Public transport and urban pollution

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Abstract

The paper studies the effect of public transport policies on urban pollution. It uses a quantitative equilibrium model with residential choice and mode choice. Pollution comes from commuting and residential energy use. The model parameters are calibrated to replicate key variables for American metropolitan areas. In the counterfactual, I study how free public transport coupled with increasing transit speed affects the equilibrium. In the baseline simulation, total pollution falls by 0.2%, as decreasing emissions from transport are partly offset by rising residential emissions. A second counterfactual compares a city with and without public transit. This large investment decreases pollution by 1.6%. When jobs are decentralized, emissions fall by 0.3% in the first and by 3% in the second counterfactual.

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1 Introduction

Does the provision of public transport reduce air pollution and/or greenhouse gas emissions? Public transport is high on the agenda of urban policymakers worldwide, and environmental concerns are often cited as one reason for their expansion, subsidisation, and other policies intended to increase its attractiveness.

Paris is a case in point. In December 2016, the city government moved to reduce the 'worst air pollution in 10 years'. The measures included allowing only cars with odd- or even-numbered license plates on any particular day. Another measure was to make public transport free for all users on several days with severe pollution.[1]

Mackett and Edwards (1998) surveyed experts involved in planning new public transit systems, and found that in eight out of 19 planned systems, planners cited 'improving the environment' as one reason for constructing the system. Thus, it seems that policy makers think of pollution reduction as one potential goal in planning transit systems.

The intuition seems simple enough: subsidizing transit should increase transit usage at the expense of driving. As long as transit produces lower emissions per person mile than cars, emissions will fall. Indeed, some studies find that transit provision has significant effects on pollution. For instance, Gendron-Carrier *et al.* (2016) find that opening a subway system reduces urban air pollution by 4%. However, whether results of empirical studies generalize to different contexts (say, buses instead of subways) is always an open question. Moreover, studies using reduced form regressions without estimating structural economic parameters are limited to identify only few parameters of interest. But the details of if and how certain policies affect pollution and welfare may depend on intricate details such as the nature of transport costs, urban structure, and so on, that may be only partially controlled in empirical studies.

Therefore, this paper sets out a quantitative general equilibrium model, where individuals choose their place of residence (city center or suburb) as well as their commuting mode (car or public transit). They also choose housing consumption. Pollution comes from commuting as well as from residential energy use. The model is calibrated to match key features of American MSAs. The paper studies the general equilibrium of the model and how it is affected by transit provision. In the first counterfactual, I study how making transit free and increasing its speed to that of cars affects the equilibrium. The simulation

[1] Paris makes all public transport free in battle against 'worst air pollution for 10 years', available at http://www.independent.co.uk/news/world/europe/paris-public-transport-free-air-pollution-spike-a74601 html

shows that pollution falls by 0.2 percent. On the one hand, subsidizing transit reduces emissions from transport, both because people switch to cleaner public transport and because aggregate commuting distances fall as people move to the city center. On the other hand, however, the subsidy increases net income, which raises housing consumption and residential energy use. The resulting rise in residential emissions partly offsets the fall in commuting emissions. Thus, the results demonstrate the importance of general equilibrium effects. I also study the welfare effect of this policy and find that welfare increases by 0.5 percent.

In a second counterfactual, I look at how introducing public transit in a 'no-transit' city affects pollution. I find that pollution falls by 1.6%.

The rest of the paper studies various extensions. I conduct various sensitivity analysis by changing parameters. Most of these have only small effects on the equilibrium. I also consider the financing of subsidies by taxes, which reduces the income increase and leads to a slightly larger emissions reduction. Finally, I extend the model to allow for endogenous job locations. This is potentially important, since transport policies affect commuting distances, which also leads to a rebalancing of jobs between central cities and suburbs (Gonzalez-Navarro and Turner, 2016). The results of this extended model partly differ from the original one: the first counterfactual (subsidizing fares and increasing transit speed) leads to a reduction of emissions of 0.3 percent and the second (introducing transit in a no-transit city) to a reduction of 3 percent.

Overall, the policies designed to improve public transport seem to have only moderate effects on pollution.

Literature. Several strands of research have analyzed the effect of public transport on pollution. Among others, Parry and Small (2009) use a theoretical transport model to quantitatively evaluate welfare effects of transit subsidies. Their model is very detailed in the modelling of externalities and margins of response, but it is not spatial. Several computable general equilibrium studies have analyzed similar questions, e.g. Proost and Dender (2001), also in a non-spatial model. Tscharaktschiew and Hirte (2012) use a spatial CGE model to study the effect of various policies related to public transport. While they also consider transport related pollution, the focus of their paper is on congestion and pollution does not seem to figure directly in utility; furthermore, in their model, emissions accrue from commuting only, while this paper also looks at the response of residential emissions.

There is also a literature studying the effect of public transport on pollution using quasi-experiments. For instance, Bauernschuster *et al.* (2017) find that transit strikes increase pollution, while Gendron-Carrier *et al.* (2016) find that opening a subway network reduces a city's air pollution by 4%. This literature, however, is typically limited to making statements about the particular experiment studied, and the welfare consequences are not based on structural modelling.

Finally, this paper is closely related to a new literature on quantitative evaluation of transport infrastructure, which uses spatial models (Allen and Arkolakis, 2016; Ahlfeldt *et al.*, 2016).[2] This literature, however, has so far not addressed pollution externalities.

The paper proceeds as follows. The next section presents the model basics. Section 3 contains the model calibration along with the counterfactual simulations. In Section 4, I extend the model to allow for endogenous job locations, and Section 5 contains the corresponding simulations. The last section concludes the paper.

2 The model

2.1 Model setup

We consider a city made up of the city center (indexed 1) and suburb (indexed 2). Individuals have identical wage incomes w which are location independent. In Section 4, I introduce job decentralization and location dependent wages into the model. Comparing the results will show the extent to which the effect of transit on pollution might be driven by job relocation.

