*	*2.0*	*0.6*

welfare gain for households that choose these alternatives is roughly three times as large as the average. However, roughly 50% of this additional gain disappears if house prices increase so as to equilibrate housing supply and demand after the extension of the metro network.

The second line in the panel referring to the dual-earner households also concerns households without a car that gain directly from better access to the metro network (81 choice alternatives). Their welfare gain is roughly four times the average. Again, a large part of it disappears when house prices adjust. The third line in this panel refers to dual-earner households with one car that live in close proximity to the new metro stations (93 choice alternatives). Their welfare gain is smaller than that of the average dual-earner household, which is due to the fact that this average is determined in part by the large welfare gain of those who do not own a car.[47] Little of this gain is left after house prices adjust.[48] Moreover, when we use the Bayer et al. (2007) type instrument, it seems the implied welfare changes are of the same order of magnitude as those resulting from simulating the basic model, see the online appendix.

Since our model refers only to owner-occupiers, it is useful to ask if the results have anything to say about the welfare effects for renters. It seems reasonable to assume that renting households experience similar benefits from the opening of the metro network as owners. Since the price mechanism is of limited importance on the regulated rental market of Copenhagen, incumbents will probably not have to pay directly for the increased attractiveness of the neighbourhoods in which they live, which makes them somewhat comparable to incumbent owners. Relocating households who want to rent will probably be faced with longer waiting times, which makes them less accessible. Again, this effect is to some extent comparable to that experienced by non-incumbent owners. To the extent that waiting times play a similar role on the rental market as price adjustments on the owner-occupied market, the welfare effects may be similar. In the longer run, this situation may result in upgrading (followed by substantially higher rent) or sale of rental housing, which decreases the stock of rental housing in the areas that benefit most of the metro network. Summarizing: our welfare calculations probably have some relevance for the rental sector, but is unable to address issues specific for that segment of the housing market.

[47] Note that the figures are unweighted averages over the choice alternatives.
[48] Note (again) that the wealth effect of the change in housing prices is not included in these welfare measures.

6. Conclusions

In this paper we develop a model for the joint choice of residential location and car ownership, focusing on the interaction with high quality public transport. While existing models of car ownership take the residential location as given, our approach shows that the presence of high quality public transport, which acts like a local public good and induces Tiebout-type sorting, can offer a good substitute for car ownership for some households. We estimated the model on register data for the Greater Copenhagen Area (GCA) and used the estimated model to simulate the impact of an extension of the metro network in Copenhagen. The model predicts a substantial increase in the interest of living in the centre of the area, that is, close to the extended metro network, especially among the higher income households, while reducing the overall car ownership rate by 2.3%. The results of the model are robust to alternative specifications.

Our results are relevant when considering policies concerned with urban area development. Place-based policies, such as the improvement of the public transport, which aim to improve some areas within a city, are frequently criticized in the economic literature because they improve places rather than the households' welfare. Our results suggest that a place-based policy which focuses on areas close to attractive city centres will attract relatively wealthier households and most likely cause more segregation. However, our model also predicts a significant increase in the relative housing prices in the areas in proximity to the new metro line and a decrease in other areas. The reaction of house prices thus acts partly as a redistribution of the benefits within an urban area after the improvement of the public transport.

The connection between public transport and gentrification suggested by our findings may come as a surprise. It has been argued in the literature that public transport only acts as a good substitute for cars among the poor (see e.g. Glaeser et al., 2008). The probable explanation is that European cities, often with historical cores that are major consumer amenities, differ substantially from most of their American counterparts as was noted by Brueckner et al. (1999) and confirmed empirically by Van Duijn and Rouwendal (2013). The connection between high quality public transport and the current strong revival of interest in inner city living is a topic that deserves more interest.

Future work may extend the results of the present paper in several directions. For instance, our study hints at implications of high quality public transport on vehicle kilometres travelled and their impact on congestion and pollution but does not quantify them. To do so, more attention should be paid to aspects that had to be treated in a relatively crude way here like the costs associated with car ownership and use and those associated with public transport use. Other suggestions already mentioned earlier in the paper are the extension of the sorting framework to explain the choice of combinations of residential and job locations, and to undertake a similar analysis for the rental market.

However, note that – these lose threads notwithstanding – the present paper suggests important additions to conventional cost benefit analyses of improvements in urban public transportation networks by providing an analytical tool for quantifying its effects – including that on welfare – on household location choices and on the number of cars owned in the context of an urban equilibrium model with heterogeneous households. Since the relationships between the number of cars on the one hand and congestion, pollution and traffic accidents on the other are usually well known in specific metropolitan areas, this will allow for meaningful calculations of the social benefits due to decreased car ownership caused by the metro.

