Productivity, Congested Commuting, and Metro Size*

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Abstract

The monocentric city model is generalized to a fully structural form with leisure in utility, congested commuting, and the equalizing of utility and perimeter land price across metros. Exogenous and agglomerative differences in TFP drive differences in metro population, radius, land use, and prices. Quantitative results approximate observed correspondences across a range of small and medium U.S. metros. Traffic congestion proves the critical force constraining metro size. Self-driving cars significantly boost the size of metros with high productivity and significantly depress the size of metros with low productivity. Population becomes less responsive to increases in TFP as metros become larger. Correspondingly, the productivity "cost" of metro population—the TFP required to support a given population—increases convexly with size. Benchmark estimates suggest that agglomerative TFP suffices to support increases in population from low and intermediate levels but falls considerably short of doing so from high levels. Chance may thus play a significant role in determining which parcels of land develop into small and medium metros. But large metros depend on high exogenous TFP ("fundamentals") together with high exogenous and agglomerative consumption amenities.

Keywords: City Size, Commuting, Congestion, Land Use, Time Use, Self-Driving Cars

JEL classifications: R12, R41, J22

1 Introduction

The size of U.S. metros varies widely. The New York City metro in 2000 had population 17.6 million and land area 3400 square miles. Portland, by population the 25th largest metro in 2000, had population 1.6 million and land area 540 square miles. Trenton, the 100th largest metro, had population 340 thousand and land area 168 square miles. Among the 100 largest metros, population-weighted mean density ranged from 1700 to 34000 per square mile. Among commuters

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driving to the CBD in these metros, the 98th percentile straight-line distance from residence to workplace ranged from 10 to 53 miles. The 95th percentile commute time ranged from 23 to 90 minutes.

From the perspective of economic theory, these differences can arise from *only* three sources: variation in total factor productivity (TFP), variation in consumption amenities, and variation in geographical constraints. In this context, TFP should be broadly interpreted as anything that makes firms willing to pay higher prices for identical inputs and so encompasses characteristics such as business taxes, regulations, and zoning (Rosen, 1979; Roback 1982). Consumption amenities should analogously be interpreted as anything that makes residents willing to accept a lower numeraire wage and pay higher prices for identical housing and other non-traded goods and so encompasses taxes that fall on individuals.

This paper focuses on the case when variations in metro TFP, either exogenous or agglomerative, drive differences in metro size while abstracting from variations in consumption amenities other than traffic congestion. To do so, I generalize the standard monocentric city (Alonso, 1964; Mills, 1967; Muth, 1969) to a fully structural form with leisure as a source of utility and commuting that is subject to congestion. I then embed this model of internal metro structure in a system-of-cities framework. Perfect mobility equalizes utility within and across metros. Land's value in non-metro use equalizes its perimeter price across metros.

Moderate variations in metro TFP imply quantitative correspondences among metro population, radius, commute time, and a number of other outcomes that approximate those within and across a range of small and medium U.S. metros. Parameterizations and assumptions that decrease the explicit or implicit demand for land, such as higher elasticity to substitute away from land in housing production and away from housing in utility, increase the responsiveness of metro population to TFP. Similarly, parameterizations and assumptions that implicitly increase the supply of land, such as more highway provision and telecommuting, increase the responsiveness of metro population to TFP. Traffic congestion proves the most important force quantitatively constraining metro size. Self-driving cars, by increasing the leisure content of commute time, significantly boost the size of metros with high TFP and significantly depress the size of metros with low TFP.

Unless commuting does not congest, population becomes less responsive to differences in TFP as metros become larger. This concave relationship of population with respect to TFP implies that the "cost" of metro population—the TFP required to support a given level—increases convexly with population. Correspondingly, the elasticity of the cost with respect to population increases with population.

Under the baseline parameterization, the TFP cost elasticity for small and medium monocentric metros lies below typical estimates of agglomerative elasticity (the TFP benefit of metro population). This suggests that random factors, such as slight variations in exogenous TFP or the chronological order of settlement, play a significant role in determining which parcels of land develop into metros and which remain agricultural or unsettled. For example, Bleakley and Lin (2010) document that locations along early nineteenth-century portages between navigable rivers remain a statistically-significant, quantitatively-meaningful determinant of variations in population density almost two centuries after such a location is likely to have conferred a productivity advantage.

But to support a large monocentric metro requires TFP well above what can plausibly be attained from agglomeration. This suggests that exogenous differences in TFP, "fundamentals," together with exogenous and agglomerative differences in consumption amenities play a significant role in supporting large size. For example, Rappaport and Sachs (2003) argue that a coastal location significantly boosted late twentieth-century population density in the U.S. even after extensively controlling for historical channels that might account for this.

More generally, the high productivity cost of metro population above some threshold suggests that monocentricity must give way to polycentricity for a metro to grow large.

The remainder of the paper is structured as follows: Section 2 discusses the empirical motivation including the relevance of the monocentric stylization. Sections 3 and 4 lay out and parameterize the model. Section 5 presents baseline quantitative results. Section 6 describes alternative scenarios that build intuition and give insight into the determinants of metro size. Section 7 describes the increasing marginal productivity cost of metro population and the resulting equilibrium, where the marginal cost equals the marginal agglomerative benefit.

2 Empirical Motivation

The Office of Management and Budget, using data from the 2000 decennial census, delineated 922 Core Based Statistical Areas (CBSA). Of these, 362 had a population of at least 50 thousand and so were labeled as "metropolitan." The remainder were labeled"micropolitan." The CBSA delineations were constrained to be combinations of whole counties and so ended up including a significant share of land that was essentially agricultural or undeveloped. A modified version of the CBSA delineations, which includes only Census tracts with a population density of at least 500 persons per square mile or an employment density of at least 1000 workers per square mile, typically captures more than four fifths of a CBSA's population while excluding more than four fifths of a CBSA's land area (Rappaport, 2014b).

Table 1 shows a partial ranking of the 210 resulting metropolitan areas with a population of at least 100 thousand. As will be described below, the highlighted seven small and medium metros— Denver, Portland, Sacramento, Columbus, Indianapolis, Omaha, and Des Moines— moderately conform to the monocentric stylization and so are used to calibrate and measure the fit of the quantitative model.

The metro population density variables are constructed by weighting the "raw" density of each census tract by its population and so describe density as experienced by metro residents (Glaeser and Kahn, 2001; Rappaport, 2008a). The commute distance and time variables are constructed based on driving flows departing from a metro tract-of-residence between 5am and 9am to a tract-

rank	Metro	Population	Land Area (sq.mi)	pop density (pers/sq.mi) mean	pop density percentile 90	pop density percentile 98	commute distance to CBD (miles) mean	commute distance pctile 90	commute distance pctile 98	commute time to CBD (minutes) mean	commute time pctile 90	commute time pctile 95
	VERY LARGE											
1	New York City	17,621,000	3,420	33,900	95,000	158,300	11.1	23.3	37.2	41	75	90
2	Los Angeles	12,181,000	1,890	12,400	23,600	39,500	9.7	19.2	27.5	30	50	60
3	Chicago	8,557,000	2,530	10,300	26,300	42,500	12.0	24.9	33.0	37	60	73
	LARGE											
4	Philadelphia	5,157,000	1,880	8,800	23,500	34,900	8.7	16.2	23.0	32	50	59
5	Miami	4,862,000	1,200	7,000	12,500	23,300	10.0	17.2	24.6	33	52	59
⋮												
15	Riverside	2,720,000	1,080	4,500	8,500	10,800	7.9	15.2	28.5	21	36	40
16	San Diego	2,588,000	660	7,600	15,000	23,500	8.6	15.6	28.2	22	34	39
	MEDIUM											
17	Minneapolis	2,435,000	1,020	4,300	8,700	15,700	8.2	15.4	20.1	24	35	40
18	Baltimore	2,223,000	840	6,800	16,000	26,500	8.0	15.4	22.3	28	41	48
⋮												
21	**Denver**	**1,965,000**	**600**	**5,400**	**9,100**	**15,900**	**6.7**	**12.5**	**15.1**	**25**	**40**	**45**
⋮												
25	**Portland OR**	**1,606,000**	**540**	**4,700**	**7,800**	**11,500**	**6.9**	**12.3**	**15.0**	**24**	**38**	**44**
⋮												
27	**Sacramento**	**1,555,000**	**530**	**5,200**	**8,600**	**11,800**	**7.8**	**15.0**	**21.5**	**23**	**38**	**45**
⋮												
35	**Columbus OH**	**1,255,000**	**560**	**4,200**	**7,700**	**13,900**	**7.0**	**11.8**	**15.0**	**22**	**31**	**35**
⋮												
37	**Indianapolis**	**1,150,000**	**550**	**3,200**	**5,700**	**8,600**	**8.1**	**13.6**	**18.0**	**25**	**35**	**38**
	SMALL											
38	Buffalo	997,000	430	5,300	11,500	16,100	6.7	11.7	14.9	22	31	34
39	Charlotte	970,000	710	2,100	4,000	6,800	8.0	14.4	20.2	27	40	43
⋮												
57	**Omaha**	**606,000**	**230**	**4,100**	**6,600**	**8,900**	**6.0**	**11.0**	**13.1**	**19**	**28**	**30**
⋮												
93	**Des Moines**	**344,000**	**160**	**3,400**	**6,200**	**7,700**	**5.2**	**9.0**	**15.6**	**18**	**24**	**30**
⋮												
119	Port St. Lucie	264,000	190	1,900	3,100	4,900	-	-	-	-	-	-
120	Winston	252,000	210	1,700	3,000	4,400	4.8	8.2	10.2	17	22	26
	VERY SMALL											
121	Rockford IL	248,000	120	3,300	6,500	6,900	4.0	6.5	12.8	17	26	33
122	Visalia CA	244,000	100	4,000	6,800	9,500	4.1	9.2	21.4	14	21	25
⋮												
209	Springfield OH	102,000	62	2,975	5,277	8,493	2.5	4.0	11.9	14	19	22
210	Tuscaloosa	100,000	72	2,300	4,200	7,600	-	-	-	-	-	-
bottom 10 (mean)		104,000	45	1,462	2,591	3,470	2.5	3.8	5.6	13	18	20
ratio to bottom 10:												
NYC		169.0	75.2	23.2	36.7	45.6	4.5	6.1	6.6	3.2	4.3	4.5
max excluding L & VL		23.4	22.5	7.9	12.6	17.6	4.2	4.8	9.5	2.1	2.5	2.6

Table 1: U.S. Metros in 2000. Metros are constructed as the combination of CBSA tracts with population density of at least 500 per square mile or employment density of at least 1000 per square mile. Means and percentiles are population weighted. Commute distances and times are based on driving flows during the morning rush hour to a tract-of-work that is part of the CBD. Missing values reflect unavailable data. Highlighted metros serve as benchmarks for the quantitative model.

of-work that is part of the central business district (CBD).[1] The CBD is delineated as the union of census tracts with an employment density of at least 8000 workers per square mile and that are within 5 miles of the Google Maps centroid of the metro's principle city (Rappaport, 2014b). Holian and Kahn (2012) show that the Google Maps centroids typically correspond closely to subjective judgments of "downtown."

The bottom rows summarize several of the many dimensions along which metro size varies. Excluding the 16 largest metros (those with population of more than 2.5 million), population and land area each vary by a multiplicative factor of 23. Mean population density and the density of the most crowded residential tracts respectively vary by factors of 8 and 18. The distance and drive time of longer commutes to the CBD respectively vary by factors of 10 and 3. The quantitative model matches much of this variation among small and medium metros with relatively moderate differences in TFP.

In contrast, the model falls considerably short of matching the additional variation of the large and very large metros. For a monocentric metro's population to exceed several million requires implausibly high TFP in order to compensate for heavily congested commuting. This shortfall can be seen as helping to validate the quantitative model as the largest metro that at least moderately conformed to the monocentric stylization in 2000, Denver, had population 2 million. All U.S. metros with population above this in 2000 had either a large number of dense employment sub-centers (McMillen and Smith, 2003) or significantly diffuse employment or both.

Several criteria were used to identify the highlighted metros as conforming to the monocentric stylization (Rappaport, 2014b). In each metro, the CBD accounted for at least a moderate share of total employment and a moderately high share of employment in agglomerative occupations. Each had no more than two employment sub-centers in addition to the CBD. And each experienced at least moderate positive population growth from 1970 to 2000, both for the entire metro as well as for the principle city portion of it. Doing so excludes metro areas whose housing stock and highways are especially likely to reflect historical rather than contemporary residence and employment patterns. Austin is also excluded from the set because its especially fast population growth from 1970 to 2000 suggests that its transportation infrastructure may not yet have caught up.

Table 2 gives some summary statistics of the highlighted metros that are used to calibrate and benchmark the quantitative model. Calibrating a monocentric city model requires recognizing that empirical metros, to the extent that they are circular, typically span considerably less than 360° (Rappaport, 2014b). I calculate an angle of occupancy, θ, of each of the seven metros that reconciles its land area and a proxy for its empirical radius, $\theta/360^\circ = \text{area}/\pi r^2$. The radius proxy is constructed as the 98th percentile distance commute of people who drive by car to work in the CBD plus an inferred radius of the CBD based on its share of metro land area. For Des Moines I use the the 97th percentile (10.3 miles) because of the especially large gap (5.3 miles) between

[1] Commuting flows and a number of related decennial census variables retabulated by place-of-work are included in the Census Transportation Planning Package 2000.

	Denver	Portland	Sacra-mento	Colum-bus	Indian-apolis	Omaha	Des Moines
population	1,970,000	1,610,000	1,560,000	1,260,000	1,150,000	610,000	340,000
land area	600 sqmi	540 sqmi	530 sqmi	560 sqmi	550 sqmi	230 sqmi	160 sqmi
CBD land area	16.3 sqmi	13.8 sqmi	10.0 sqmi	14.2 sqmi	5.2 sqmi	3.7 sqmi	3.6 sqmi
radius	18.1 mi	17.8 mi	25 mi	17.8 mi	19.9 mi	15.0 mi	13.0 mi
98th pctile commute	15.1 mi	15.0 mi	21.5 mi	15.0 mi	18.0 mi	13.1 mi	10.3 mi*
CBD radius	3.0 mi	2.8 mi	3.4 mi	2.8 mi	1.9 mi	1.9 mi	2.7 mi
span of occupancy	211°	195°	97°	204°	159°	117°	111°
180° population	1,670,000	1,480,000	2,890,000	1,110,000	1,310,000	930,000	560,000
quantitative equiv pop	1,580,000	1,410,000	2,660,000	1,060,000	1,370,000	1,000,000	530,000

Table 2: Benchmark monocentric metros (Values are for 2000). The CBD radius is inferred from its land area relative to that of the metro. The 180° population proportionally scales actual metro population to a semicircular span of occupancy. The quantitative equivalent additionally normalizes population to the assumed 2.4 mile CBD radius in the quantitative model. *Des Moines' population is normalized using the 97th percentile distance rather than the 98th because of the large discrete jump (5.3 miles) between the two.

it and the 98th percentile distance The implied angles vary considerably, only a small portion of which can accounted for by topological land constraints such as those identified by Saiz (2010). Understanding why this is so is left for future research.

For quantitative purposes, it is necessary to normalize metros' empirical population to a common span of occupancy. The monocentric model is typically implemented linearly, without any circumferential component such as arterial commutes, and so it cannot match empirical outcomes arising from differences in span. Table 2 includes the population level of each metro normalized to span a semicircle as well as further normalized to have a CBD radius of 2.4 miles. The latter, which is within the range of observed values of the seven metros, implies that population exactly equals 1 million for a quantitative "anchor" metro calibrated to match Omaha.