Individuals living in part $k = 1, 2$ of the city commute distance d_k to work and pay rent p_k per square foot. Individuals can either commute by car (indexed A) or transit (indexed B). Commuting via mode $j = A, B$ incurs a fixed cost F_j as well as a variable cost per mile of τ_{jk}. The variable cost is made up of a monetary cost, m_{jk}, as well as a time cost which is proportional to the wage.

An indvidual who lives in part k of the city and commutes via mode j has Cobb-Douglas utility

$$u_{jk} = q_{jk}^{\alpha} c_{jk}^{1-\alpha} E^{-\beta},$$

where q is housing consumption in sq. feet, c consumption of a composite good, and E environmental pollution. Note that pollution is assumed to be the same regardless of where

[2] See Redding and Rossi-Hansberg (2017) for an overview of this literature.

the individual lives. In Appendix C, by contrast, pollution is assumed to be completely local. The simulation results are, however, very close to the current setup with spatially invariant pollution.

The individual budget constraint is

$$w = p_k q_{jk} + F_j + \tau_{jk} d_k. \tag{1}$$

Housing rent is assumed to accrue to absentee land owners. In Appendix D, however, I show that the welfare effect of the counterfactual policies do not depend on this assumption. If rent is instead redistributed to local residents, the welfare levels change, but the percentage change of the counterfactual policies do not. Therefore, I stick with the simpler assumption of absentee landowners.

Maximizing utility subject to (1) gives optimal housing consumption and indirect utility, v:

$$q_{jk} = \frac{\alpha(w - F_j - \tau_{jk} d_k)}{p_k} \tag{2}$$

$$v_{jk} = (w - F_j - \tau_{jk} d_k) p_k^{-\alpha} E^{-\beta}. \tag{3}$$

In the spirit of the discrete choice literature, individuals have heterogeneous tastes for which part of the city to live in and which mode to use.[3] In particular, individual i's utility if she lives in part k and uses mode j is

$$u_{ijk} = v_{jk} \eta_{ijk}, \tag{4}$$

where η_{ijk} is person i's idiosyncratic taste parameter. I assume that the η_{ijk} are distributed according to a Fréchet distribution

$$G(\eta_{ijk}) = e^{A_{jk} \eta_{ijk}^{-\epsilon}} \tag{5}$$

where the scale parameter A_{jk} gives the average utility of using mode j in part k of the city, and the shape parameter $\epsilon > 1$ controls the dispersion of idiosyncratic utility. Then,

[3] For a classic application in travel demand, see McFadden (1974). For an early paper using this approach in urban economics, see Anas (1990).

the choice probabilities for mode j and part k are given by

$$\pi_{jk} = \frac{A_{jk} v_{jk}^{\epsilon}}{\sum_{\ell=A}^{B} \sum_{m=1}^{2} A_{\ell m} v_{\ell m}^{\epsilon}}, \quad j = A, B, \; k = 1, 2. \tag{6}$$

I assume that the housing supply in part k of the city has constant price elasticity θ, $H_k = \Theta p_k^{\theta}$. The housing market clearing conditions are

$$H_k = \sum_{j=A}^{B} n_{jk} q_{jk}, \quad k = 1, 2, \tag{7}$$

where n_{jk} is the number of residents in part k of the city who commute via mode j. Using (2) in (7) and solving gives the equilibrium housing price in k:

$$p_k = \left(\frac{\alpha Y_k}{\Theta} \right)^{\frac{1}{1+\theta}}, \quad k = 1, 2, \tag{8}$$

where $Y_k \equiv \sum_{j=A}^{B} (w - F_j - \tau_{jk} d_k)$ is residents' aggregate income in k.

Total city population is exogenous and given by N. To close the model, the location equilibrium is defined by the following equations:

$$n_{jk} = \pi_{jk} N, \quad j = A, B, k = 1, 2. \tag{9}$$

Given (3), (6), and (8), the equilibrium is defined by the four equations in (9). This pins down the number of individuals using mode j in both parts of the city.

In order to compute the welfare effects of transit policies, later on in the counterfactual simulations, we will compute the expected welfare of a resident

$$\mathbb{E}(u) = \Gamma \left(\frac{\epsilon - 1}{\epsilon} \right) \left[\sum_{j=A}^{B} \sum_{k=1}^{2} A_{jk} v_{jk}^{\epsilon} \right]^{1/\epsilon}, \tag{10}$$

where $\Gamma(\cdot)$ is the gamma function.

2.2 Pollution

Pollution is produced by two sources: commuting and residential energy use. Households' residential energy use for space heating, cooling, and electricity is assumed to be proportional to the housing floor space they consume.[4] In contrast, pollution from commuting is related to the total distance travelled by the city's residents. Let e_H be the emissions factor on housing, i.e. the emissions produced by households per square foot of housing. Likewise, let $e_j, j = A, B$, be the emissions factors for commuting, that is, the emissions produced by commuting one person mile on mode j. Then total emissions are

$$E = \sum_{j=A}^{B} \sum_{k=1}^{2} n_{jk}(e_H q_{jk} + e_j d_k). \tag{11}$$

We are interested in how policies which affect the attractiveness of public transit impact pollution. In practice, this could happen through subsidizing fares or infrastructure provision, such as constructing new lines, increasing travel speed via traffic control policies, and so on. In terms of the model, we will think of policies that reduce either the fixed cost, F_B or the variable cost, τ_{Bk} of transit use.

Inspection of (11) shows the following margins of adjustment. When transit is subsidized, first, since the costs of using it fall relative to cars, some individuals will switch from driving to transit. Second, depending on whether the cost decrease is larger in the city center or the suburb, some individuals will relocate. Commuting distances may therefore rise or fall depending on the direction of this effect. And third, subsidies will increase net incomes and affect housing prices due to the relocation effect.[5] As a result of this combined effect, when housing supply is elastic, aggregate housing consumption will tend to increase which raises residential emissions. The total effect depends on the balance of the three effects. In the next section, in order to gauge the magnitude of potential emissions reductions, I simulate the model numerically.