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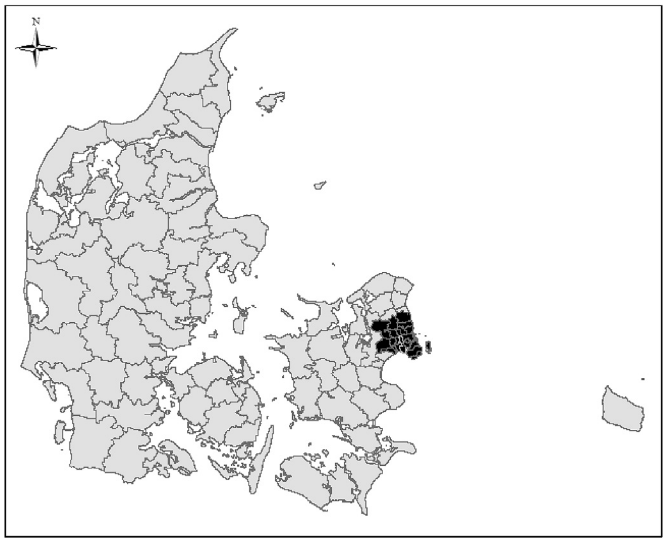
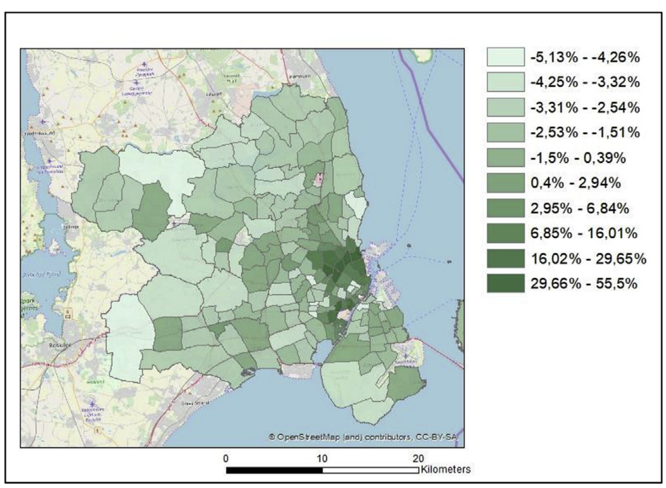
Appendix A

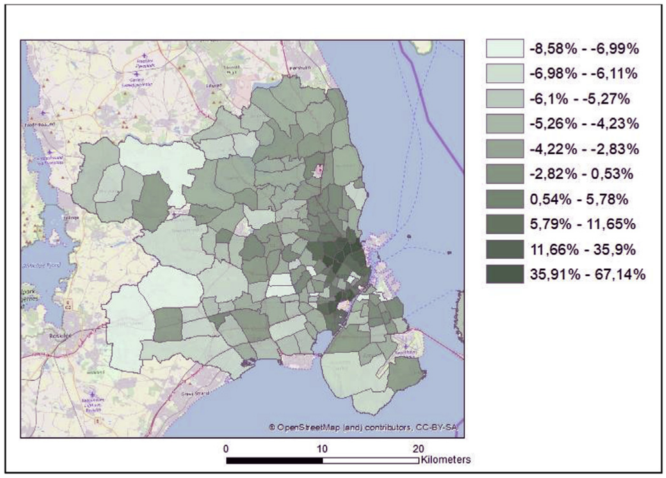
A.1 Maps.



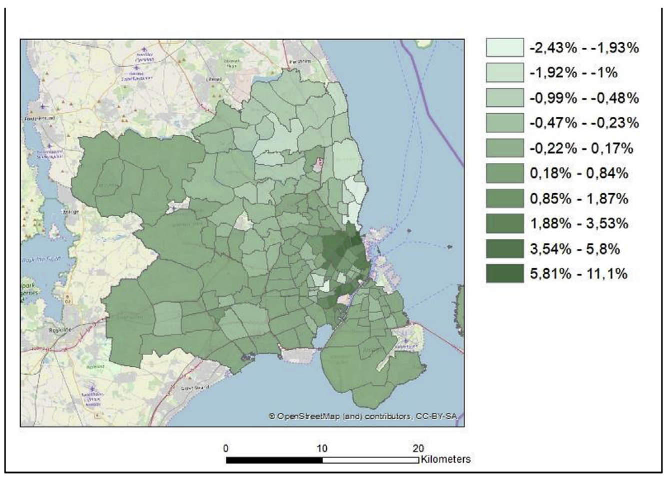
Map A.1. The Greater Copenhagen Area (GCA).



Map A.2. Pct. change in population of the households in the GCA caused by the metro extension (elastic supply and house prices fixed).



Map A.3. Pct. change in the share of higher educated in the GCA caused by the metro extension (elastic supply and house prices fixed).



Map A.4. Change in household income caused by the metro extension (fixed supply and house prices adjust).

A.2 First step results for the IV regressions.

Table A.2.1
First step IV estimation results for single-earner households.