3 Model

The setup is static and so should be interpreted as a long-run steady state. A system of monocentric metros is composed of a "closed" anchor metro, $m{=}A$, with exogenous population and radius and an undetermined number of "open" metros, $m \in \{B, C, D, ...\}$, with endogenous population and radius. The anchor metro establishes a reservation utility that must be attained by residents in all other metros and a reservation value of land that must be at least matched at the perimeter of all other metros. It also serves as the main basis for calibrating the model. Remaining metros differ in their total factor productivity, both exogenously and due to agglomeration.[2]

Each metro consists of a central business district with fixed radius, $\widehat{d}_0$, and an endogenous number of concentric rings, indexed by $j \in \{1, 2, ..., J_m\}$, surrounding it.[3] Each ring except for the outermost one has predetermined width, $\widehat{\widetilde{d}}_j$. Workers drive to a place-of-work in the CBD, where they combine with capital and land inputs to produce a numeraire good. Capital combines with the land in each residential ring to produce housing services. In order to better match observed land use, metros may exogenously span less than a full circle, $\widehat{\theta}_m \leq 360°$. Figure 1 illustrates for a generic metro (with metro subscript suppressed).

3.1 Production

Numeraire production, which takes place exclusively in the CBD (ring 0), is Cobb Douglas in land, capital, and aggregate labor hours. Each factor is paid its marginal product,

$$X_m = A_{X,m} \, L_{m,0}^{\alpha_L} \, K_{m,0}^{\alpha_K} \, N_m^{1 - \alpha_L - \alpha_K} \tag{1}$$

$$r_{m,0}^L = \frac{\partial X_m}{\partial L_{m,0}} \qquad r_{m,0}^K = \frac{\partial X_m}{\partial K_{m,0}} \qquad w_m = \frac{\partial X_m}{\partial N_m}$$

Capital in the CBD is determined residually by achieving an exogenously-specified required rent, $r_{m,0}^K = \widehat{r}^K$. Aggregate labor hours are the sum of labor hours supplied by residents in each residential ring, j,

$$N_m = \sum_{j=1}^{J_m} POP_{m,j} \cdot n_{m,j} \tag{2}$$

Housing in each residential ring is produced with constant elasticity of substitution between land and capital, with each factor being paid its marginal revenue product

$$H_{m,j} = A_{H,m} \left(\eta_L \, L_{m,j}^{\frac{\sigma_L - 1}{\sigma_L}} + (1 - \eta_L) \, K_{m,j}^{\frac{\sigma_L - 1}{\sigma_L}} \right)^{\frac{\sigma_L}{\sigma_L - 1}} \tag{3}$$

$$r_{m,j}^L = p_{m,j} \cdot \frac{\partial H_{m,j}}{\partial L_{m,j}} \qquad r_{m,j}^K = p_{m,j} \cdot \frac{\partial H_{m,j}}{\partial K_{m,j}} \tag{4}$$

The capital input can be interpreted as structure. As in the CBD, the quantity of capital in each ring is residually determined such that $r_{m,j}^K = \widehat{r}^K$.

For both types of production, factor payments to land and capital are paid to absentee owners.

[2] This model setup is in the tradition of Henderson (1974) and adds internal metro structure to the quantitative system in Rappaport (2008a, 2008b). A earlier version of the present setup, Rappaport (2014a), additionally allows variations in consumption amenities to drive variations in metro size. Larson and Yezer (2015) present a similar quantitative system of monocentric metros, which they developed independently.

[3] Modeling urban land use as discrete is standard in rich quantitative specifications of the Alonso-Muth-Mills framework (e.g., Muth, 1975; Arnott and MacKinnon, 1977b; Sullivan, 1983, 1986).

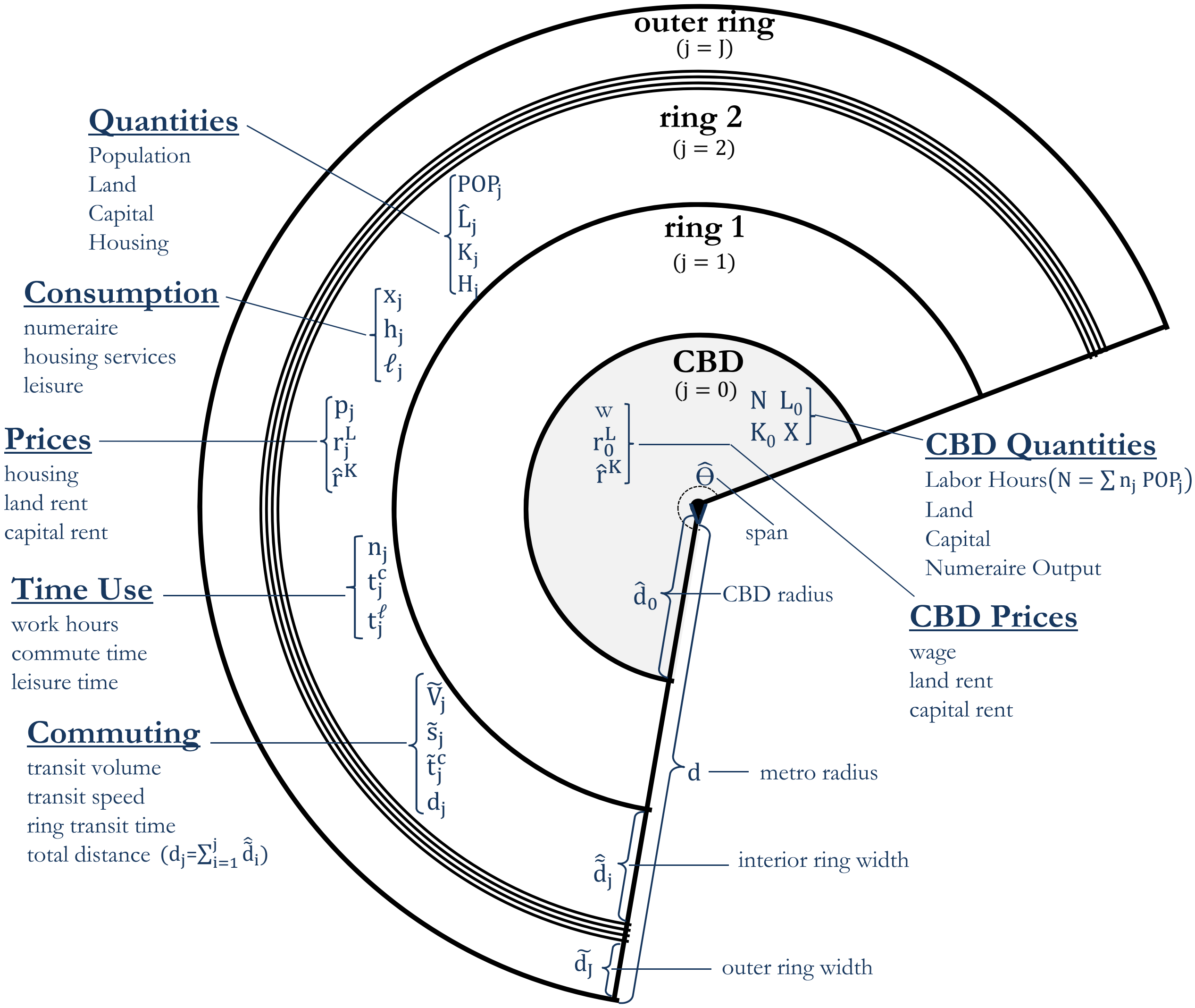

Figure 1: Internal Metro Structure. Residents of metro m live in rings $j \in \{1, 2, ..., J_m\}$ and commute to work radially from the outer border of their ring to the border of the CBD. Decorative hats denote an exogenous variable. Decorative tildes denote a variable that applies to commuters passing through a ring. The number of rings and the width of the outermost one are endogenously determined. The widths of interior rings are pre-determined.

3.2 Individuals

Individuals derive utility from housing, numeraire, and leisure with nested constant elasticity of substitution,

$$U^{hx}_{m,j} = \left(\eta_h \, (h_{m,j})^{\dfrac{\sigma_h - 1}{\sigma_h}} + (1-\eta_h) \, (x_{m,j})^{\dfrac{\sigma_h - 1}{\sigma_h}} \right)^{\dfrac{\sigma_h}{\sigma_h - 1}} \tag{5a}$$

$$U_{m,j} = \left(\eta_\ell \, (\ell_{m,j})^{\dfrac{\sigma_\ell - 1}{\sigma_\ell}} + (1-\eta_\ell) \, \left(U^{hx}_{m,j}\right)^{\dfrac{\sigma_\ell - 1}{\sigma_\ell}} \right)^{\dfrac{\sigma_\ell}{\sigma_\ell - 1}} \tag{5b}$$

This reduces to a standard non-nested form when the two elasticities of substitution, σ_h and σ_ℓ, equal each other. It further simplifies to Cobb Douglas when they both equal 1.

Including leisure in utility allows for the elastic supply of labor hours and micro-founds the negative effect of commute time on wellbeing. Most AMM models instead assume that labor is supplied inelastically and that commute time decreases disposable income at some fraction of the wage rate. The latter discount is motivated by surveys finding that workers' marginal willingness to pay (MWTP) to shorten their commute time is below their after-tax wage rate. A natural interpretation is that individuals derive some leisure content from commuting, for example listening to the radio or talking on their cell phone. I make this interpretation explicit by letting leisure sum together time explicitly devoted to it and leisure accumulated while commuting. An advantage of this approach is that MWTP can be modeled as increasing as commute congestion worsens: leisure content is surely lower, perhaps even negative, when stuck in traffic.[4]

$$\ell_{m,j} = t^{\ell}_{m,j} + \ell^{c}_{m,j} \tag{6}$$

Let disposable income, $y^d_{m,j}$, be total wage income less numeraire commute costs, let $d_{m,j}$ denote the distance of each one-way commute, and let δ denote the per mile numeraire cost of commuting. Then,

$$y^d_{m,j} \;=\; w_m \cdot n_{m,j} \;-\; \delta \cdot d_{m,j} \cdot \text{trips} \tag{7}$$

Individuals face the numeraire budget constraint that their consumption expenditure not exceed their disposable income. Similarly, they face the time constraint that the sum of their weekly work hours, commute hours, and leisure-time hours not exceed total weekly hours less some minimum time for necessities such as sleeping and eating.The excluded minimum time, $\widehat{t^z}$, can be interpreted as a Stone-Geary minimum level of leisure.[5]

$$x_{m,j} + p_{m,j} \cdot h_{m,j} \;\leq\; y^d_{m,j} \tag{8}$$

[4]The only AMM models of which I am aware that explicitly include leisure in utility are Arnott and MacKinnon (1977b), Fujita (1989), and Duranton and Puga (2015). Modeling leisure as entering utility in a nested CES specification follows Aguiar and Hurst (2007). In a macro context, McGrattan, Rogerson, Wright (1997) combine a consumption hybrid and leisure in the outer nesting of a CES utility function. Their innermost nesting, market consumption and home production, seems especially relevant to an AMM setup that models the utility of households rather than individuals. More typically, macro models assume a reduced-form specification in which utility includes a separable component that decreases with hours worked.

[5]A caveat is that the leisure component of commuting probably ought not "count" towards $\widehat{t^z}$.

$$n_{m,j} \; + \; t^{c}_{m,j} \cdot \text{trips} \; + \; t^{\ell}_{m,j} \; \leq \; 24 \cdot 7 \; - \; \widehat{t^{z}} \tag{9}$$

Individuals choose the consumption bundle, $\{x^{*}_{m,j},\, h^{*}_{m,j},\, \ell^{*}_{m,j}\}$, that equates the marginal utility relative to price for each of numeraire, housing, and leisure consumption,

$$\partial U_{m,j} / \partial x_{m,j} \; = \; \frac{\Big(\partial U_{m,j} / \partial h_{m,j}\Big)}{p_{m,j}} \; = \; \frac{\Big(\partial U_{m,j} / \partial \ell_{m,j}\Big)}{w_m} \tag{10}$$

3.3 Commuting

Individuals drive directly from the outer perimeter of their residential ring to the outer perimeter of the CBD. Commute distance is simply the sum of the ring widths through which a commuter must pass, $d_{m,j} = \sum_{i=1}^{j} \widetilde{d}_{m,i}$.

Traffic slows drive speed. Let $\widetilde{V}^{K}_{m,j}$ denote highway capacity through a residential ring and $\widetilde{V}_{m,j}$ denote the volume of commuters driving through the ring,

$$\widetilde{V}_{m,j} \; = \; \sum_{i=j}^{J_m} POP_{m,i} \tag{11}$$

Feasible speed decreases from a "free-flow" upper-bound, $\widehat{s}^{f}$, as volume increases relative to capacity according to a standard formula (Small and Verhoef, 2007),

$$\frac{1}{\widetilde{\widetilde{s}}_{m,j}} \; = \; \frac{1}{\widehat{s}^{f}} \cdot \left(1 + a \cdot \left(\frac{\widetilde{V}_{m,j}}{\widetilde{V}^{K}_{m,j}} \right)^{b} \right) \qquad a, b \; > \; 0 \tag{12a}$$

Commuters additionally obey a speed limit, s^{max}. I also impose a lower-bound speed, s^{min}. The latter might be interpreted as capturing unmodeled alternative modes of transport likely to be available in the large metros where the minimum binds. Realized speed is given by,

$$\widetilde{s}_{m,j} \; = \; \max\Big(\min\Big(\widetilde{\widetilde{s}}_{m,j} \,,\, s^{max} \Big) \,,\, s^{min} \Big) \tag{12b}$$

Highway capacity is assumed to depend on commute volume according to,

$$\widetilde{V}^{K}_{m,j} \; = \; \widehat{V} \cdot \left(\frac{\widetilde{V}_{m,j}}{\widehat{V}} \right)^{\sigma_V} \qquad 0 \; \leq \sigma_V \; \leq 1 \tag{13}$$

The term $\widehat{V}$ is an exogenously-specified value at which road capacity equals commute volume. Higher values of $\widehat{V}$ imply a larger volume of commuters can be accommodated before congestion sets in. The term σ_V is the elasticity of highway capacity with respect to volume. Parameterizing σ_V to equal 1 implies that speed is constant. Parameterizing it to equal 0 implies that highway capacity is constant. Speed falls off more rapidly with metro population as σ_V decreases.

The time to commute through a ring, $\widetilde{t}^{c}_{m,j}$, is just the width of the ring divided by the speed through it. Total commute time sums a fixed time component with the cumulative time to pass through each required residential ring.

$$t^{c}_{m,j} \;=\; \widehat{t}^{c} \,+\, \sum_{i=1}^{j} \widetilde{t}^{c}_{m,i} \tag{14}$$

Anecdotes suggest that people dislike traffic congestion. To capture this, I allow the leisure content of commuting to increase with speed. Total leisure from commuting sums together the leisure derived while passing through each ring.

$$\ell^{c}_{m,j} \;=\; \sum_{i=1}^{j} \lambda\left(\widetilde{s}_{m,i}\right) \cdot \widetilde{t}^{c}_{m,i} \qquad\qquad \lambda'(s) \geq 0 \tag{15}$$

3.4 Model Closure

The model is first solved for the anchor metro, A, which has exogenous radius and total population. The exogenous radius implies that the number of interior rings, which have pre-determined width, and the width of the outermost ring are exogenous as well. The exogenous population implies an adding-up condition over the population in each ring,

$$\sum_{j=1}^{\widehat{J}_A} POP_{A,j} \;=\; \widehat{POP}_A \tag{16}$$

Equilibrium in the anchor metro requires that utility must be equal across rings. This can be written as requiring utility in the second through outermost ring of the anchor metro to equal utility in its innermost ring.

$$U_{A,j} \;=\; U_{A,1} \qquad\quad \forall\{j\} \in \{2, 3, ..., J_A\} \tag{17a}$$

In addition, the land and housing markets in each ring must clear. Land market clearing, in the sense of matching demand to its fixed supply in each ring, follows from the constant-returns-to-scale production of housing, (3), together with paying land its marginal revenue product, (4). For housing services, clearing requires that,

$$H_{m,j} = POP_{m,j} \cdot h_{m,j} \tag{18}$$

If all structural parameters were known, the anchor-metro equilibrium could be solved as an exactly-identified system of $4 \cdot J_A$ equations and unknowns. Optimal housing consumption and leisure values, $\{h^{*}_{A,j}\}$ and $\{\ell^{*}_{A,j}\}$, correspond to (10) and account for $2 \cdot J_A$ equations. The price of housing, $\{p_{A,j}\}$, that equates supply and demand in each ring corresponds to (18) and accounts for J_A equations. The population in each ring, $\{POP_{A,j}\}$, that satisfies utility equalization corresponds to (17a) and accounts for $J_A - 1$ equations. Lastly, population adding up, (16), determines the the ordinal value at which utility is equalized (1 equation). Optimal numeraire consumption, $\{x^*_{A,j}\}$, is then implied residually. In practice, I solve the anchor system together with additional equations to calibrate the weighting parameters, $\{\eta_L, \eta_h, \eta_\ell\}$ and the per mile numeraire cost of commuting, δ.