3 Numerical simulation

3.1 Baseline simulation

Choice of parameters. In order to simulate the model numerically, I use parameters taken from literature and official data sources. The rest of the parameters are calibrated to match key variables of US metropolitan areas. I use the following parameter values.

[4] Borck and Brueckner (2016) present a model where residential energy use is proportional to a building's surface area instead of housing floor space.

[5] The income effect depends on whether or not subsidies are financed by tax increases. More on this effect below.

Income is set to $w = \$53,889$, the median annual household income in the U.S. in 2015 (see www.census.gov). I set total city population to 5 mill., the size of a large US metro area. Following the National Transportation statistics (NTS), I set the fixed cost of a car to $\$6,350$.[6] I assume that the out-of pocket cost of transit is entirely fixed with respect to distance.[7] Assuming an average round-trip ticket price of \$3 (\$1.50 one-way) and 250 workdays, the fixed cost is $F_B = \$750$. Variable costs have two components: monetary and time costs. All cost components are computed on a round trip basis per year, assuming 250 work days per year. For transit, I assume variable monetary costs are zero. For cars, following the NTS, the monetary costs are set to \$0.15 per mile. I assume that time costs are proportional to t_{jk}, the inverse of travel speed, for individuals using mode j in part k and valued at half the wage (Small, 2012).

The main source for the data used here is the National Household Travel Survey (NHTS), a survey of over 100 mill. US households on their transport behaviour. In the following, I use the data for households living in MSAs with more than 1 mill. inhabitants. Because the model does not consider commuting between cities, I drop all households who work in a different state from the one where they live, and those who commute more than 150 minutes one-way.

I compute travel speed for commuters living in urban areas and suburbs commuting by car and transit from the NHTS (see Appendix A for details). The inverse travel speeds (hours commute time per mile) for mode j in part k of the city are $t_{A1} = 0.053, t_{B1} = 0.191, t_{A2} = 0.042, t_{B2} = 0.148$.

Commuting distances also come from the NHTS. I use the average distance to work for individuals living in locations designated urban and suburban. This gives $d_1 = 10.05, d_2 = 12.68$.

Following Davis and Ortalo-Magné (2011), I set the expenditure share of housing α to 0.24. I set the housing supply elasticity to $\theta = 1.75$, the average elasticity across US metropolitan areas according to Saiz (2010). The constant Θ is calibrated to target the mean housing floor space in US cities and suburbs, 1500 and 2100 sq ft.

Ahlfeldt *et al.* (2015) calibrate ϵ from commuting data at the block level in Berlin and find a value of 6.83. Monte *et al.* (2015) use commuting flows between US counties and estimate a value of 3.3. Since the data in Ahlfeldt *et al.* (2015) are at the block level, while those from Monte *et al.* (2015) are at the county level, I use an intermediate value of 5.5.

[6] See https://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/index.html.

[7] This seems reasonable since city transit fares tend to be independent of distance.

However, I will also use lower and higher values to assess the sensitivity of the results. The shape parameter determines the dispersion of the idiosyncratic utility component and hence governs how strongly individuals react to changes in parameters.

Finally, the emissions factors for public and private transport are taken from Borck and Brueckner (2016). The detailed procedure is described in Appendix A. The emissions factors are $e_A = 554.375$ for cars and for public transport $e_B = 288.275$ (measured in kg CO_2 equivalents per mile). The emissions factor for residential energy use is $e_H = 6.5269$ kg CO_2e per sq. ft of floor space.

Baseline results. I calibrate the remaining parameters to match the share of residents residing in suburbs and inner cities as well modal shares for using public and private transport by part of the city.

I partition the cities into those that have high and low transit ridership, where high ridership is defined as a share of transit users above the median. I then calibrate the scale parameters to target the equilibrium distribution of households across central city and suburb as well as across modes in cities with low transit ridership. The idea is to use low ridership cities as baseline and study the effect of counterfactual policies which stimulate transit use.

According to the NHTS, in these MSAs, 94.31% of individuals use cars in the city center and 97.57% in the suburb. The corresponding figures are 78.14% and 94.07% in cities with high ridership. The percentage of households living in the central city is 25.07% in cities with low ridership and 43.08% with subway. The target values for the calibration are then $s_{A1} = 0.9431, s_{A2} = 0.9757, s_1 = 0.2507$ (the remaining target values are determined residually from (9)), where s_{A1} is the share of car users in the city center and so on. I set $A_{B2} = 1$. I then substitute the target values for the n_{jk} into (6), and solve for the remaining A_{jk}. The amenity values that rationalize the equilibrium are computed as $A_{A1} = 25.904, A_{B1} = 1.557$, and $A_{A2} = 51.382$.

Tab. 1 shows the result from the baseline calibration. 34% of total city emissions are due to commuting, the rest to residential emissions.[8]

Counterfactual. I now study how policies to make public transit more attractive affect the equilibrium allocation and therefore pollution. The transport policy consists of

[8] According to Borck and Brueckner (2016), residential and commercial GHG emissions in the US are about twice as high as emissions from commuting, so the 34% emissions from commuting in the model are a good fit of the data.

Table 1: Calibration results

	s_{A1}	s_{A2}	s_1	E^C (kt)	E^H (kt)	E (kt)
Baseline	94.31%	97.57%	25.07%	33,821.8	63,623.6	96,445.4
Counterfactual	88.03%	95.46%	25.59%	32,302.0	63,948.7	96,250.6
Δ	−6.66%	−2.17%	+2.07%	−1.58%	+0.51%	−0.20%

the following elements: transit travel speed in either part of the city is increased to match that of automobiles, and the fixed transit fee is reduced to zero. Given that the average travel speed for drivers in the NHTS data used here is about 2.5 times that of transit users, this is a sizeable improvement.