	[1]	[2]	[3]
	Log (std. house price)	Share of higher educated	Employment access with public transport for no car owners
Proximity to the nearest metro station (km) * dummy variable indicating no car	0.001 (0.003)	−0.026* (0.014)	15.998*** (2.017)
Number of conserved/protected buildings per sq.km.	0.003 (0.003)	−0.010 (0.012)	−4.101** (1.722)
Distance to the CBD.	0.0003 (0.0002)	0.005*** (0.001)	−0.861*** (0.094)
Dummy variable indicating non-apartment	0.014*** (0.003)	−0.202*** (0.014)	−0.899 (2.022)
Dummy variable indicating non-apartment * dummy variable indicating one car	−0.002 (0.003)	0.004 (0.011)	3.490** (1.546)
Dummy variable indicating parking charging * dummy variable indicating one car	0.003 (0.003)	0.037*** (0.014)	−2.444 (2.002)
Social housing (share)	0.001 (0.003)	−0.079*** (0.014)	5.701*** (2.057)
Dummy variable indicating one car	−0.001 (0.002)	−0.032*** (0.009)	−77.689*** (1.319)
Prices that would clear the market if there were no unobserved heterogeneity (IV)	*0.971*** (0.004)*	*0.298*** (0.018)*	*−3.844 (2.646)*
Distance to the nearest school in 1890 (IV)	*−0.001** (0.0002)*	*−0.012*** (0.001)*	*0.679*** (0.136)*
*Distance to the nearest train station in 1939 *dummy indicating no car (IV)*	*−0.0002 (0.001)*	*−0.022*** (0.004)*	*−15.167*** (0.653)*
Constant	0.013*** (0.004)	0.163 (0.018)	85.424*** (2.620)
Partial R-squared	0.3877	0.2578	0.4689
No. of observations	538	538	538

Notes: standard errors are in parentheses; standardized house price, and share of higher educated and employment access with public transport are instrumented; ***, ** indicate that estimates are significantly different from zero at the 0.01 and 0.05 levels, respectively. Durbin (score) $\chi^2(3) = 263.321$ and Wu-Hausman $F(3,532) = 167$.

Table A.2.2
First step IV estimation results for dual-earner households.

	[1] Log (std. house price)	[2] Share of higher educated	[3] Employment access with public transport for no car owners	[4] Employment access with public transport for one car owners
Proximity to the nearest metro station (km) * dummy variable indicating no car	−0.0003 (0.003)	−0.024* (0.013)	14.024*** (1.803)	−4.291** (1.953)
Proximity to the nearest metro station (km) * dummy variable indicating one car	−0.0001 (0.003)	−0.029** (0.013)	−4.350** (1.846)	10.529*** (1.999)
Number of conserved/protected buildings per sq.km.	−0.001 (0.002)	−0.005 (0.010)	−3.606*** (1.377)	−2.650* (1.491)
Distance to the CBD.	−3.03E-07 (0.001)	0.006*** (0.001)	−0.677*** (0.080)	−0.775*** (0.087)
Dummy variable indicating non-apartment	0.004 (0.003)	−0.244*** (0.014)	−5.937*** (1.943)	3.311 (2.104)
Dummy variable indicating non-apartment * dummy variable indicating one car	0.0003 (0.003)	0.019* (0.011)	6.043*** (1.438)	−2.460 (1.557)
Dummy variable indicating non-apartment * dummy variable indicating two cars	0.0002 (0.004)	−0.035** (0.014)	6.033*** (2.060)	−1.524 (2.230)
Dummy variable indicating parking charging * dummy variable indicating one car	0.00001 (0.003)	0.035*** (0.013)	−0.372 (1.818)	12.941*** (1.969)
Dummy variable indicating parking charging * dummy variable indicating two cars	0.001 (0.006)	0.078*** (0.026)	−3.083 (3.690)	−2.995 (3.996)
Social housing (share)	−0.002 (0.003)	−0.054*** (0.012)	2.936* (1.710)	6.884*** (1.851)
Dummy variable indicating one car	9.85E-06 (0.002)	−0.016* (0.009)	−78.845*** (1.313)	76.091*** (1.421)
Dummy variable indicating two cars	0.00003 (0.003)	−0.009 (0.013)	−78.778*** (1.822)	0.921 (1.972)
Prices that would clear the market if there were no unobserved heterogeneity (IV)	0.994*** (0.004)	0.349*** (0.017)	0.153 (2.379)	−4.137 (2.576)
Distance to the nearest school in 1890 (IV)	−0.0002 (0.0002)	−0.008*** (0.001)	0.513*** (0.112)	0.556*** (0.121)
*Distance to the nearest train station in 1939 *dummy indicating no car (IV)*	0.0001 (0.001)	−0.032*** (0.004)	−14.112*** (0.628)	−0.422 (0.680)
*Distance to the nearest train station in 1939 *dummy indicating one car (IV)*	−0.0001 (0.001)	−0.036*** (0.004)	0.143 (0.575)	−14.971*** (0.623)
Constant	0.001 (0.004)	0.114*** (0.016)	84.472 (2.250)	7.369*** (2.436)
Partial R-squared	0.3034	0.2150	0.4059	0.3770
No. of observations	636	636	636	636

Notes: standard errors are in parentheses; standardized house price and, share of higher educated and employment access with public transport are instrumented; ***, ** indicate that estimates are significantly different from zero at the 0.01 and 0.05 levels, respectively. Durbin (score) $\chi^2(4) = 634.483$ and Wu-Hausman $F(4, 615) = 285$.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.regsciurbeco.2020.103543.

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