The solution to the system of equations for the anchor metro gives the ordinal level of utility there, U_A, and the price of land in its outermost ring, r^L_{A,J_A}. These must be matched in each open metro. The sequential nature of the solution lets the anchor values be interpreted as pre-determined.

$$U_{m,j} = \widehat{U} = U_A \qquad \forall\{m\} \in \{B, C, D, ...\} \tag{17b}$$

$$r^L_{m,J_m} = \widehat{r}^L_J = r^L_{A,J_A} \qquad \forall\{m\} \in \{B, C, D, ...\} \tag{19}$$

The system of equations for each open metro encompasses $4 \cdot J_m + 1$ equations and unknowns. Compared to the anchor-metro system, open-metro utility equalization swaps in (17b) for (17a). Doing so accounts for J_m equations rather than $J_A - 1$ equations. The population adding up constraint is dropped (0 rather than 1 equation). The width of the outermost residential ring, $\widetilde{d}_{m,J_M}$, is pinned down by the required land price equalization, (19) (1 additional equation). The determination of optimal housing and leisure values remain unchanged ($2 \cdot J_m + 1$ equations).

The number of rings of each open metro, J_m, is determined iteratively. I solve for an open metro with candidate K residential rings, all of which have a default width including the outermost one. To do so, I use the open system of equations excluding the land-price matching one. If the price of land in the outermost ring exceeds the price of land in the outermost ring of the anchor metro, $r^L_{m,K} > r^L_{A,J_A}$, I solve for a candidate metro with $K+1$ residential rings. If $r^L_{m,K} < r^L_{A,J_A}$, I set $J_m = K$ and re-solve, allowing the width of the outermost ring to adjust to achieve perimeter land-price matching.

4 Parameterization

The model requires setting values for a large number of structural parameters. The population and radius of the anchor metro are set to match normalized equivalents for Omaha. Several key parameters are set to estimates from existing literature. Others are calibrated by requiring a moment of the anchor metro to exactly match a moment in aggregate U.S. data. Lastly, the parameters governing highway provision are jointly calibrated to imply correspondences between commute time and commute distance that collectively approximate those in Omaha, Des Moines, Portland, and Denver. The sensitivity of outcomes to the parameterization, discussed in Section 6, gives insight into the key forces mediating the correspondence between TFP and metro size.

As will be emphasized below, calibrated parameter values closely depend on the model's exact specification including arbitrary assumptions such as whether individuals receive capital income and the weekly number of hours required for biological necessities.

4.1 Population and Geography

Baseline parameter values other than those for commuting are shown in Table 3. Calibrated values of the housing production and utility weighting parameters (η_L and η_h and η_ℓ) lack inherent interpretation and so are not reported.

The anchor metro is arbitrarily assumed to span 180°, which is within the range of the seven metros that partly conform with the monocentric stylization (Table 2). Its outer commute is set to 13.1 miles, the 98th percentile commute distance of Omaha residents who drive to a place-of-work in Omaha's CBD. The anchor metro's CBD radius is set to 2.4 miles, which together with the assumed semicircular span implies a population of exactly 1 million to match the normalized population of Omaha. Quantitative results are nearly identical with a fixed CBD radius of 1 mile.

The width of the innermost ring is set to 0.1 miles. The short distance implies a similar commute time regardless of congestion, which proves helpful for calibrating the utility parameters. The widths of the eighth and higher interior rings are set to 2 miles. The width of the outermost ring, whatever its number, is endogenously determined so that perimeter land price matching holds. The solution method, described in the previous section, implies that the outermost ring's width will be less than 2 miles. Results are fairly insensitive to alternative assumed interior widths.

4.2 Production

Cobb Douglas production of numeraire requires parameterizing the factor income shares accruing to land, capital, and labor, $\{\alpha_L, \alpha_K, 1-\alpha_L-\alpha_K\}$. The land share is set to 1.6 percent, corresponding to a weighted average of intermediate-input shares across a large number of industries (Jorgenson, Ho, and Stiroh, 2005).[6] Ciccone (2002) suggests using a nearly identical value to approximate the land share of manufacturing. One third of remaining factor income is assumed to accrue to capital; two thirds is assumed to accrue to labor (Gollin, 2002).

Production of housing services requires calibrating the elasticity of substitution between land and structure, σ_L, and the relative weight on land, η_L. The former is set to 0.90, consistent with a number of estimates that it lies between 0.5 and 1 (Jackson, Johnson, and Kaserman, 1984; Thorsnes, 1997). Recent research suggests that σ_L lies at the upper end of this range (Ahlfeldt and McMillen, 2014; Combes, Gobillion, and Duranton, 2016). An important caveat is that the existing estimates are based on prices and attributes of *single-family* units and lots. Construction pricing guides suggest that producing multifamily housing services allows for much higher substitutability (**RH Means 2007**). The weight on land is calibrated such that the population-weighted mean share of housing factor income accruing to land, $\overline{\mu}_A^L$, equals 0.35, consistent with Davis and Heathcote (2007).[7] As described in the sensitivity analysis, increasing the production elasticity and decreasing

[6]The industry-specific intermediate input estimates, which are not included in the publication, were kindly provided by the authors.

[7]Davis and Heathcote find that between 1975 and 2004, land accounted for an average of 47 percent of the sales value of the aggregate U.S. housing stock. Adjusting for the fact that structures depreciate but land does not brings

Description	Notation	Value/Target	Rationale
Population & Geography			
population (anchor metro)	POP_A	1 million	Omaha normalized to 180° and 2.4 mi CBD radius
outermost commute (anchor metro)	$d_{A,J}$	13.1 mi	Omaha 98th pctile drive to CBD
CBD radius	d_0	2.4 mi	very small loss of generality
span of settlement	θ	180°	normalization
rings (anchor metro)	J_A	10	very small loss of generality
ring widths except outermost	$\{\tilde{d}_1, ..., \tilde{d}_4\}$ $\{\tilde{d}_5, ...\}$	$\{0.1 \text{ mi}, 0.4, 0.7, 1.1\}$ $\{1.6, 1.6, 1.6, 2, 2, 2, ...\}$	very small loss of generality
Numeraire Production			
land factor share	α_L	0.016	Jorgenson et al. (2005)
capital factor share	α_K	0.328	Jorgenson et al. (2005)
required capital rent	$\widehat{r}^K$	0.05	no loss of generality
Housing Production			
CES, L and K	σ_L	0.90	Thorsnes (1997), Ahlfeldt and McMillen (2014); (observations are single-family houses)
weight on land	η_L	–	calibrated s.t. mean land factor share in anchor metro is 0.35 (Davis and Heathcote, 2007)
Utility			
CES, h and x	σ_h	0.67	Albuoy, Ehrlich, and Liu (2014)
weight on housing	η_h	–	calibrated s.t. mean house expend share in anchor metro is 0.17 (housing expend share of market PCE, avg 1990-2000, U.S. NIPA)
CES, h-x and ℓ	σ_ℓ	0.34	calibrated s.t. Frisch elasticity in anchor metro inner ring is 0.20 (Reichling and Whalen, 2012); *depends on* $\widehat{t}^z$
weight on leisure	η_ℓ	–	calibrated s.t. residents in inner ring of anchor metro choose to work 40 hours per week
weekly time for necessities	$\widehat{t}^z$	70 hrs	very small loss of generality with contingent calibration of σ_ℓ and baseline assumption that individuals freely choose their work hours

Table 3: Non-Commuting Parameterization. Calibrated values of weighting parameters depend closely on model-specific assumptions and lack inherent interpretation. For this reason, they are not reported.

the land factor share each significantly boost the elasticity of metro size with respect to TFP.

4.3 Utility

The utility specification, (5a) and (5b), requires setting values for four key parameters: two elasticities of substitution—which together describe the curvature of the tradeoffs among numeraire, housing, and leisure—and two weights, which pin down the housing expenditure share and leisure time in the anchor metro. The calibrated values for the leisure elasticity and weight depend on the number of hours reserved for necessities.

The elasticity of substitution between housing and the numeraire good, σ_h, is set to 0.67. This is the preferred value of Albuoy, Ehrlich, and Liu (2014), who report estimates that range from 0.42 to 0.76. Estimates using microdata are typically lower. For example, Li et al. (2015), using simulated method of moments applied to a structural model of life-cycle housing consumption, estimate σ_h to be 0.32. The weight on housing, η_h, is calibrated such that the population-weighted mean consumption expenditure share on housing in the anchor metro, $\overline{\mu}^h_A$, equals 0.17.[8] This matches the U.S. aggregate ratio during the 1990s and early 2000s of the sum of nominal rent and owners' equivalent rent relative to nominal market personal consumption expenditures. For comparison, Davis and Ortalo-Magné (2011) report a somewhat higher average housing expenditure share for renter households, 0.24, across 50 large U.S. metros in 1980, 1990, and 2000.[9] As is intuitive, increasing housing's expenditure share and decreasing its substitutability with numeraire each dampen the elasticity of metro population with respect to TFP.

The calibration of leisure in utility depends closely on the assumed number of weekly hours required for sleep and other necessities, $\widehat{t^z}$. This makes sense as $\widehat{t^z}$ can be interpreted as a required minimum level of leisure and so affects curvature. I arbitrarily set it to 70 hours, leaving 98 hours to be split among work time, commute time, and leisure time. The elasticity of substitution between leisure and the numeraire-housing hybrid, σ_ℓ, is calibrated such that the compensated elasticity of work hours with respect to wages (the "Frisch elasticity") in the innermost ring of the anchor metro equals 0.20, the central value from a comprehensive survey of estimates by Reichling and Whalen (2012).[10] With $\widehat{t^z}$ set to 70, doing so implies a value of 0.34 for σ_ℓ. The weight on leisure,

the land share down to approximately 35 percent.

[8] I exclude commuting expenses from the calculation of the housing expenditure share, $\mu_{m,j} \equiv (p_{m,j} \cdot h_{m,j})/(x_{m,j} + p_{m,j} \cdot h_{m,j})$.

[9] Several factors may account for the higher estimate of the housing expenditure share in Davis and Ortalo-Magné. First, they include spending on utilities in housing expenditure, which is necessary given the underlying data. Second, their estimate is based only on renter households. If the income elasticity for housing is less than one as estimated by Albuoy, Ehrlich, and Liu (2014), renter housing expenditure shares will be above average. Third, the 50 metros used by Davis and Ortalo-Magné are relatively large and so are likely to have above-average housing prices. If the elasticity of substitution is indeed below one as calibrated, expenditure shares in these metros will be above average as well.

[10] The Frisch elasticity used here describes the intensive margin of work hours supplied contingent on supplying positive hours. Macro models are more typically calibrated to a reduced-form Frisch elasticity that describes aggregate hours supplied and so includes the extensive margin of participation. The latter, extensive elasticity is typically estimated to be about 2.

η_ℓ, is calibrated such that individuals in the innermost ring of the anchor metro choose to work 40 hours per week ($n_{A,1} = 40$), which is consistent with average market work hours for employed adult males in 1985 and 2003 (Robinson and Godbey, 1999; Aguiar and Hurst, 2007).

Under the baseline assumption that individuals can freely choose the number of hours to work, quantitative results are close to identical across a wide range of assumed values of $\widehat{t^z}$. The reason is that the unchanged targets for the Frisch elasticity and weekly work hours require the calibrated values of σ_ℓ and η_ℓ to "adjust" to keep the curvature of utility with respect to leisure exactly unchanged at an unchanged consumption bundle, $\{x^*_{A,1}\,,\, h^*_{A,1}\,,\, \ell^*_{A,1}\}$. For example, as $\widehat{t^z}$ is set to values from 0 to 84, the calibrated value of σ_ℓ increases from 0.26 to 0.39. So long as individuals can adjust their work hours, the curvature of utility with respect to leisure remains approximately unchanged at chosen bundles, $\{x^*_{m,j}\,,\, h^*_{m,j}\,,\, \ell^*_{m,j}\}$. The dependence of σ_L on an arbitrary assumption illustrates the caution against interpreting calibrated values as structural estimates. Quantitative results also prove relatively insensitive to the targeted Frisch elasticity if individuals can choose the number of hours they work.

4.4 Commuting

Baseline values of commuting parameters are reported in Table 4. Individuals make ten weekly one-way commutes. The numeraire cost per mile, δ, is set such that the population-weighted mean ratio of commute costs to wage income equals 0.05 (Albouy and Lue, 2014). An alternative scenario describes outcomes when workers in some metros instead make only eight.

I set the leisure content of commute time to decline linearly from 0.5 at the calibrated 50 mph speed limit to 0 at an assumed minimum speed of 10 mph. A leisure content of 0.5 conforms with numerous estimates based on stated preferences of commuters MWTP to shorten their commute time (Small and Verhoef, 2007). Zero leisure content is consistent with estimates based on revealed preference (Small, Winston, and Yang, 2005) along with studies of subjective well being (Krueger et al., 2009).

I set the parameters governing commute speed to approximately match fitted kernels of mean commute time on straight-line distance of workers who drive during the morning commute to the CBDs of Omaha, Des Moines, Portland, and Denver (Figure 2, left panel).The kernel estimates (dashed lines) are weighted by tract-to-tract flows and so implicitly account for the co-location of settlement and highways. As is intuitive, the relationship is concave reflecting faster average drive speed as distance from the CBD increases. The speeds implied by the fitted kernel are shown in the right panel. The calibrated upper-bound speed limit of 50 mph is slow relative to kernel estimate of the speed through the outer suburbs of Des Moines (66 mph) and may also be slow relative to the *highway* speed through the outer suburbs of the other three metros. Longer arterial commutes at further distances may account for the difference. The assumed 10 mph lower bound on speed is arbitrary as the estimated kernels imply speeds near the CBD of at least 20 mph. But for metros

Description	Notation	Value/Target	Rationale
Commuting General			
weekly 1-way commutes	$trips$	10	
per mile cost	δ	–	calibrated s.t. mean cost to income in anchor metro is 0.05 (Albouy and Lue, 2014)
leisure content	$\lambda(s)$	0.50@$\geq$50mph declines linearly to 0@$\leq$10mph	Small, Winston, and Yan (2005)
Speed			
fixed time	$\widehat{t}^c$	8 min	calibrated
free-flow speed	$\widehat{s}^f$	70 mph	calibrated
maximum speed	$\widehat{s}^{max}$	50 mph	calibrated
minimum speed	$\widehat{s}^{min}$	10 mph	arbitrary
elasticity, highway capacity to volume	σ_V	0.92	calibrated
benchmark highway capacity	$\widehat{V}$	77 ths	calibrated
speed vs volume technical parameters	a, b	0.2, 10	Small and Verhoef (2007)

Table 4: Commuting Calibration. Speed parameters are jointly calibrated to fit estimated kernels of time versus distance for workers who drive to a place-of-work in the CBDs of Omaha, Des Moines, Portland, and Denver. The calibrated per mile driving cost has no inherent interpretation and so is not reported.

larger than those used for the calibration, speed near the CBD is likely to be slower.

The quantitative correspondences of commute time and distance (left panel, solid lines) characterize metros with normalized TFP that corresponds to the normalized, quantitative equivalent populations of Des Moines, Omaha, Portland, and Denver. The anchor metro, which is calibrated to Omaha, has normalized TFP in the production of numeraire and housing services, $A_{X,m}$ and $A_{H,m}$, equal to 1. Under the baseline calibration and letting housing TFP be the same as in the anchor, a metro with population equal to the normalized equivalent of Des Moines (530 thousand) requires numeraire TFP equal to 0.960. In other words, a metro with numeraire 4 percent below that of the anchor metro will have a population of 530 thousand. Metros with population equal to the normalized values of Portland and Denver require respective numeraire TFP of 1.025 and 1.037.