The fourth row of Table 1 shows the results (Δ denotes percentage change rates). Transit ridership increases by 6.7% in the central city and by 2.2% in the suburb. The share of central city residents increases by 2.1%. As a result, housing prices increase both in the central city and the suburb, but more so in the center. Income net of commuting costs rises by 8% for transit users.

Results on urban emissions are also found in Table 1. Transport emissions are reduced both through the increased mode share of transit and the shorter average commuting distance. The combined effect is a fall in transport emissions of 1.6%. However, residential emissions increase by 0.5%. Since residential emissions account for two thirds of total emissions, the net effect is that total emissions fall by only 0.2%. Hence, in the baseline scenario, improving public transit has only a moderate effect on total emissions. This points to the importance of general equilibrium effects.

Note that subsidies are not financed by city residents. If they were, net incomes would be lower, which would induce general equilibrium effects. Most importantly, since net incomes would be lower in the counterfactual, one would suspect that the increase in housing consumption in the counterfactual would be reduced. Indeed, as shown in Appendix B, this is what I find when the subsidies to public transport are financed by lump-sum taxes. However, I also find that the reduction in emissions in this case is only marginally lower than in the original counterfactual, 0.22% instead of of 0.2%.[9] Of course, whether and how exactly subsidies to transit are financed will depend on details. Subsidies may sometimes be financed by grants from higher levels of government, so in these instances,

[9] As detailed in the Appendix, this number assumes that only monetary subsidies are financed by taxes. If instead the monetary value of the time cost reduction is also tax financed, the emissions reduction is 0.67%.

the model predicts lower pollution effects than when cities have to fully finance transit provision policies.

Even though the considered policy seems stark, the effect on emissions is moderate. Transit ridership in the counterfactual is not close to the ridership of US cities with high transit shares. Two distinct explanations are possible. First, cities with high and low transit shares may differ in many respects beyond transport policies, such as urban structure, labor markets, population composition, and so on.

The second explanation, which we will explore now, looks at the preferences of the city population. In fact, the preference parameters A_{jk} have been calibrated to match features of low-ridership cities. Given these preferences, city residents do not seem to be very responsive to transit policies. So it might be that households select into cities partly based on their preferences. In other words, households living in car cities may be those who are particularly attached to driving.

I therefore now consider a different construction of baseline and counterfactual. Now, the A_{jk}s are calibrated to target cities with high transit ridership. The targets are now $s_{A1} = 78.14\%$, $s_{A2} = 94.07\%$, and $s_1 = 43.08\%$. Again, setting $A_{B2} = 1$ and solving the urban equilibrium like before now gives $A_{A1} = 39.328, A_{B1} = 4.862, A_{A2} = 38.787$. The results are displayed in Table 2. Note that the baseline is again the equilibrium with costly transit.

Apparently, households are now more responsive to transit policies. The counterfactual policy increases transit ridership strongly by 12% in the central city and by 2.8% in the suburb. The central city population increases by 3.5%. The effect on total emissions is stronger but still moderate, at -0.54%. This is due to the fact that both the negative effect on emissions from commuting and the positive effect on emissions from residential energy use are magnified.

The upshot seems to be that it is difficult to reconcile existing ridership patterns with a homogeneous household model. If this is correct, then the effects of transport policies would depend on the type of city where they are introduced. Making transit more attractive will obviously prove to work less well if the population is very attached to driving. More research would seem to be needed to judge whether this conjecture is true.

Welfare. I now evaluate the welfare effect of the transit policy. Obviously, the welfare effect will depend on β. The larger β, the larger is the pollution damage. Borck and Tabuchi (2016) calibrate β in a similar model to match a social cost of carbon value of

Table 2: Calibration results II

	s_{A1}	s_{A2}	s_1	E^C (kt)	E^H (kt)	E (kt)
Baseline	88.90%	96.79%	41.64%	31,177.0	59,585.9	90,762.9
Counterfactual	78.142%	94.07%	43.08%	30,178.1	60,097.1	90,275.2
Δ	−12.10%	−2.81%	+3.45%	−3.20%	+0.86%	−0.54%

Table 3: Calibration results: sensitivity

	s_{A1}	s_{A2}	s_1	E^C	E^H	E
Baseline	−2.97%	−1.01%	+0.87%	−0.72%	+0.24%	−0.09%
$\epsilon = 2.5$	−2.48%	−0.82%	+0.93%	−0.60%	+0.38%	+0.04%
$\epsilon = 8.5$	−12.50%	−4.01%	+3.39%	−2.93%	+0.71%	−0.53%
$w = 65,139$	−6.48%	−2.10%	+2.05%	−1.54%	+0.43%	−0.24%
$w = 41,493$	−6.97%	−2.29%	+2.11%	−1.66%	+0.67%	−0.13%
$d_1 = 5.03, d_2 = 6.34$	−2.92%	−1.01%	+0.84%	−0.71%	+0.25%	+0.05%
$d_1 = 15.75, d_2 = 19.2$	−12.43%	−3.85%	+4.20%	−2.92%	+0.86%	−0.79%
$\theta = 0.5$	−6.66%	−2.17%	+1.43%	−1.54%	+0.28%	−0.34%
$\theta = 3.0$	−6.66%	−2.17%	+2.42%	−1.61%	+0.58%	−0.16%

\$40 per metric ton CO_2 which gives a value of $\beta = 0.022$. I use a slightly higher value of $\beta = 0.05$ here, but changes in β have only very small effects on the computed welfare effect.

I then compute the expected welfare in the baseline and the counterfactual, using (10). Doing so yields a small welfare gain of the considered policy of 0.53 percent. I also compute the equivalent variation EV, i.e. the amount of wealth individuals would have to be given in the baseline that would make them indifferent between the baseline and the counterfactual. This leads to a value of $EV = \$272.4$, or 0.5 percent of income. The conclusion is that the welfare effect of the considered policy seems to be relatively small.

Sensitivity. Table 3 shows the results from varying some parameters. The table represents the changes (Δ in Tab. 1) in the counterfactual exercise using the baseline parameters as well as variations of parameters, one at a time.

I first vary the shape parameter of the Fréchet distribution, ϵ. As discussed above, the baseline value of ϵ is in between those that were calibrated or estimated in similar models by Monte *et al.* (2015) and Ahlfeldt *et al.* (2015). I therefore use both a lower value of 2.5 and a higher value of 8.5.

Second, I vary household income. I first increase income to the 90th percentile of median household income across US MSAs, \$65,139. I then lower income to the 10th percentile of median household income across US MSAs, \$41,493.

Third, I decrease commuting distances for both center city and suburban residents by 50% (to 5.03 and 6.34 miles), and then increase both by 50% to 15.075 and 19.02 miles.[10]

Finally, I vary the housing elasticity to a lower value of 0.5 and a higher value of 3.

Interestingly, the table shows that the change in emissions does not seem to be very sensitive to varying parameters. The largest reduction in emissions occurs when the shape parameter ϵ is large or when the commuting distances are large. In the first case, consumers are not very attached to residences or commuting modes (the dispersion of idiosyncratic tastes is small), so they respond more strongly to changes in commuting technology. In the second case, commuting costs are large, so changing them has a proportionately larger effect on the equilibrium. Reducing the elasticity of housing supply limits the increase in housing consumption, which dampens the increase in residential emissions following transit expansions.

3.2 Large transit investment

In this subsection, I consider a large public transport investment to gauge the potential environmental impact of such large investments. Consider the following thought experiment. On average, MSAs in the NHTS sample have transit ridership of 84.34% and 96.12% in the central city and suburb, and 33.78% of residents live in the city center. Suppose that public transport was not available at all in this representative city. What would be the effect on pollution? Or, turning the question around, what is the effect of the availability of public transport on pollution in the average city?

In order to answer this question, I proceed like before, solving the location equilibrium for the scale parameters of the Fréchet distribution. Setting $A_{B2} = 1$, this gives $A_{A1} = 22.12, A_{B1} = 4.092$, and $A_{A2} = 31.702$. I then compute emissions in the benchmark with transport. After that, I compute the equilibrium when public transport is not available so that everyone commutes by car. The results are shown in Tab. 4.

Obviously, the effects are qualitatively similar to those of the policies considered before, but larger. In particular, transport emissions decrease by 3.9%, while residential emissions decrease by 0.4 percent. Total emissions decrease by about 1.6%. Interestingly, residential

[10] Increasing population does not affect the location equilibrium and therefore produces the same percentage changes due to transport policies (while obviously total pollution is affected).

Table 4: Effects of large transit investment

	s_{A1}	s_{A2}	s_1	E^C (kt)	E^H (kt)	E (kt)
No public transport	100%	100%	31.86%	31,544.0	61,918.1	93,462.1
Baseline	84.34%	96.12%	33.78%	32,115.0	61,939.6	94,054.7
Δ	−15.66%	−3.88%	+6.03%	−3.90%	−0.36%	−1.58%

emissions fall in this scenario, whereas they rise in the baseline scenario. The fall in transport emissions is similar in magnitude to the pollution reduction that Gendron-Carrier *et al.* (2016) attribute to the opening of a subway system in a city.

The larger emissions reduction is mirrored by a larger welfare effect. Welfare with public transport is 1.6% higher than without. The equivalent variation is $810.83 or 1.48% of income.

4 Public transport and job decentralization

Until now, I have assumed job location to be independent of transit provision. However, transport policies may affect not only residence location but job location as well. For instance, Gonzalez-Navarro and Turner (2016) find that subway construction leads to modest suburbanization. This obviously affects commuting distances and, via net income changes, also residential energy use. Hence, job decentralization has potentially important consequences for how public transport affects pollution.

Consider, as before, a city with two areas. Households now have the choice where to live and where to work. Let the utility of a household who lives in k and works in ℓ be

$$v_{jk\ell} = (w_k - F_j - \tau_{jk} d_{k\ell}) p_k^{-\alpha}, \tag{12}$$

where $d_{k\ell}$ is the commuting distance between k and ℓ.

Firms produce the composite good under perfect competition using labour and a fixed factor as inputs. The constant-returns production function of a representative firm who produces in area k is given by

$$A_k L^\beta,$$

where A_k is total factor productivity (TFP) in k. I assume that TFP differences between areas are driven by agglomeration economies external to the firm. For simplicity and in line with a large literature, I assume that this agglomeration force is given by $A_k = B_k L_k^\gamma$, where γ is the agglomeration elasticity.[11]

Firms maximize profits. From the first order condition for choice of L_k, labour demand is given by

$$L_k^D = \beta^{\frac{1}{1-\beta}} A_k^{\frac{1}{1-\beta}} w_k^{\frac{1}{\beta-1}} = \beta^{\frac{1}{1-\beta}} w_k^{\frac{1}{\beta-1}} \left(B_k (L_k^D)^{\gamma}\right)^{\frac{1}{1-\beta}} \tag{13}$$

Free entry in the composite goods sector leads to zero profits, so the operating profit is absorbed by the rent to the fixed factor. I assume that the fixed factor rent accrues to absentee owners.[12]