The quantitative commute times tightly match their respective empirical kernels. This is especially true for Des Moines and Portland, with quantitative commute times that run no more than a minute faster at every distance. The Omaha quantitative commute eventually exceeds its empirical kernel by slightly less than 2 minutes. The Denver quantitative commute eventually runs slightly less than 3 minutes faster than its empirical kernel. These tight fits were achieved, by trial and error, with an elasticity of highway capacity with respect to volume, σ_V, equal to 0.92 and a benchmark capacity of 77 thousand. Lowering the elasticity increases the curvature of commute

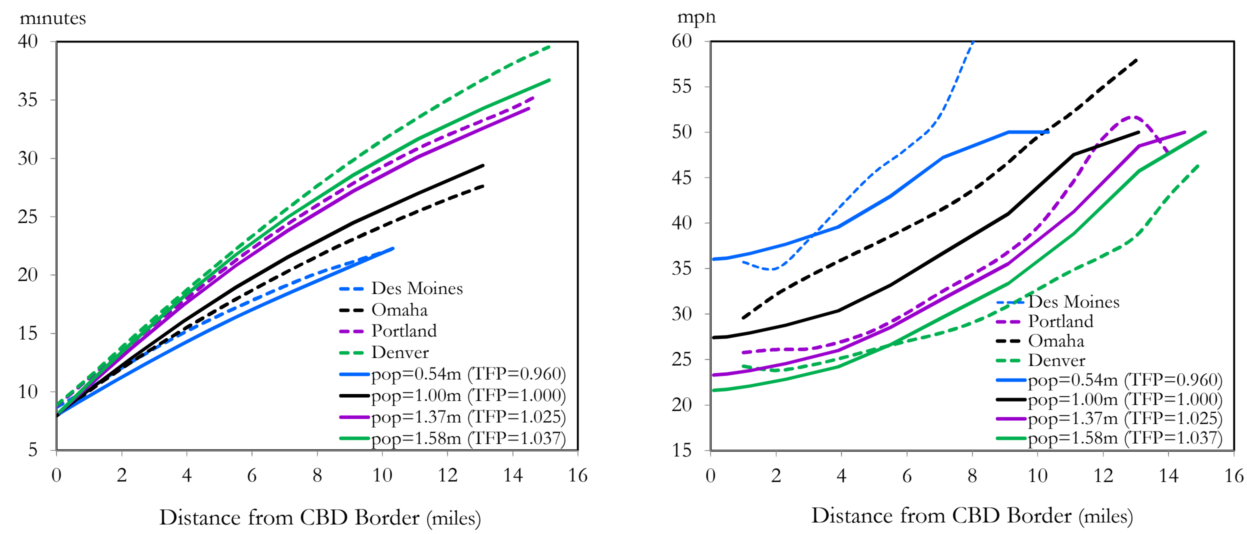

Figure 2: Commute Time and Speed Left panel shows commute time against commute distance from the CBD boundary. TFP for the numerical large and small metros is chosen such that their population respectively equals 1.5 million and 300 thousand. Dashed lines show fitted empirical splines constructed as a worker-weighted regression of drive time on distance from place of residence to their place of work. Right panel shows the implied driving speed.

times. Increasing the benchmark capacity rotates the commute time locus clockwise.

Quantitative outermost commute distances also tightly match their empirical counterparts. By construction the anchor metro has a 13.1 mile outermost commute, the same as the 98th percentile distance of commuters who drive to the CBD of Omaha. The quantitative outermost commutes for the three remaining metros are determined by perimeter land-price equalization. The match is within a tenth of a mile of the 98th percentile commute of Denver and the 97th commute of Des Moines.[11] It falls short of the 98th percentile commute of Portland by a half a mile, notwithstanding Portland's urban growth boundary.

5 Baseline Quantitative Results

The quantitative model approximately matches land use—population density gradients and the distance distribution of CBD commuters—of the four metros to which its commute speed is calibrated. It also approximately matches the correspondences among population, density, commute times, and commute distances across small and medium metros. Given the model's many first-order abstractions—including no decentralized employment, no land use regulations, no heterogeneity, and a single mode of transport—this ability to approximate observed outcomes is surprising. More importantly, the ability approximate observed outcomes helps validate the model's empirical relevance, suggesting that it can give insight into various factors determining metro size.

[11] As described in Section 2, I use the 97th percentile commute distance for Des Moines because of the especially large gap between it and the 98th percentile distance.

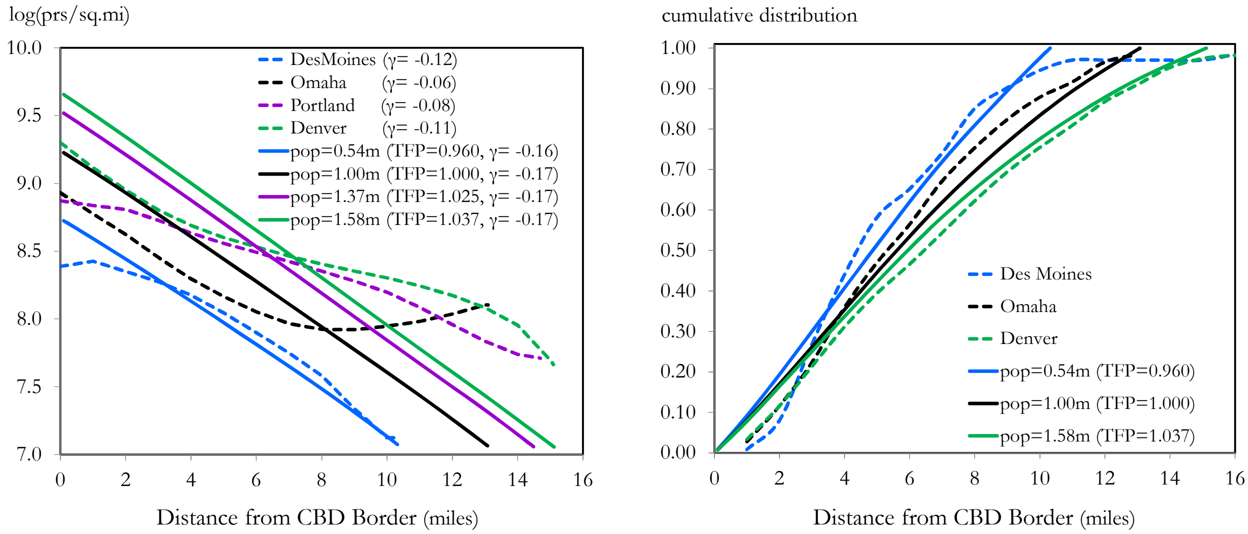

Figure 3: Population Density Gradient and Cumulative Population Distribution. Left panel: Solid lines show population density against commute distance for the anchor metro and metros with relative TFP that endogenously generates normalized population levels equal to those of Des Moines, Portland, and Denver. Dashed lines show empirical density gradients with distance measured as a straight line from the CBD centroid to the centroid of the census tract of residence. Summary gradients, γ, denote the slope coefficient from a population-weighted regression of log density on distance and a constant. **Right panel**: solid lines show the cumulative distribution of population. Dashed lines show the empirical cumulative distribution individuals who drive to work in the CBD against the distance of their residential tract from their place-of-work tract. Portland is excluded for legibility.

In contrast, the model does a less good job approximating outcomes of large metros, all of which are polycentric. But this limitation also serves as validation. The quantitative results robustly show that attaining a population above about five million while remaining monocentric requires relative levels of TFP above most upper-bound estimates or implausibly little traffic congestion or both. Quantitative results that suggested otherwise—that a plausibly high TFP could suffice to motivate several million workers to endure long, hyper-congested commutes to a single central business district rather than take otherwise identical jobs in less crowded metros—would be worrisome.

5.1 Metro Land Use

Density gradients for metros with population corresponding to Des Moines, Omaha, Portland, Denver are shown in Figure 3 (left panel, solid lines). These are the "same" metros used to calibrate commute speed in the sense that they are generated by the same relative TFP for producing numeriare. As is intuitive, the density gradients shift upward with metro population. Consistent with empirical estimates, they decline at an almost perfectly exponential rate (Anas, Arnott, and Small, 1998; Glaeser and Kahn, 2001). Under the baseline parameterization they have nearly identical slope, listed in parentheses. But under plausible alternative parameterizations, slopes meaningfully steepen with metro population.

Dashed lines show corresponding empirical gradients, based on population-weighted kernel regressions of log tract population density on distance to the Google centroid. Quantitative population adjacent to the CBD falls about half a log point short of actual density for each of the metros. The Des Moines quantitative gradient closely matches the empirical one beginning about 2 miles away from the CBD. The quantitative gradients for Omaha and Denver match the slope of their empirical counterpart at shorter distances but then turn flatter. The quantitative gradient for Portland is everywhere steeper than its empirical counterpart. The greater steepness of the quantitative gradients is unsurprising given the abstractions from land use regulation and decentralized employment.

The right panel of Figure 3 shows the quantitative cumulative distribution of population moving away the CBD (solid lines) and the empirical cumulative distribution of workers who commute by car to a CBD tract by the distance between their residence and workplace (dashed lines). The key difference from the density gradients is that the empirical distribution here describes only people who work in the CBD.

The quantitative cumulative distributions match the empirical ones relatively tightly. To be sure, at near distances the quantitative ones rise significantly more steeply. But beginning about 3 miles from the CBD, the empirical distributions catch up and thereafter the corresponding distributions remain quite close. The same holds for Portland, which is excluded from the figure to improve legibility. For Denver, which has the tightest match, the quantitative CDF remains within 4 percentage points of the empirical one from mile 3 through the quantitative perimeter.

Rappaport (2014) includes an extensive description of land use, commuting, house and land prices, and other outcomes within the anchor metro.

5.2 Productivity and Metro Size

The remainder of this section describes the cross-sectional correspondences among TFP, population, population density, and a number of other metro outcomes that arise as TFP for producing numeraire varies from moderately below its anchor level to moderately above it. The correspondences prove mostly intuitive and hold regardless of whether the source of the variation is exogenous or arises from the endogenous effect of size on productivity.

Metro population increases concavely with increases in metro TFP (Figure 4, left panel). The concavity arises from curvature in utility and production together with a sufficiently inelastic supply of land, which holds so long as commuting is subject to congestion. The anchor metro, with normalized unitary TFP and population 1 million, is shown by the black dot. As TFP increases to 1.05 and then further to 1.10, population increases to 1.8 million and then to 2.8 million. Denver, which has normalized population of 1.6 million, is arguably the largest U.S. metro for which the monocentric stylization applies. So as relative TFP relative increases above 1.05, the present model is likely to increasingly deviate from the empirical data generating process. This reinforces the required caution in interpreting exact quantities.

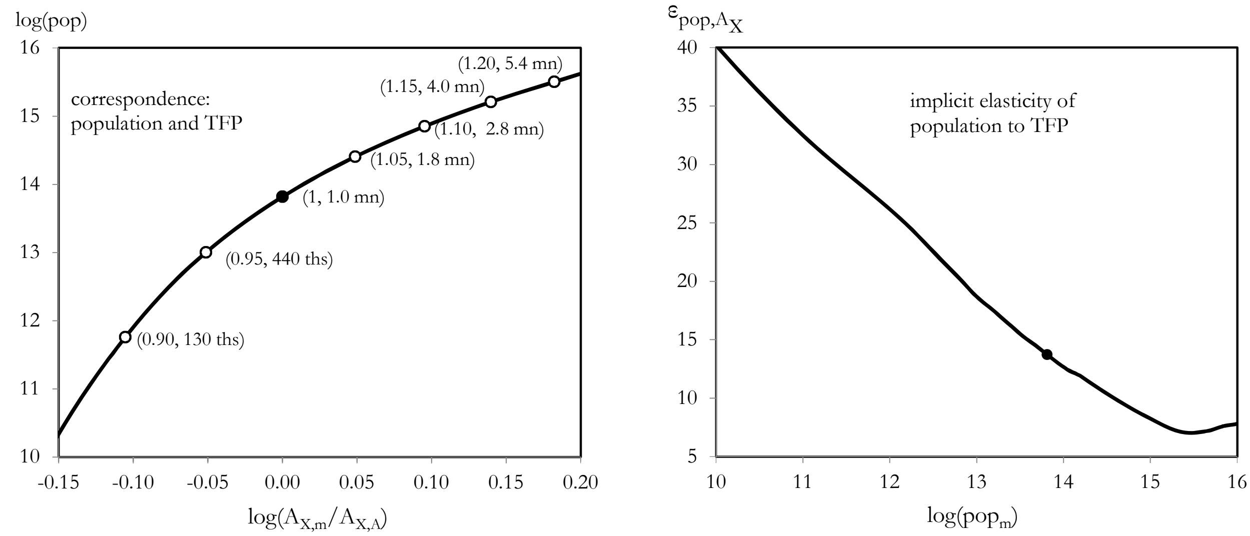

Figure 4: Total Factor Productivity and Population Left panel shows the correspondence between population and TFP relative to that in the anchor metro. Right panel shows the implied non-causal elasticity of population with respect to numeraire TFP. Solid markers indicate outcomes in the anchor metro.

The concavity of population with respect to TFP implies that the non-causal elasticity of population with respect to TFP, $\epsilon_{\text{pop},A_X}$, decreases with population (right panel). As metros become larger, population becomes less responsive to proportional increases in productivity. Under the baseline calibration, $\epsilon_{\text{pop},A_X}$ decreases from above 25 when log population is below 12 (population below 160 thousand) to less than 10 when log population is above 15 (population above 3.3 million)

Increases in population are partly accommodated by concave increases in metro land area (Figure 5, left panel, black line). Land area increase almost one-to-one with increases in population from low levels. But from high population levels, land area increases considerably less than proportionally. Instead, worsening traffic congestion channels population to increase via infill. Reflecting infill, mean commute distance remains approximately flat as population increases above its anchor level (right panel, black line). This flatness also characterizes the mean empirical distance of driving commutes to the CBDs of the medium and large metros reported in Table 1. Corresponding to the concave response of land area, weighted population density remains relatively unchanged as population increases from low levels but then increases proportionately with population from intermediate and high levels (left panel, green line).

The worsening congestion is illustrated in Figure 6. Highway provision suffices to keep outermost commute speed equal to its assumed maximum, 50 mph, regardless of metro size (left panel, blue line). Commute speed through the innermost residential ring falls increasingly below 50 mph as log population increasingly exceeds 12 (population 160 thousand), hitting 27 mph at the anchor metro population and 14 mph at log population 15 (population 3.3 million)(green line). Mean speed, calculated as aggregate miles driven by aggregate driving time, falls from 50 mph to 33 mph to 14 mph over this population range (black line).

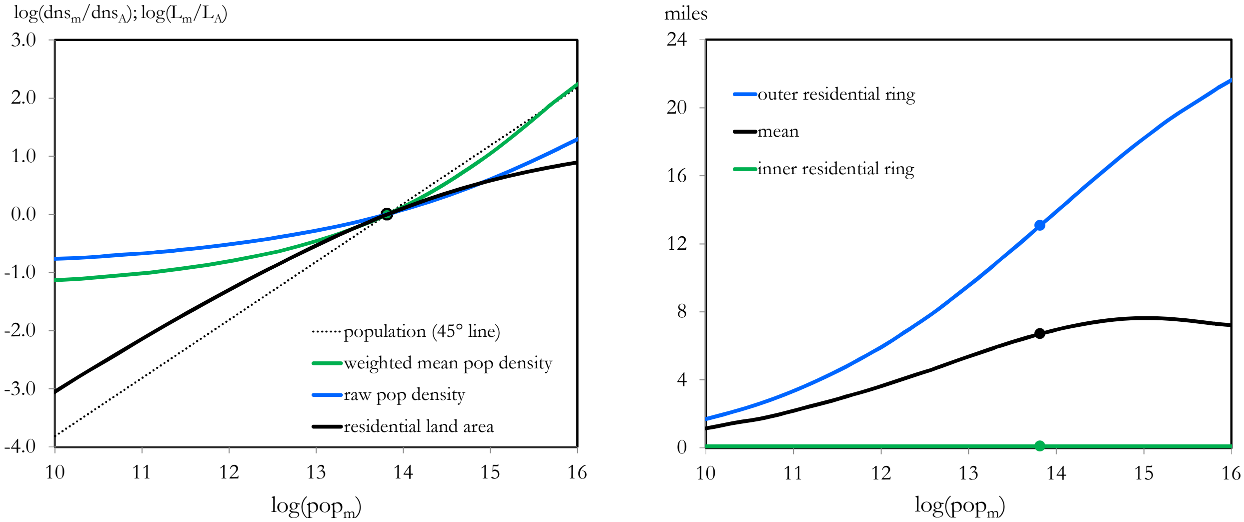

Figure 5: Distance, Density, and Land Area Left panel shows metro population correspondences with land area, raw population density, and mean population density. Right panel shows metro population correspondences with inner, mean, and outermost commute distance. Metro radiuses equal the outermost distance plus 2.4 miles.