In addition to the housing market equilibrium, which takes the same form as before, there now are additional conditions for the labour market equilibrium in area k, namely, labour demand has to equal labour supply. Labour is supplied inelastically by the workers living in k and working there and those who live in $\ell \neq k$ who commute to k. Solving $L_k^D = L_k^S$ gives the wage in k:

$$w_k = \beta B_k (L_k^S)^{\beta+\gamma-1}. \tag{14}$$

Solving the housing market equilibrium gives the same form for the housing price in k as (8), where now $Y_k \equiv \sum_{m=1}^{2} \sum_{j=A}^{B} (w_k - F_j - \tau_{jm} d_{jm})$. The equilibrium now involves the discrete choice of place of residence and place of work. Again, assume that households have an idiosyncratic component, $\eta_{ijk\ell}$, for living in k and commuting to ℓ using mode j. This component is distributed with a Fréchet distribution with scale parameter $A_{jk\ell}$ and shape parameter $\epsilon > 1$. The equilibrium is defined by the choice probabilities and location conditions

$$\pi_{jk\ell} = \frac{A_{jk\ell} v_{jk\ell}^{\epsilon}}{\sum_{m=A}^{B} \sum_{r=1}^{2} \sum_{s=1}^{2} A_{mrs} v_{mrs}^{\epsilon}} \tag{15}$$

$$n_{jk\ell} = \pi_{jk\ell} N, \quad j = A, B, k = 1, 2, \ell = 1, 2. \tag{16}$$

5 Simulation

5.1 Baseline

I now simulate the model with decentralized jobs numerically. I use the same baseline parameters as in Section 3. Following Valentinyi and Herrendorf (2008), I set the labour

[11] See, e.g. Duranton and Puga (2004) for a variety of approaches that all yield a reduced form like the one used here.

[12] An argument analogous to that in Appendix D shows that redistributing operating profits to residents would not alter the results.

share β to 0.65. The literature on agglomeration economies suggests values of γ between 0.03 and 0.08, so I set $\gamma = 0.05$ (see e.g. Combes and Gobillon, 2015; Rosenthal and Strange, 2004). I set the productivity parameters to $B_1 = B_2 = 6.9154 \times 10^6$ to target the average US wage income $\bar{w} = 53,889$ in the baseline.

Since the NHTS does not ask about place of work, I base the following analysis on data from the 2011 American Community Survey (ACS).[13] According to the ACS, in low-transit cities (defined as before), 29.67% of respondents living in MSAs live in the central city, and the share of workers in central cities is 41.58%. Of those residing in central cities, 79.51% also work in central cities, while the rest commute to suburbs. For those residing outside central cities, 74.41% also work where they live and the rest commute to central cities. In the model city with 5 mill. inhabitants, there is net commuting from the suburb to the center of 596,000 workers.[14]

As above, the eight equations in (16) can then be solved for the amenity levels that rationalize this equilibrium. As before, I set $A_{2B2} = 1$ and solve for the remaining 7 amenity levels, which gives $A_{1A1} = 12.18, A_{1B1} = 1.15, A_{1A2} = 6.84, A_{B12} = 0.38, A_{A21} = 6.22, A_{2B1} = 0.18$, and $A_{2A2} = 31.42$.

The results of the baseline calibration are found in Tab. 5. The table also shows the result from the counterfactual analysis, where again, fixed transit fees are reduced to zero and transit speed is increased to that of cars. Commuting by car falls by 9.4 percent in the city center and by 4 percent in the suburb. The share of central city residents increases by two percent. The share of jobs in the city center, s_1^w, increases slightly, by 0.4%. The table shows that aggregate emissions fall by 0.3 percent. This is the combined effect of a 2.7% fall in commuting emissions and a 0.8% rise in residential emissions.

To compare the results to those of the baseline model with exogenous job locations, I rerun the baseline simulation from Section 3 with the ACS data. The results are shown in Table A.3 in Appendix E. As the table shows, emissions in this baseline scenario decrease by 0.3% in this counterfactual as well. So it does not seem like endogenous job location explains a large part of the effect of public transit on pollution.

[13] See https://www.census.gov/programs-surveys/acs/.

[14] All those workers who commute outside of the MSA in which they live (13% of all workers living in MSAs) are excluded from the sample.

Table 5: Calibration results with decentralized jobs

	s_{A1}	s_{A2}	s_1	s_1^w	E^C (kt)	E^H (kt)	E (kt)
Baseline	92.79%	97.17%	29.67%	41.58%	30,042.4	62,722.9	92,765.3
Counterfactual	84.12%	93.24%	30.25%	41.70%	29,238.8	63,207.6	92,446.3
Δ	−9.35%	−4.04%	+1.95%	+0.42%	−2.68%	+0.77%	−0.34%

Table 6: Large investment with decentralized jobs

	s_{A1}	s_{A2}	s_1	s_1^w	E^C (kt)	E^H (kt)	E (kt)
Baseline	100%	100%	29.14%	41.45%	30,772.4	62,226.9	92,999.3
Counterfactual	69.07%	92.51%	34.13%	48.07%	28,395.9	61,849.6	90,245.5
Δ	−30.93%	−7.49%	+9.93%	+4.47%	−7.72%	−0.61%	−2.96%

5.2 Large investment

As before, I now compare a city with and without transit. The results are displayed in Table 6. The total fall in emissions is now much larger, at 3%. Transit provision now leads to large increases in transit ridership and in the share of central city residents, which rises by 10%. Moreover, compared with the car city, the share of central jobs increases by 4.5%, which leads to a fall in commuting distances. Due to the increase in ridership and decreased commuting distances, transport emissions fall strongly, by 7.7%. Residential energy use falls by 0.6%.[15]

6 Conclusion

I study the effect of public transport policies in a quantitative equilibrium model, where households choose their residence, commuting mode and housing floor space. Pollution is produced by commuting and residential energy use. In the calibrated baseline model, I then vary transport policies to study their effect on pollution. Reducing transit fares to zero and increasing speed to that of cars would lead to a small emissions reduction of 0.2%. A larger policy which introduces public transit in a car city reduces pollution by 1.6%.