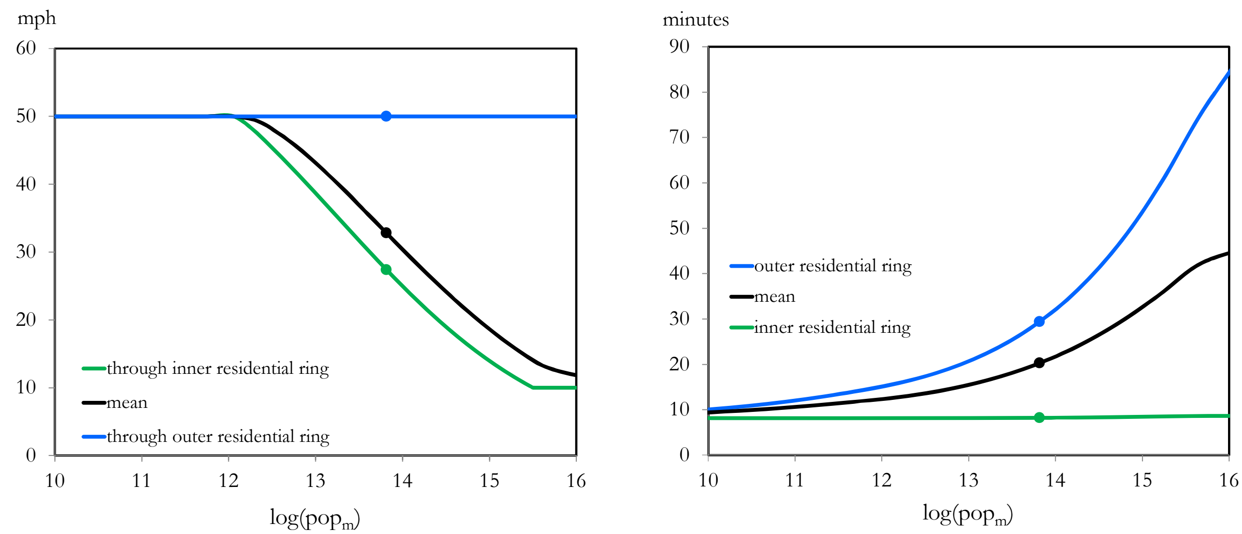

Figure 6: Commute Time and Speed Left panel shows the commute speed through the innermost and outermost residential rings as well as mean commute speed. The latter is constructed as aggregate commute distance divided by aggregate commute time. Right panel shows the correspondence of one-way commute times with metro population. Markers indicate outcomes in the anchor metro.

The pattern of congestion together with the changing distance of commutes cause mean commute time to increases from 10 minutes to 20 minutes to 33 minutes as log population increases from 12 to its anchor level to 15 (left panel, black line). Outermost commute time increases from 10 minutes to 30 minutes to 54 minutes over the same population range (blue line). These times match up nicely with the range of times reported across the small, medium, and large metros in

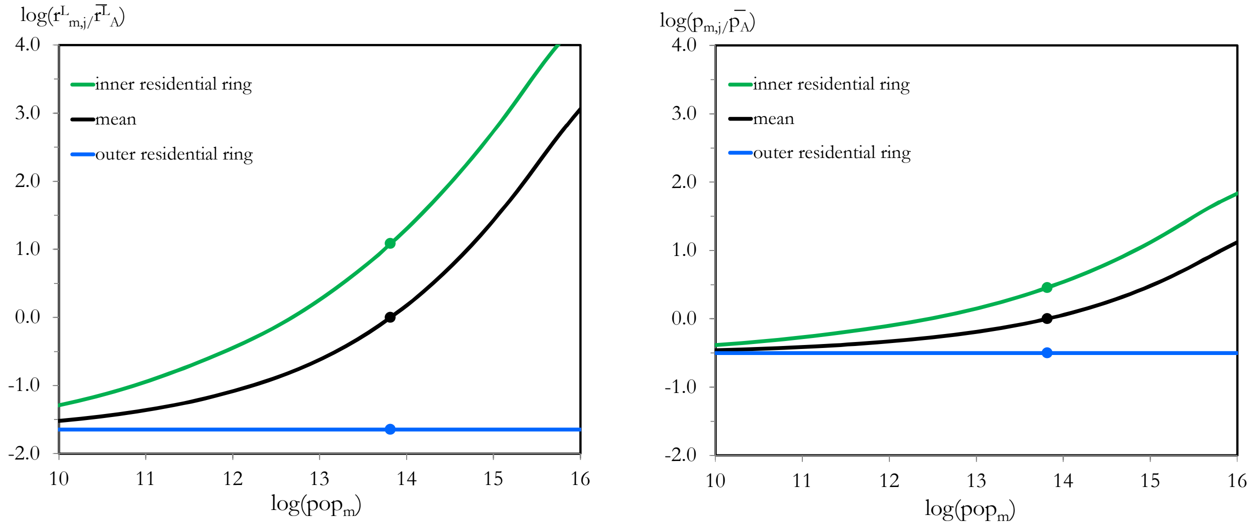

Figure 7: Land and House Prices Left panel shows the correspondences of land prices and metro population. Right panel shows the correspondences of housing services prices and metro population. Markers indicate outcomes in the anchor metro.

Table 1.

Unsurprisingly, the price of land varies considerably across metros (Figure 7, left panel). By construction, land price in the outermost residential ring is equal regardless of size (blue line). Mean land price as log population increases from 12 to 15 (population increases from 160 thousand to 3.3 million) increases from about one third to about four times its value in the anchor metro (black line). This span is consistent with Larson (2015), who estimates that the average value of land in a metro with population above 1 million is about four times that of a metro with population less than 1 million. Maximum land price, which occurs in the innermost ring, increases from about two thirds to about 15 times the mean value in the anchor metro (green line).

The price of housing services also varies considerably across metros, but by far less than does the price of land. Because both land and capital prices are the same across outer residential rings, the housing-service price must be equal as well (right panel, blue line). As log population increases from 12 to 15, the mean price of housing services increases from about 0.7 to about 1.6 its value in the anchor metro (black line). This dispersion of rental prices is similar to that reported in Davis and Ortalo-Magné (2011) for 50 medium and large U.S. metros in 2000. Over the same population range, the price of housing services in the inner residential ring rises from about 0.9 to about 3.1 times the mean price in the anchor metro (green line).

As metros grow larger, rising prices dampen housing consumption (Figure 8, left panel, black and green lines). Mean and especially inner housing consumption decrease steeply as population increases Relative to the mean in the anchor metro, mean housing consumption falls from 1.16 at log population 12 (population 160 thousand) to 0.82 at log population 15 (population 3.3 million). Over the same range, innermost housing consumption falls from 1.00 to 0.52. In contrast, housing

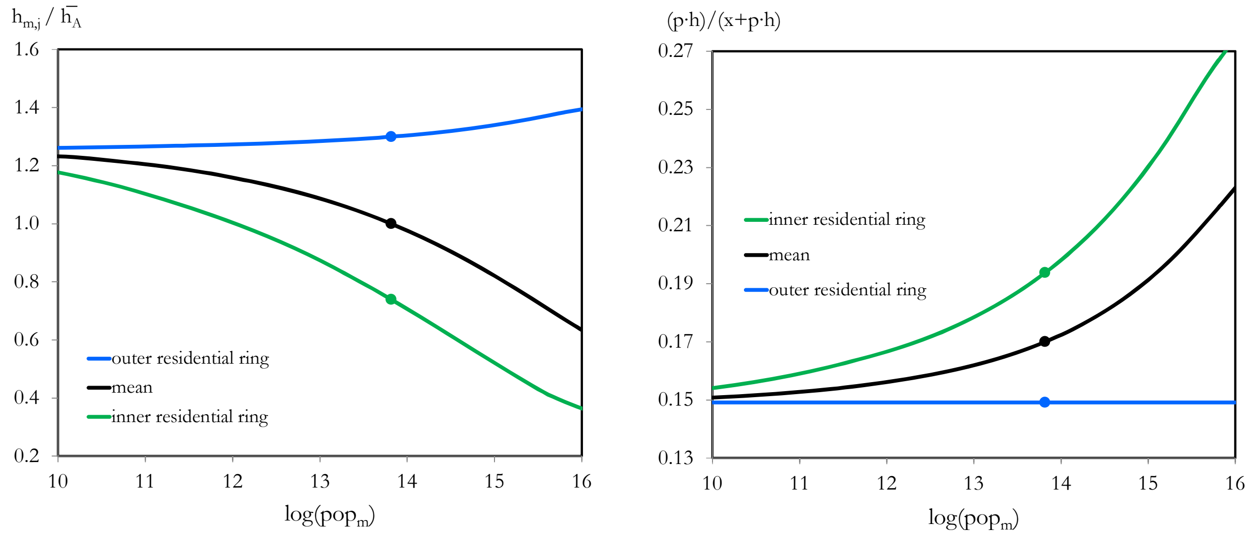

Figure 8: Housing Consumption and Expenditure Share Left panel shows the correspondence of normalized housing consumption and metro population. Right panel shows the correspondence of the housing share of consumption expenditure and population. Markers indicate outcomes in the anchor metro.

consumption in the outermost ring increases with metro size (blue line). This increase reflects the higher numeraire wage in larger metros together with the identical outermost housing price. More substantively, the increase in outermost housing consumption contributes to the compensation for longer distance, more congested commutes.

The decreases in housing consumption are tempered by the parameterization of numeraire and housing as complements ($\sigma_h = 0.67$). The mean and inner housing expenditure shares thus increase with metro size (right panel, black and green lines). The model is calibrated to set the mean housing share in the anchor metro to 0.17. As log population increases from 12 to 15, the mean and inner housing expenditure shares respectively increase from 0.16 to 0.19 and from 0.17 to 0.23. These ranges are within those reported in Davis and Ortalo-Magné (2011).

Leisure decreases only modestly with metro size (Figure 9, left panel). Measured by "hours equivalent," the sum of leisure time and leisure derived from commuting, mean leisure drops from 57 hours equivalent to 56.6 to 56.2 as log population increases from 12 to the anchor level to 15 (black line). Outermost leisure drops from 56.8 hours equivalent to 56.0 to 55.0 over the same range (blue line).

The small size of reduced leisure may seem surprising, given longer commute times from any fixed distance from the CBD, longer distance commutes, and a lower leisure content of commute time. It is facilitated by individuals sharply cutting back weekly workhours (Figure 9, right panel). By construction, individuals in the inner ring of the anchor metro choose to supply 40 hours. The inner-ring commute, 0.1 mile, is sufficiently short that individuals in the inner rings of all metros choose to supply very close to 40 hours (green line). Commutes from all rings in small metros remain sufficiently short and leisure content sufficiently high for hours supplied to remain close to

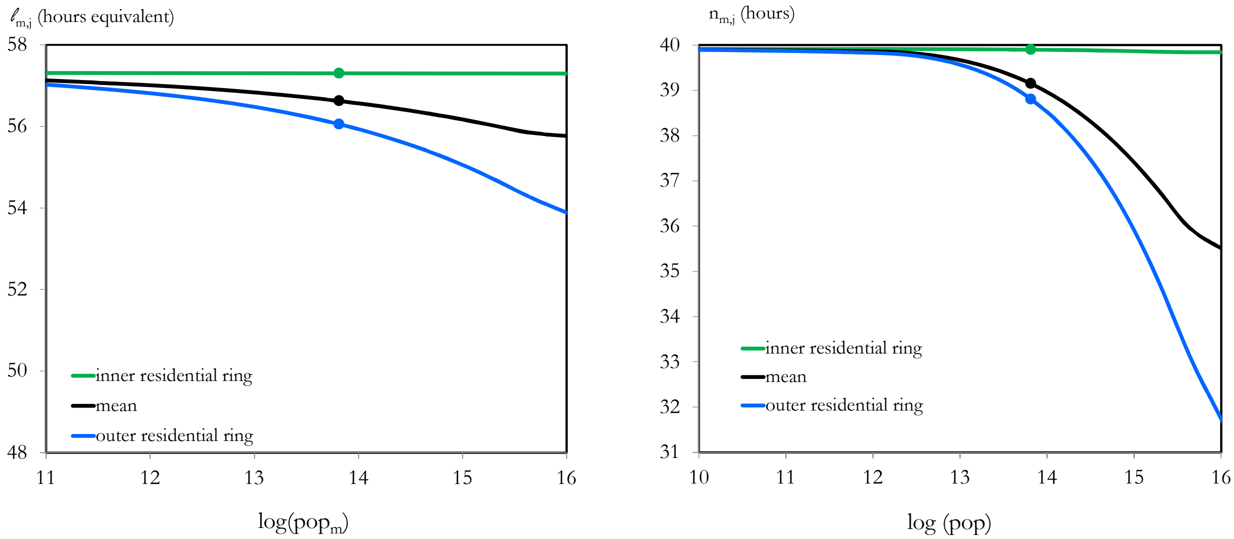

Figure 9: Leisure and Weekly Workhours Left panel shows the correspondence between leisure, the sum of leisure time and leisure from commute time, and population. Right panel shows the correspondence of weekly workhours and population. Markers indicate outcomes in the anchor metro.

40. As log population increases from its anchor to 15 (population 3.3 million), mean work hours fall from 39.2 to 37.5 (black line); outer ring work hours fall off more steeply: from 38.9 to 36.0 (blue line). The lattermost, cutback, four hours, is quite reasonable upon reinterpreting individuals as households. But many individual fulltime workers lack the choice to do so. As described in the next section, constraining individuals to supply 40 hours dampens the population response to productivity by forcing the cost of long, congested commutes to be disproportionately borne by foregoing leisure.

The increase in house prices as population increases elicits a vigorous increase in structure intensity (Figure 10, left panel). As log population increases from 12 to 15, mean housing capital per unit land increases by a multiplicative factor of 9. Inner capital per unit land increases by a multiplicative factor of 18. Mean and inner supplied housing services per unit land respectively increase by multiplicative factors of 4 and 6 (right panel). The implied price elasticity of housing supply ranges from 1.24 in the inner ring of a metro with log population 15 to a mean value of 1.68 in the anchor metro to 1.92 in the outer ring of all metros. These lie in the middle of a benchmark range of estimated supply elasticities across medium and large U.S. metros in 2000 (Saiz, 2010). An alternative parametrization of substitutability between land and structure based on multifamily construction would make it easier to build vertically and so elicit a considerably stronger supply response.

Detailed tables summarizing baseline results are included as Appendix A.