Various extensions show that this finding seems robust to a variety of extensions in

[15] Again, to make the current exercise more comparable to the simulation with exogenous job locations, I redo the simulation in Section 3.2 with the ACS data. In that case, the total fall in emissions is 3.18%, close to the result in the current exercise. Commuting emissions fall by 7.7% and residential emissions rise by 0.74%.

the model considered here. Varying parameters has only small effects on the results. So does financing subsidies by head taxes on city residents. Finally, the results are relatively similar in an extended model where households have to choose their job location along with their residence. In summary, the model shows that transit policies may not be a blanket policy to reduce pollution.

Finally, the welfare analysis indicates moderately positive welfare effects of transit policy. However, since public transport affects a variety of other externalities, most notably congestion, as well as accidents and noise, a more complete welfare analysis which takes account of these additional externalities would be needed to judge whether and to what extent transit should be subsidized.

Appendix

A Data

To calculate emissions factors, I follow Borck and Brueckner (2016), who present emissions factors for driving. To derive GHG and local emissions from commuting, we use data from the National Research Council (2010), along with a standard estimate of GHG damage equal to \$40/metric ton CO_2, or \$0.04 per kg CO_2. National Research Council Committee on Health, Environmental, and Other External Costs and Benefits of Energy Production and Consumption (2010), Table 3-5 (p. 180), gives 0.552 kg CO_2/mile as GHG emissions from gasoline. Local damage exists as well, however, and NRC estimates this damage as \$0.0134/mile. Local damage can be viewed as the product of local commuting emissions per mile, e_l^A, and social damage per unit of local automobile emissions, μ_l^{com}, which must satisfy $\mu_l^{com} e_l^A = \$0.0134/\text{mile}$. However, by choice of units of local pollution, we can set μ_l^{com} equal to \$0.040/kg, the same damage as per unit of GHG emissions, and then use the previous equation to determine e_l^A, which equals $0.0134/0.04 = 0.335$ kg/mile. Therefore, composite emissions from commuting consist of 0.552 kg CO_2/mile of GHG emissions and 0.335 kg/mile of local emissions, for a total of 0.887 kg/mile. Converting the 0.887 value to an annualized per mile value by multiplying by 625 ($2 \times 500 \times 1.25$) yields $e_A = 554.375$/mile.

Borck (2016) uses emissions factors for CO_2 emissions for public and private transport; according to these, public transport (which consists of buses and subways) produces 52% of the emissions of private transport. Therefore, the emissions factor for cars is $e_A = 554.375$

and for public transport $e_B = 0.52 \times 554.375 = 288.275$.

Turning to residential emissions, we use the Residential Energy Consumption Survey to apportion total BTUs of household energy use for space heating and air conditioning (converted to kwh) across five sources: electricity, natural gas, propane/LPG, and fuel oil and diesel/kerosene. Then, from Carbon Trust,[16] we get CO_2 generation per kwh of energy for the five sources: 0.5246 kg CO2e/kwh for electricity, 0.1836 for natural gas, 0.2147 for LPG, 0.2674 for fuel oil, 0.2517 for diesel/kerosene. Multiplying by kwh for each source and summing gives total residential CO_2 generation, and dividing by total residential kwh gives CO_2 generation per kwh of residential energy use. This quantity is 0.1997 kg CO_2/kwh, which equals the e_H value for GHG emissions.

However, the local emissions component of composite residential emissions remains to be considered. (National Research Council Committee on Health, Environmental, and Other External Costs and Benefits of Energy Production and Consumption, 2010, p. 235) gives \$0.016/kwh as the local emissions damage from electricity generation, while the spreadsheet from Parry *et al.* (2014)[17] gives local damage from the natural gas used in heating as \$0.322/GJ or \$0.00116/kwh. We weigh these values by the adjusted electricity and natural gas proportions in heating and cooling from the RECS (ignoring the other energy sources), which equal 53.79% and 46.21% respectively. The resulting local residential emissions damage is then \$0.00914/kwh. As in the case of commuting, this damage is the product of a local e_H, denoted e_l^H, and a social damage per unit of local residential emissions, μ_l^{res}, whose product must satisfy $\mu_l^{res} e_l^H = \$0.00914$. As before, we can choose the units of local residential emissions so that the social damage μ_l^{res} per unit is the same \$0.04/kg value as for GHG emissions. The implied value of eH_l is then given by $e_l^H = 0.00914/0.04 = 0.2285$ kg/kwh. Adding this value to the value of 0.1997 for GHG emissions gives an overall e_H equal $0.2285 + 0.1997 = 0.4283$ kg CO_2/kwh. Finally, from the RECS, I compute total annual residential energy use in kwh for urban residents, and divide by the dwelling's total square footage to get energy use per sq. ft., which equals 15.239 kwh per sq. ft. per year. The final value for residential emissions per sq. ft. is then $e_H = 0.4283 \times 15.239 = 6.5269$ kg CO_2e per sq. ft.

Inverse travel speed is computed from the NHTS sample. I take the travel time to work and divide by the distance between the individual's residence and workplace. I define

[16] See Carbon Trust, Conversion factors: Energy and carbon conversions, 2011 update (http://www.carbontrust.com/media/18223/ctl153_conversion_factors.pdf).

[17] The spreadsheet can be found at http://www.imf.org/external/np/fad/environ/data/\penalty-\@Mdata.xlsx.

Table A.1: Calibration with tax financing

	s_{A1}	s_{A2}	s_1	E^C (kt)	E^H (kt)	E (kt)
Baseline	94.31%	97.57%	25.07%	33,821.8	63,623.6	96,445.4
Counterfactual	88.03%	95.46%	25.59%	33,111.9	63,786.2	96,898.2
Δ	−6.66%	−2.17%	+2.07%	−1.58%	+0.48%	−0.22%

the commuting mode to be the car if the individual's transportation mode to work last week was car, van, SUV, pickup truck, or motorcycle, and public transit if the mode was local public bus, commuter bus, commuter train, subway/elevated train, street car/trolley, bicycle, or walk. Doing so results in the following inverse travel speed (hours per mile): cars in suburb: 0.042, transit in suburb: 0.148. Cars in city center: 0.053, transit in city center: 0.191.