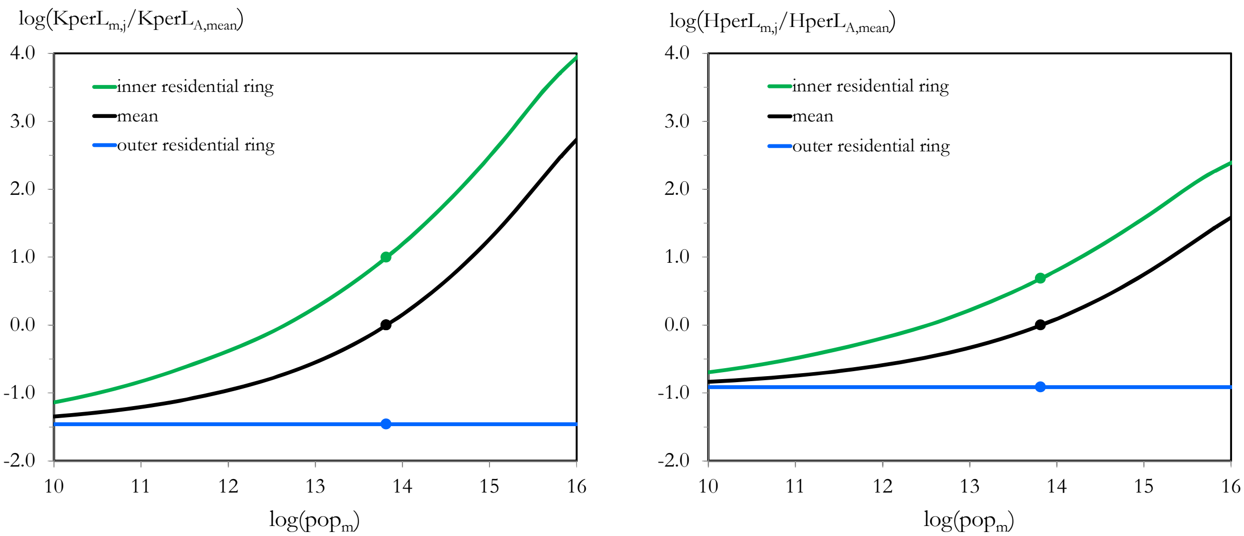

Figure 10: Housing Structure and Services Density Figure shows the correspondences metro population with housing capital per unit of land and housing services quantity per unit of land. Markers indicate outcomes in the anchor metro.

6 Alternative Scenarios

The structural estimates and data moments used to parameterize the model are subject to considerable uncertainty. Even if the model fully captured the process generating actual metros, its baseline quantitative results would come with wide error bands. In addition, as is the case with all economic models, the present one makes a slew of first-order simplifications that are likely to significantly affect quantitative outcomes. These simplifications include no dynamics, no consumption amenities, no heterogeneity, no household structure, no alternative modes of transport, no arterial commuting, no land use by streets and highways, no local non-traded services other than housing, no employment outside the CBD, no commute segments within the CBD, and no parking.

In this context, quantitative correspondences may best be interpreted qualitatively. Alternative scenarios help to do so by illuminating the mechanics by which metro TFP affects metro population, radius, and other outcomes. As is intuitive, alternatives that dampen demand for land and increase its effective supply strengthen the responsiveness of population to TFP. The latter supply channel proves to be more important quantitatively. Detailed summary tables of all alternative scenarios are included as Appendix B.

6.1 Alternative Parameterizations of Production, Utility, and Commuting

A first group of alternative scenarios describe alternative parameterizations of the model.

The correspondence of population with TFP depends on parameterization choices that affect demand for land. Increasing land's factor share of numeraire production, α_L, land's average factor share of housing production in the anchor metro, $\overline{\mu}_A^L$, and housing's average consumption expenditure share in the anchor metro, $\overline{\mu}_A^h$, each explicitly or implicitly increase demand for land and so dampen the responsiveness of population to TFP. Increasing the elasticity of substitution between land and structure in the production of housing, σ_L, and between housing and numeraire in utility, σ_h, make it easier to explicitly or implicitly substitute away from land and so accentuate the responsiveness of population to TFP. The magnitude of the changes in responsiveness turn out to be asymmetric, both with respect to the direction of change in the parameterization and with respect to whether metro TFP is relatively high or low. Appendix B.1 includes detailed summaries. Here I highlight several examples.

The baseline parameterization of α_L (0.016) may fail to capture that a significant share of CBD land enters numeraire production externally such as via its use for sidewalks, streets, and parking. Alternatively quadrupling α_L to 0.064 significantly limits the population of high-TFP metros. For example, population at relative TFP 1.15 is a third below its baseline level (i.e., below 4.0 million, the baseline population at relative TFP 1.15). Quadrupling α_L boosts population at low relative TFP by even more, almost doubling it compared to its baseline at relative TFP 0.90. The higher land share increases the incentive to keep numeraire production where CBD land is inexpensive rather than moving it to someplace more productive.

Land's share of housing factor income also powerfully affects the population correspondence at high relative TFP. For example, as $\overline{\mu}_A^L$ increases from 0.25 to its baseline (0.35) to 0.50, metro population at relative TFP 1.15 increases from more than 15 percent below baseline to more than 40 percent above it. In contrast, $\overline{\mu}_A^L$ only modestly effects the population correspondence at low relative, reflecting the plentifulness of residential land in small metros.

Counterintuitively, the elasticities of substitution only moderately affect the responsiveness of population to TFP. As σ_L increases from 0.75 to its baseline (0.90) to 1.05, metro population at relative TFP 1.15 increases from about 10 percent lower to about 20 percent higher. As σ_h increases from 0.50 to its baseline (0.67) to 0.90, metro population at relative TFP 1.15 increases from about 5 percent lower to about 15 percent higher. These elasticities do not exert more leverage because the corresponding weights, η_L and η_h, are recalibrated to partly "offset" changes in parameterized values. For example, setting σ_L to 1.05 rather than 0.90 recalibrates η_L to a higher value so as to hit the unchanged target land share of housing production ($\overline{\mu}_A^L$=0.35). While it is easier to substitute away from land under the new parameterization, land is also more important.[12]

Utility also depends on leisure consumption, suggesting that the elasticity of substitution with leisure, σ_ℓ, importantly affects correspondences. However, this proves not to be the case under the baseline assumption that individuals freely choose their workhours. Instead, the correspondence of TFP and population remains almost identical across a wide range of calibrated values of σ_ℓ and remaining correspondences other than those with workhours remain very similar. As individuals face longer commutes, they adjust workhours such that their marginal valuation of leisure remains effectively pinned down by the curvature of the tradeoff between housing and numeraire.

[12] Alternative parameterizations also typically require recalibration of the benchmark level of highway capacity and the numeraire per mile cost of commuting, δ.

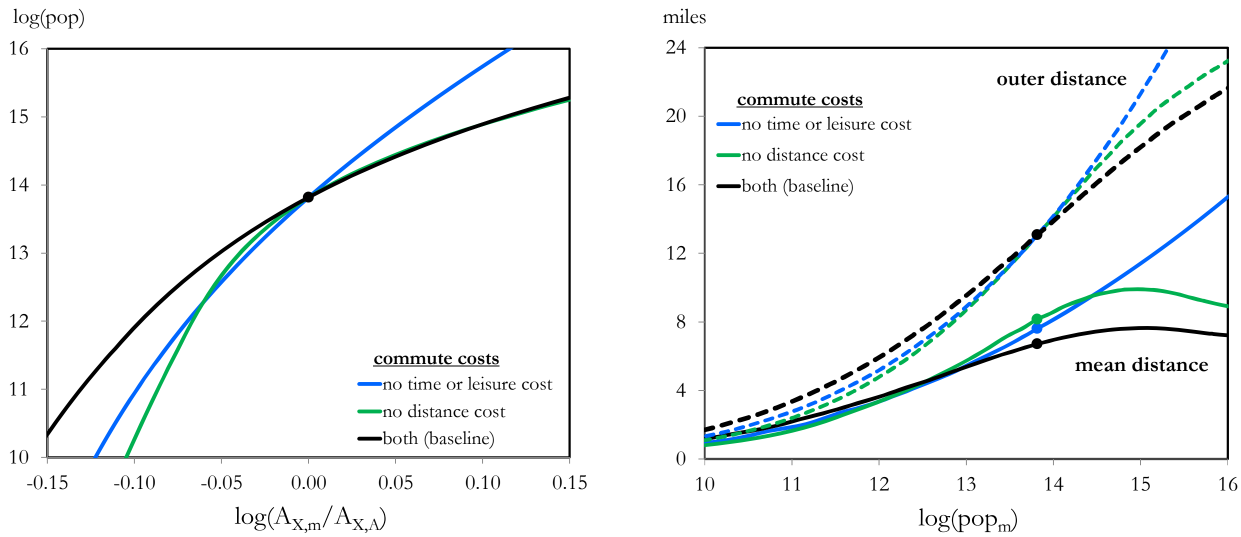

Figure 11: Distance and Time Costs. Left Panel shows the population correspondence with TFP and right panel shows the commute distance correspondence with population when there no distance cost to commuting (green line) and when there is no time cost (blue line). Markers indicate outcomes for the anchor metro.

The correspondence of population with TFP depends even more closely on the elasticity with which metro land supply can accommodate changes in metro land demand. This supply elasticity depends on commuting technology—the numeraire, time, and leisure costs of getting from home to work and back.

As a starting point for building intuition, Figure 11 shows the population and commute distance correspondences when there is no distance cost to commuting (green lines) and when there is no foregone leisure time from commuting (blue lines).[13] The latter scenario maps to infinite commute speed but can also be interpreted as commuting time having a unitary leisure component (λ=1) and so yielding the same leisure as explicit leisure time.

The distance cost proves essentially irrelevant in determining metro population at intermediate and high relative TFP. Even with no distance cost, the population correspondence almost exactly matches its baseline as TFP rises above its level in the anchor metro. But at low relative TFP, eliminating the distance cost sharply steepens the population correspondence. The asymmetry at least partly reflects that the real cost of commute distance, measured in terms of foregone utility, decreases as productivity and hence numeraire wages increase.

The time cost critically shapes the population correspondence at all relative levels of TFP. In its absence, population becomes extremely sensitive to TFP. For example, metro population at relative TFP 1.15 more than triples from its baseline value (to 13 million rather than 4 million).

[13]In contrast to the other alternative parameterizations, the no distance cost scenario does not recalibrate highway capacity, $\widehat{V}$, to approximate the observed correspondence between commute time and distance. Similarly, the no time and leisure cost scenario does not recalibrate the per mile distance cost to match the baseline target of the mean ratio of commute costs to income in the anchor metro.

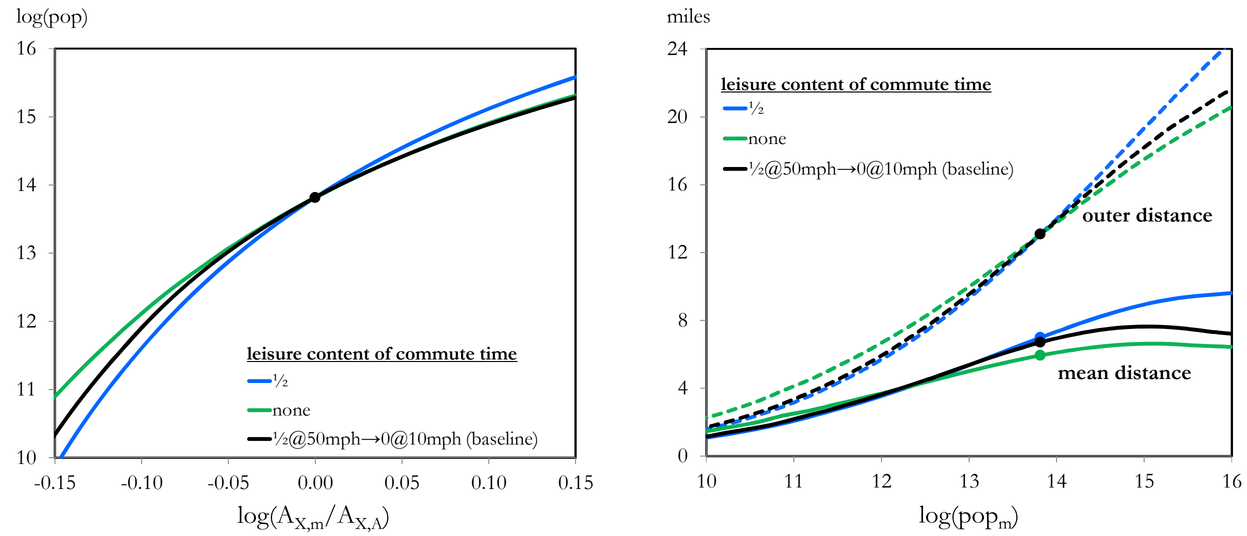

Figure 12: The Leisure Content of Commuting. Left panel shows the population correspondence with TFP and right panel shows the commute distance correspondence with population when the leisure content of commute time is constant at 0.5 (blue lines) and at 0 (green lines). Markers indicate outcomes for the anchor metro.

Unsurprisingly, eliminating the time cost also significantly boosts commute distances (right panel, blue lines). At relative TFP 1.15, mean commute distance more than doubles (from 8 to 17 miles) and outer commute distance increases by more than three quarters (from 19 to 35 miles). Eliminating the distance cost moderately increases mean commute distance but only modestly increases outermost distance (green lines).

The next two alternative scenarios assume that the leisure content of commute time, λ, remains constant rather than decreasing from 0.5 at 50 mph to 0 at 10 mph. Holding leisure content at 0.5 steepens the correspondence between population and TFP (Figure 12, left panel, blue line). This increased responsiveness is intuitive for large metros: the higher leisure content lessens the opportunity cost of commute time and so allows for longer outer commute distances (right panel, blue lines). For smaller metros, the higher leisure content devalues the brief commutes afforded by short distances and low congestion. In consequence, population falls off more quickly as TFP decreases from its anchor level.

Holding leisure content constant at zero rather than 0.5 increases the benefit of the fast commute speeds in small metros and so flattens the population correspondence when relative TFP is low (left panel, green line). But the population correspondence remains essentially the same as under the baseline at high relative TFP. This partly reflects that a significant share of commute time in large metros under the baseline is at slower speed and so has low leisure content. Zero leisure content does, however, modestly decrease commute distances (right panel, green lines).

A third pair of alternative commute parameterizations vary the elasticity of highway provision, σ_V, below and above baseline, each coupled with a recalibration of baseline capacity, $\widehat{V}$, to approximate the baseline correspondence between commute time and distance. Doing so moderately affects the population correspondence. At relative TFP 1.15, decreasing σ_V to 0.90 (from its 0.92 baseline) and increasing it to 0.94 respectively push down and boost population by a little more than 10 percent. For relative TFP below 1, the population correspondence is essentially unchanged. Commute distances at high relative TFP modestly decrease at the lower highway elasticity and modestly increase at the higher one. As discussed in a subsection below, changing the highway elasticity in a single open metro while leaving it at its baseline in the anchor metro more significantly affects the population and distance correspondences.

Detailed tables summarizing outcomes under these and other alternative parameterizations of production, utility, and commuting are included as Appendix B.1.

6.2 Alternative Assumptions: Fixed Workhours, Capital Income, and Endogenous CBD Radius

A second group of alternative scenarios describe alternative assumptions regarding the data generating process.

Under the baseline specification, individuals living in the outer rings of large metros significantly pare back workhours to offset long, congested commutes (Figure 9, right panel). To the extent that modeled individuals can be interpreted as households, doing so seems plausible. But for individual workers with fulltime jobs, it probably is not.

Alternatively requiring individuals to work 40 hours per week modestly flattens the responsiveness of population and outer commute distance for large metros (Figure 13, left panel, green line; right panel, green dashed line). It also strengthens infill as population increases above its anchor level, reflected by decreasing mean commute distance (right panel, green solid line).

Fixed workhours bite more strongly as individuals become less willing to substitute away from leisure. For example, at relative TFP of 1.15 with the Frisch elasticity targeted to 0.10 rather than 0.20, population is more than 20 percent below its free-choice baseline, outer commute distance is shorter by 4.4 miles, and mean commute distance is shorter by 2.4 miles (left panel, blue line; right panel, dashed and solid blue lines). This sensitivity to the targeted Frisch elasticity contrasts with the almost perfect insensitivity to it when individuals can choose their workhours.