B Financing subsidies

This Appendix considers the financing of subsidies. This is potentially important because of general equilibrium effects. In the original counterfactual, subsidizing public transit increases housing consumption since net incomes rise, and this increase induces higher pollution. If instead subsidies are financed by taxes, the increase in housing consumption should be tamed.

Therefore, I now assume that each city resident has to pay a subsidy

$$Z = \frac{n_{B1} + n_{B2}}{N} F_B,$$

so total subsidy outlays (i.e. the fixed costs of transit) are financed by the tax.

Tab. A.1 shows that the results differ only slightly from the original counterfactual. In particular, the increase in housing consumption is a little less pronounced and the fall in total emissions slightly larger than in the original counterfactual.

As a second exercise, I assume that the tax also has to cover the monetary equivalent of the reduction in time costs, so

$$Z = \frac{(n_{B1} + n_{B2})F_B + n_{B1}w(t_{B1} - t_{A1}) + n_{B2}w(t_{B2} - t_{A2})}{N}.$$

Now the total reduction in emissions in the counterfactual is somewhat larger but still

Table A.2: Localized pollution

	s_{A1}	s_{A2}	s_1	E^C (kt)	E^H (kt)	E (kt)
Baseline	94.31%	97.57%	25.07%	33,821.8	63,623.6	96,445.4
Counterfactual	88.09%	95.48%	25.53%	32,312.3	63,952.6	96,264.9
Δ	−6.59%	−2.14%	+1.84%	−1.68%	+0.55%	−0.19%

moderate, at 0.67%.

C Localized pollution

In this appendix, I assume that pollution is completely local. In the case of residential emissions, this may be partly accurate (only partly, since the energy production is usually not local and its pollution effect depends on how and where energy is produced), while in the case of commuting, this would depend the exact location of jobs. Nonetheless, it may be a useful approximation that allows to gauge whether the assumption of non-localized pollution is crucial. Utility is now

$$u_{jk} = q_{jk}^{\alpha} c_{jk}^{1-\alpha} E_k^{-\beta},$$

and pollution is defined as before, but within area k.

Tab. A.2 shows the simulation results. As can be seen, the results are very close to the original counterfactual. Therefore, it does not seem like the modelling of the dispersion of locally produced pollution is essential for the results.

D Rent redistribution

In this Appendix, I show that results are not affected by allowing for a redistribution of rental income. To see this, let income net of transportation costs be denoted by $\tilde{w} \equiv w - td - F$ (location and mode specific subscripts will be dropped for now). Denote total rental income by R and assume that it is partly redistributed lump-sum to all residents. In particular, suppose that residents receive the share ρ/N per capita and absentee landowners the share $1-\rho$ of rental income. Indirect utility for residents is

$$v = (\tilde{w} + \rho R/N)p^{-\alpha}. \tag{A.1}$$

Aggregate demand is $D = Nq = N\alpha(\tilde{w} + \rho R/N)/p$. Solving $R = pD$ gives

$$R = \frac{\alpha N \tilde{w}}{1 - \alpha\rho}. \tag{A.2}$$

Using (A.2) in (A.1) gives

$$v = \frac{\tilde{w}}{1 - \alpha\rho} p^{-\alpha}. \tag{A.3}$$

Solving $D = p^{\eta}$ gives the equilibrium housing price

$$p = \alpha^{\frac{1}{1+\eta}} N^{\frac{1}{1+\eta}} \tilde{w}^{\frac{1}{1+\eta}} (1 - \alpha\rho)^{-\frac{1}{1+\eta}}, \tag{A.4}$$

and finally substituting in (A.3) gives

$$v = \alpha^{-\frac{\alpha}{1+\eta}} N^{-\frac{\alpha}{1+\eta}} \tilde{w}^{1-\frac{\alpha}{1+\eta}} (1 - \alpha\rho)^{\frac{\alpha}{1+\eta}-1}. \tag{A.5}$$

Hence, utility for a resident of part k of the city who uses mode j is

$$v_{jk} = \alpha^{-\frac{\alpha}{1+\eta}} (N_{Ak} + N_{Bk})^{-\frac{\alpha}{1+\eta}} \tilde{w}_{jk}^{1-\frac{\alpha}{1+\eta}} (1 - \alpha\rho)^{\frac{\alpha}{1+\eta}-1}, \tag{A.6}$$

where $\tilde{w}_{jk} \equiv w - F_j - \tau_{jk} d_k$.

Changes in transport policies affect utility through changes in 'net income', $\tilde{w}_{jk}$, or through changes in population $N_{jk}, j = A, B$. Inspection of (A.6) shows that as long as ρ is the same in both areas of the city, the choice probabilities and therefore the residential and mode choice equilibrium are not affected by the level of ρ (see 6). Further, since indirect utility is proportional to $(1 - \alpha\rho)$, while the welfare level is affected by ρ (see (10)), the percentage changes relative to the baseline induced by a policy change are not. Hence, the analysis of the welfare effects of transport policies is not affected by redistribution of rental income.

E Baseline calibration with ACS data

Here, I rerun the baseline calibration with the ACS data. All parameters are as in Section 3, but the model is calibrated to target the ACS data used in Section 5. Tab. A.3 shows the result of the baseline and the counterfactual.

Table A.3: Calibration results (ACS data)

	s_{A1}	s_{A2}	s_1	E^C (kt)	E^H (kt)	E (kt)
Baseline	92.79%	97.17%	29.67%	32,950.6	62,722.9	95,673.5
Counterfactual	84.79%	94.74%	30.47%	32,267.1	63,108.7	95,375.9
Δ	−8.63%	−2.50%	+2.68%	−2.07%	+0.62%	−0.31%

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