Not being able to optimally choose leisure can drive its marginal value considerably above the wage rate. The first order conditions (10) imply that individuals would like to choose their leisure time, and so residually their workhours, to equate the marginal value of leisure, $\frac{\partial U_{m,j}}{\partial \ell_{m,j}} / \frac{\partial U_{m,j}}{\partial x_{m,j}}$, with the metro wage rate, w_m. By construction, individuals in the inner ring of the anchor metro prefer to work the required 40 hours per week and so the ratio of their marginal valuation of leisure to their wage exactly equals 1. With the Frisch elasticity targeted to its baseline, the mean and outer-ring valuation ratios in the anchor metro respective equal 1.10 and 1.16 (Figure 14, right panel, green markers). With the Frisch elasticity instead targeted to 0.10, the mean and outer valuation ratios respectively equal 1.37 and 1.72 (blue markers)

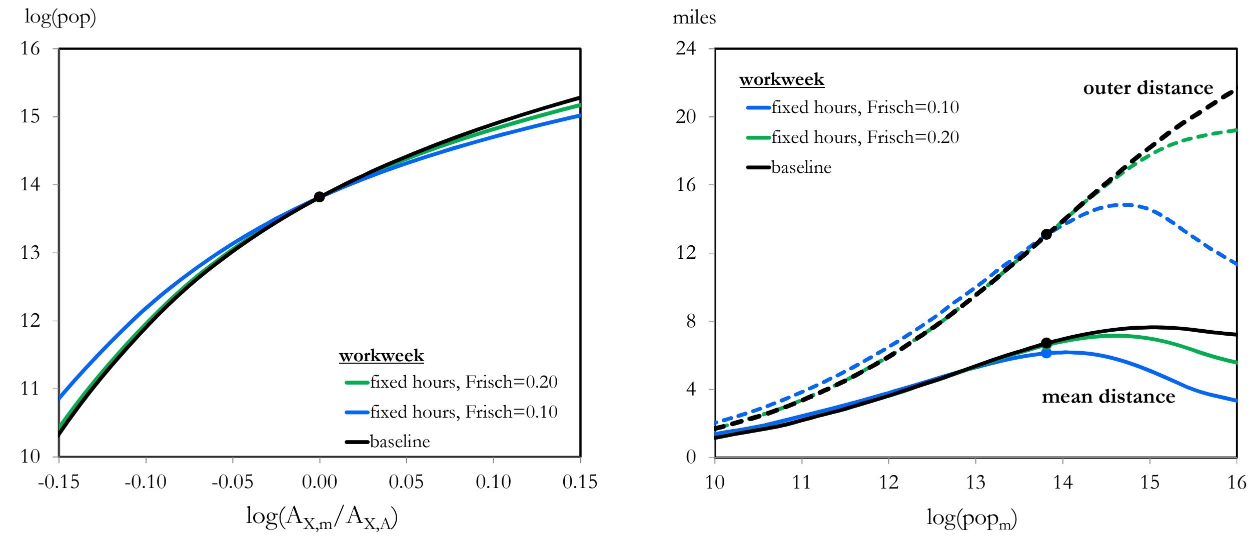

Figure 13: Fixed Weekly Workhours Left Panel shows the population correspondence with TFP and right panel shows the commute distance correspondence with population when workers are required to work 40 hours each week. The Frisch elasticity is targeted to its baseline, 0.20 (green lines) or to 0.10 (blue lines). Markers indicate outcomes in the anchor metro.

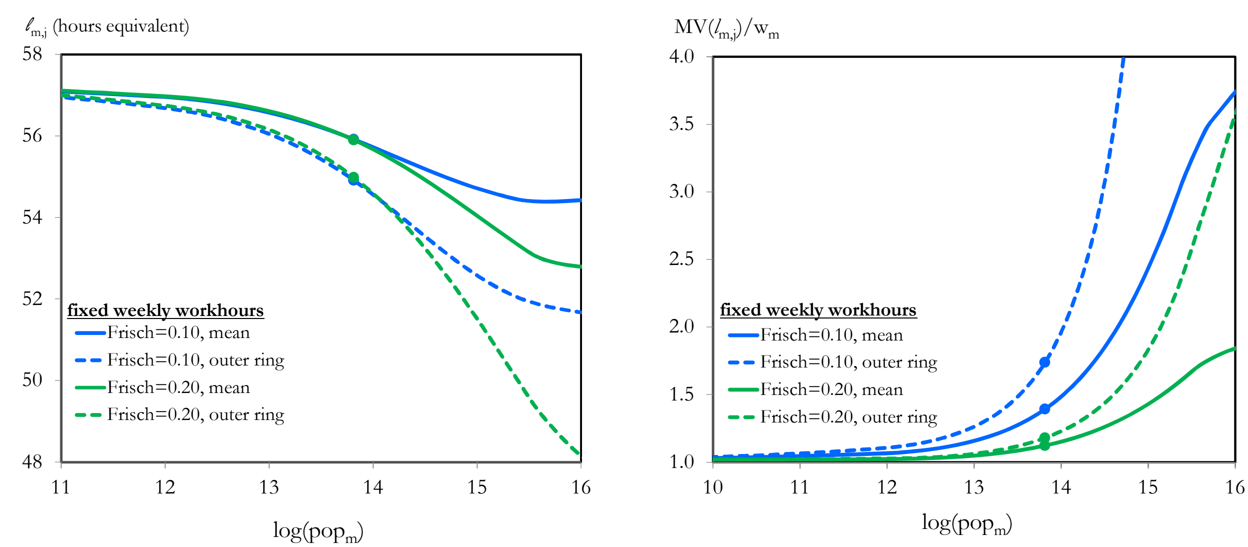

Figure 14: The Marginal Value of Leisure Left Panel shows weekly hours under the baseline specification. Right panel shows the marginal valuation of leisure relative to the metro wage when workers are required to supply 40 hours per week. Markers indicate outcomes for the anchor metro.

As higher relative TFP drives up metro size, the baseline ratios of the mean and outer marginal value of leisure relative to the metro wage increase steeply (right panel, green lines).[14] Under the

[14]The underlying increase in the marginal value of leisure with commute time is consistent with the finding by Small, Winston, and Yan (2005) that individuals' MWTP to shorten their commute time increases with the distance

lower Frisch target, the mean marginal value ratio similarly increases steeply (solid blue line) and the outer marginal value ratio soars (dashed blue line). Wages, the denominator in these ratios, also increase with population, and so individuals' willingness to pay for services that free up time for leisure rises even more steeply than shown by the relative valuations.

A second baseline assumption is that individuals do not receive any income other than wages. Equivalently, all payments to land and capital used in the production of housing and numeraire are paid to absentee landlords, who either live outside the system of metros or who have measure zero. Capital income importantly affects the correspondence between TFP and population by decreasing the marginal utility return to working. A first alternative assumption is that individuals—regardless of where they live—receive a lump sum transfer equal to per capita payments to land and capital used to produce housing services in the anchor metro.[15] Doing so moderately dampens responsiveness. At relative TFP 1.15, population is 10 percent below baseline; at relative TFP 0.90, it is 20 percent above baseline. A second alternative assumption is that individuals receive a lump sum transfer equal to per capita payments to all land and capital in the anchor metro. In this case, the dampening is much larger: 20 percent below baseline at the higher relative TFP and 90 percent above baseline at the lower relative TFP.

A third baseline assumption is that the radius of the CBD is the same across all metros. In contrast, the inferred CBD radiuses for the seven metros summarized in Table 2 range from 1.9 miles to 3.4 miles. I alternatively endogenize the CBD radius by requiring the ratio of the price of land in the CBD to the price of land in the innermost residential ring to remain the same as in the anchor metro.[16] Doing so intuitively increases the responsiveness of population at low relative TFP. For example, at relative TFP 0.90, the endogenous CBD radius is 1.6 miles (versus 2.4 miles in the anchor), implying CBD land area that is less than half that in the anchor metro. In consequence, metro population is more than a third below its baseline value.

Paradoxically, endogenizing the CBD in this way dampens population responsiveness at high relative TFP. As relative TFP increases above some intermediate threshold and holding the CBD radius constant, the price of land in the inner residential ring increases faster than does the price of land in the CBD. Maintaining the ratio in the anchor metro requires the CBD radius to contract. At relative TFP 1.15, for example, the endogenous CBD radius is 1.9 miles and metro population falls a tenth below baseline.

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of their commute.

[15]It is critical that the transfer not depend on where individuals live as doing so significantly distorts location decisions. The larger transfer that would accompany living in a location with expensive housing would significantly dampen the disincentive of the high price. Such location-based transfers might misleadingly be labeled as "lump sum" as individuals do not internalize the effect on the rebate when choosing their quantity of housing (or else they would choose to consume an infinite amount).

[16]The baseline ratio of the price of land in the CBD to the price of land in the inner ring is 3.6. A more natural assumption would be to require land price equalization between the CBD and the inner ring. However, doing so implies CBD radiuses that are implausibly large. This reflects that land's aggregate factor income from numeraire production per square mile of CBD land considerably exceeds land's aggregate factor income from housing production per square mile of inner-ring land for any plausible CBD radius.

Detailed tables summarizing outcomes for these alternative assumptions are included in Appendix B.2.

6.3 Alternative Metros: No Congestion, Telecommuting, and Growth Boundaries

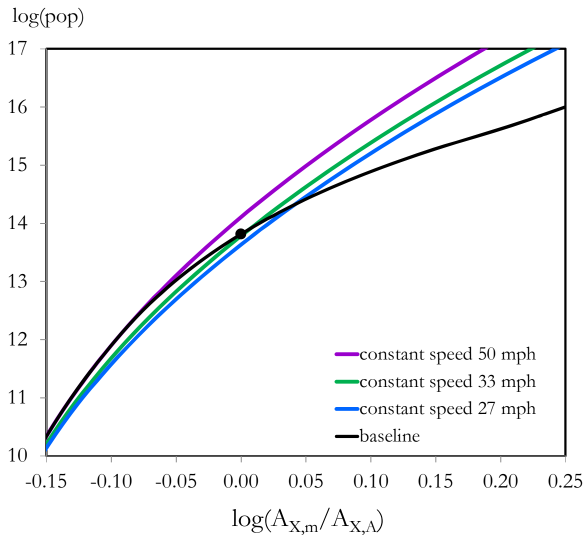
The alternative parameterizations and assumptions described above are "system" scenarios in the sense that differences from the baseline apply to all metros including the anchor metro. This subsection instead describes alternative processes that generate outcomes in only one or a few open metros. This limitation on the number of alternative metros reflects that they collectively must remain sufficiently "small" to not affect the shared reservation level of utility that must be attained in all metros.

As stated above, congested commuting proves the critical force quantitatively constraining metro size. Figure 15 shows alternative open metros with assumed constant speed equal to its 27 mph minimum in the baseline anchor metro (blue lines) and equal to 33 mph, its average in the baseline anchor metro. Under either scenario, the correspondence of population to TFP remains highly elastic to extremely high metro population (left panel; note that the axes extend to higher values than in the similar figures above). For example, under the baseline calibration of commuting congestion, relative TFP levels of 1.15 and 1.25 respectively correspond to metros with population of 4.0 and 7.2 million At a constant speed of 27 mph, they correspond to metros with population 6.9 and 19.4 million. At a constant speed 33 mph, to metros with population 8.4 and 24.0 million.[17]

An alternative way to increase the responsiveness of an alternative metro's population to TFP is to increase the elasticity of its highway provision with respect to volume (Figure 17, left panel, green lines). Another is allow individuals to telecommute from home one day a week, thereby reducing their weekly oneway commutes from 10 to 8 and highway volume by 20 percent for a given population (blue lines). Both alternatives considerably shift up the correspondence between population and TFP. But the marginal increases in TFP required to support a marginal increase in population remains about the same as under the baseline. At relative TFP of 1.15 and above, the higher levels of population attained under these alternatives fall considerably short of those achieved with uncongested commuting.

Of course, actual congestion is subject to congestion and so the telecommuting alternative illustrates a plausible way to accommodate increases in population without lowering utility. At the same time, it is important to note that telecommuting actually worsens congestion. For an alternative metro with given level of relative TFP, the endogenous population response to telecommuting increase commuting times from all distances.

[17] The increase in open metro population is larger when a constant speed of 27 mph holds in all metros. This makes intuitive sense as the reservation level of utility established by the anchor metro should be lower than under the baseline—because 27 mph was its minimum speed—and so the TFP required to attain this threshold for a given open-metro population should be lower as well. While this intuition goes through, it is technically incorrect because utility is calibrated slightly differently under the two scenarios and so is not strictly comparable between them. Appendix B.2 includes a summary of outcomes for this alternative system scenario.



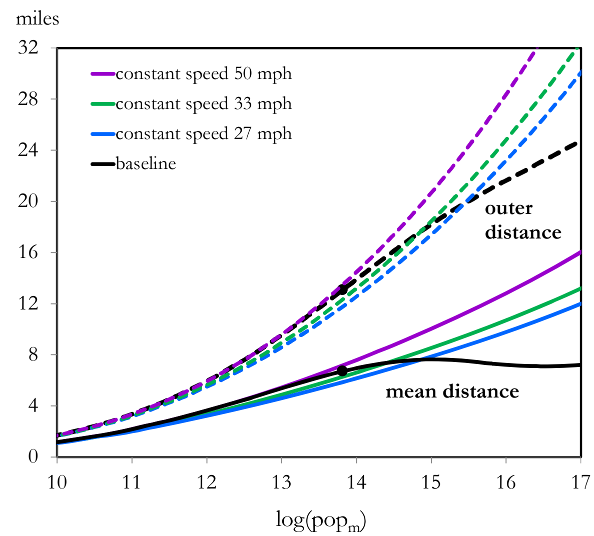
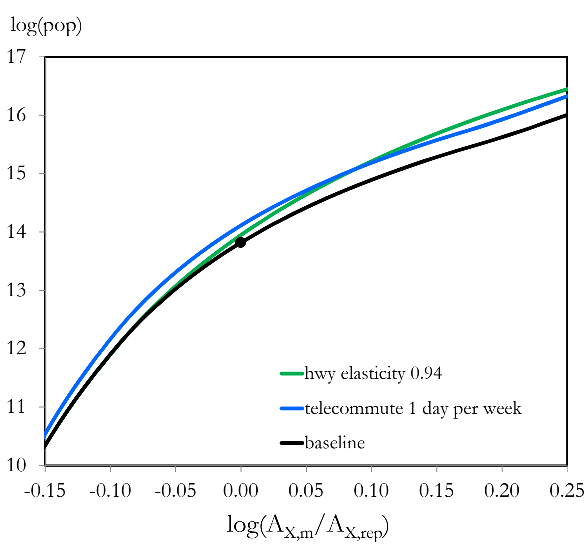


Figure 15: Constant Commute Speed Left Panel shows population correspondence and right panel shows commute distances when workers commute speed remains constant at 50 mph (purple line), 33 mph (green line), and 27 mph (blue line). These respectively are the maximum, mean and minimum commute speed in the anchor metro. The anchor metro continues to be driven by the baseline data generating process. Markers indicate outcomes for the anchor metro.



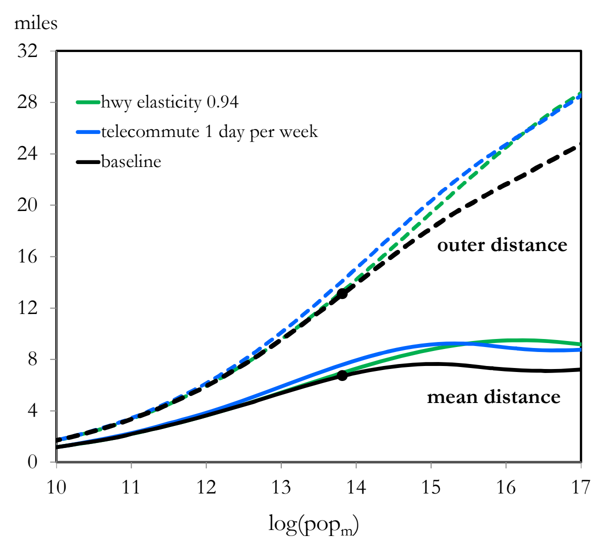


Figure 16: More Elastic Highway Provision and Telecommuting Left Panel shows population correspondence and right panel shows commute distances when the elasticity of highway provision is 0.94 (green line) and workers telecommute one day out of five (blue line). The anchor metro continues to be driven by the baseline data generating process. Markers indicate outcomes for the anchor metro.

Detailed tables summarizing outcomes for a variety of alternative metros are included in Appendix B.2.

6.4 Unanchored Systems: Self-Driving Cars and Multifamily Construction

Each of the alternatives above are anchored in the sense that the calibration of weighting parameters and commute costs approximate cause the anchor metro to approximate observed outcomes. This subsection instead describes alternative system scenarios that are clearly counterfactual and so for which there are no observed outcomes to match and shared level of utility across metros may significantly differ from its level under plausible data generating processes.

The invention of the automobile in the early twentieth century coupled with massive highway construction in the years following World War II unleashed a decentralizing force that massively transformed residential location. In the context of the present modeling framework, suburbanization resulted from the huge decrease in the time cost of commuting, both along radial highway segments and arterial ones that reached one's home.

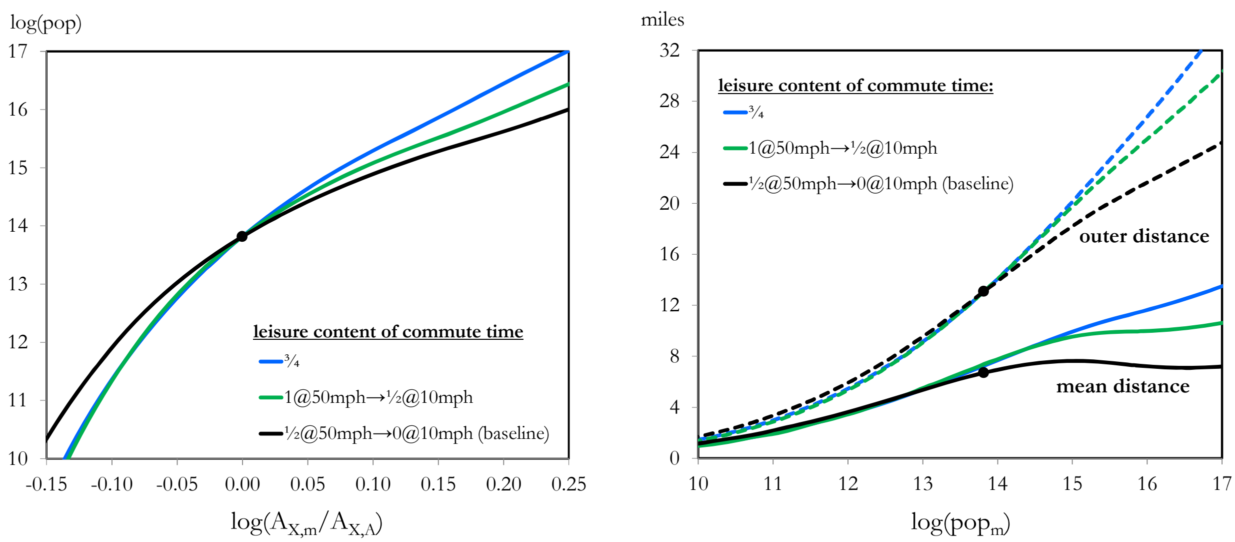


Figure 17: Self-Driving Cars Left Panel shows population correspondence and right panel shows commute distances when the leisure content of commute time linearly decreases from 1 at 50 mph to $\frac{1}{2}$ at 10 mph (green lines) and when it remains constant at $\frac{3}{4}$ (blue lines).

... description ....

A second alternative scenario that unanchors quantitative results is to allow for significantly greater ability to substitute away from land in the production of housing. The baseline parameterization of the elasticity of substitution between land and structure, $\sigma_L = 0.90$, is based on estimates that use single-family housing as observations. This elasticity may be significantly higher for multifamily construction. ...

7 The Costs and Benefits of Metro Size

A fundamental goal of urban economics is understanding the endogenous productivity benefits of metro size. The present framework complements this goal by illustrating the bidirectional causality between metro productivity and metro population and giving a sense of the relative magnitudes. As is intuitive, agglomeration amplifies exogenous TFP variations. Equilibrium metro size is determined by the intersection of this amplification benefit with the endogenous "cost" of metro size.

Figure 18 inverts the log population and log productivity axes used in many of the figures above to show the baseline correspondence of productivity against population (left panel, black line). This presentation emphasizes interpreting the correspondence as capturing the productivity required to support a given population. By construction, a metro with log population of 13.8 (population of 1 million) requires a log TFP of 0. Metros with the normalized log population of Des Moines (13.2) and Denver (14.3) respectively require log TFP of -0.041 and 0.037. Required log productivity increases convexly with log population. This convexity is extremely robust to alternative calibrations of the model, consistent with the robust concave correspondence of log population with respect to log TFP illustrated in Sections 6 and 7 above.

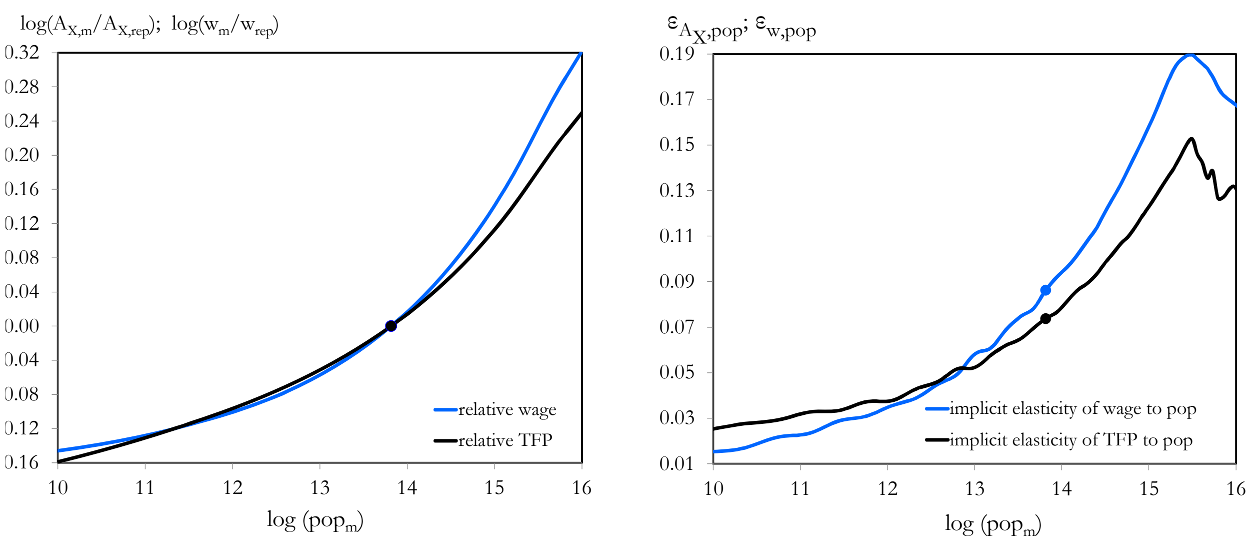


Figure 18: Population, Productivity, and Wages Left panel shows the correspondences of metro TFP and wages with metro population. Right panel shows the implied non-causal elasticity of TFP and wages with respect to population. Markers indicate outcomes in the anchor metro.

The correspondence of log wages against log population (blue line) can be interpreted as the cost of population because wages summarize the compensation required to offset higher housing prices and longer, more congested commutes. For small and medium metros, the wage correspondence approximately matches the productivity correspondence. But for larger metros, the wage correspondence lies increasingly above the productivity one. This is made possible by increases in capital intensity in production of numeraire that sufficiently outpace decreases in land intensity.

The convex productivity and wage correspondences immediately imply that the (non-causal) elasticities of productivity and wages to population, $\epsilon_{TFP,pop}$ and $\epsilon_{w,pop}$ increase as population increases (right panel).[18] At the anchor metro normalized population of 1 million, $\epsilon_{w,pop}$, equals 0.086. This modestly exceeds empirical estimates that the average of $\epsilon_{w,pop}$ across metros probably lies between 0.035 and 0.07 (Combes and Gobillion, 2015). As population increases above 1 million, the wage elasticity becomes implausibly high. For example as log population rises to 15 and then 16 (population equal to 3.3 million and 8.9 million), the wage elasticity rises to 0.16 and then to 0.32.

Many of the model's simplifications help account for such high quantitative wage elasticities. For example, multiple modes of transport, moderate decentralized employment, and heterogenous tastes for commuting would all contribute to lowering the wage elasticity. Consumption amenities that are correlated with metro size would similarly contribute to doing so by complementing wages as compensation for high housing prices and congestion. As argued in the empirical motivation section above, however, monocentricity clearly must give way to polycentricity or highly diffuse employment above some threshold population.

The benefit of population is the endogenous increase in productivity due to agglomeration. As is standard, let metro TFP be the product of an exogenous term and an endogenous one that increases with population with agglomerative elasticity, $\sigma_{TFP,pop}$,

$$A_{X,m} = \widehat{A}_{X,m} \exp(\sigma_{TFP,pop} \cdot POP_m) \tag{20}$$

Figure 19 illustrates the equilibrium determination of metro population at the intersection of benefits and costs. For costs, it uses the correspondence of required TFP with respect to population as a proxy for the correspondence of wages with respect to population (black line). This implies that costs contingent on monocentricity are understated as population increases above some threshold.

The benefit of population is captured by the upward slope of the dashed lines. The long-run elasticity of agglomeration, which encompasses both the static changes in labor productivity as workers move between metros and the cumulative dynamic benefits from faster learning in large metros, likely lies between 0.02 and 0.06 (Combes and Gobillion, 2015). For each of four alternative levels of exogenous TFP, $\widehat{A}_X$, the dashed lines show all combinations of TFP and population that are attainable with $\sigma_{TFP,pop}$ equal to 0.04.

Differences in exogenous TFP shift the locci vertically. The exogenous TFP of the anchor metro, $\widehat{A}_{X,rep}$, is normalized to equal 1. The black dashed line, which includes the anchor metro, thus shows all possible values of $A_{X,rep}$ that can be attained assuming an agglomerative elasticity

[18] The wobbles in the elasticity correspondences likely reflect numerical imprecision. The decrease in elasticity that sets in at very high population is substantive and robust across calibrations and assumptions. The mechanics driving it are not clear.

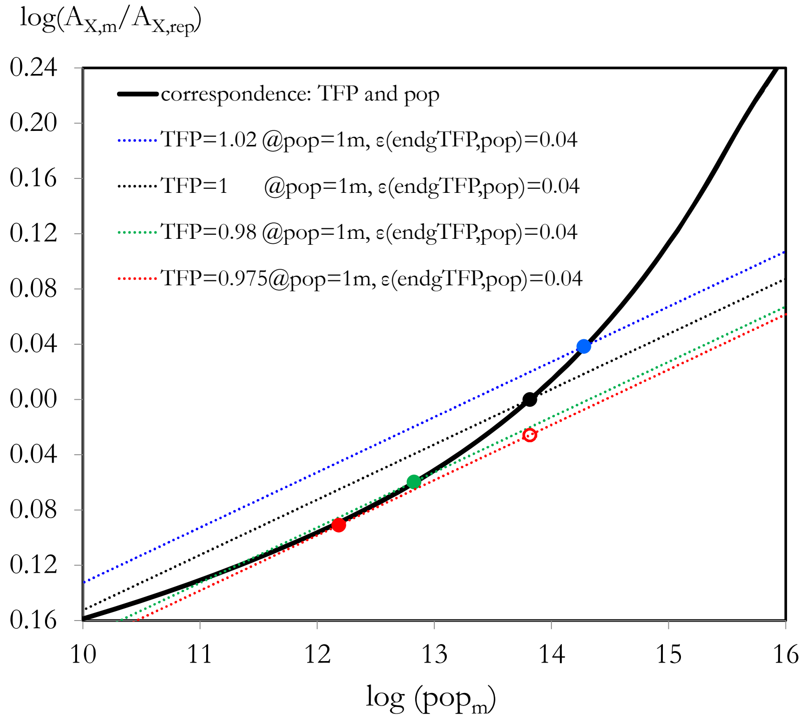


Figure 19: The Interaction of Endogenous and Exogenous Total Factor Productivity Solid line shows the correspondence of TFP and metro population. The dashed lines show feasible combinations of TFP and population that are attainable with agglomerative elasticity of 0.04 from four alternative levels of exogenous TFP. The black marker corresponds to the anchor metro.

of 4 percent. The blue dashed line is shifted up by 2 percentage points. In other words, $\widehat{A}_{X,blue}$ equals 1.02 as does $A_{X,rep}$ at the anchor metro population of 1 million. The green and red dashed lines are respectively shifted down by 2 percent and 2.25 percent.

Equilibrium metro population for each exogenous TFP lies at the intersection of its benefit locus (dashed line) and the costs locus (solid line). As the benefit locus cuts the benefits locus from below, the equilibrium is stable. Perturb population up and not sufficient TFP to support. Perturb population down and TFP exceeds that needed to support.[19]

Under the baseline calibration and 4 percent agglomerative elasticity, $\widehat{A}_{X,red}$ (0.975), is the lowest exogenous TFP for which a metro can exist. With lower exogenous TFP, total TFP at all populations is below what is required for land to be used for metro purposes. This minimum exogenous value is highly sensitive both to the assumed agglomerative elasticity and to the assumptions and calibration of the model.

Asymmetry: decreases in exogenous productivity are significantly amplified. Suggests that in a

[19]The intersections in Figure 19 identify the metro cost correspondence. Instead identifying the benefit relationship relies on finding sources of variation in cost relationship. The Saiz (2010) measure of land suitable for development nicely does so for the present model as cost do not depend on the span of settlement.

dynamic setting with durable housing and capital stock, moving costs, etc, history dependence will be important in determining which locations with exogenous TFP near the min actually develop into metros. increases in exogenous productivity are amplified much less. For a metro to become very large, it must have exogenous TFP significantly above the baseline. In other words, agglomerative productivity does not suffice to support a very large metro such as New York City.

8 Conclusion

- **quantitative model approximates correspondences across small and medium U.S. metros of population with a number of metro outcomes**
- **exact quantities should be interpreted with with caution**
  - normalization to 180°
  - slew of first-order simplifications in addition to monocentricity
    * that mitigate costs of population: no arterial commutes, no commutes within CBD, no dynamics (and so legacy housing, infrastructure), no land regulation
    * that increase costs of population: no alternative modes of transport, no decentralized employment, no heterogenous tastes for commuting

- **builds intuition/ gives insight on forces determining metro size**
  - commuting congestion as quantitatively most important force constraining metro size
  - the more moderate but significant constraints from competing uses of land
  - concavity of population response (convexity of costs)
  - constrained work hours causing high marginal value of leisure

- **importance of consumption amenities** (exogenously correlated or agglomerative)
  - to temper high quant elasticity of wage to pop
    * Albouy and Stuart (2014) estimates that variation in consumption amenities accounts for a large share of variation in metro size
    * Albouy (2012): estimates that metro quality of life, inclusive of commuting, is uncorrelated with metro size. This implies that consumption amenities, must increase with metro size to offset disutility of longer, more congested commutes. This increase need only take place in suburbs.
  - agglomerative from sorting of high human capital households, who have high demand for amenities, into large metro areas

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Non-Land Inputs in the Production of Housing." *Journal of Urban Economics* 42, 98-108.

A Summary Tables of Baseline Results

baseline	@tfp 0.90	@tfp 0.95	@tfp 1.00	@tfp 1.05	@tfp 1.10	@tfp 1.15
Size						
population	130,000	440,000	1,000,000	1,800,000	2,820,000	4,020,000
land area	90 sq.mi	230 sq.mi	380 sq.mi	520 sq.mi	630 sq.mi	720 sq.mi
Commute Distance						
mean	3.3 mi	5.4 mi	6.7 mi	7.4 mi	7.6 mi	7.6 mi
inner	0.1 mi	0.1 mi	0.1 mi	0.1 mi	0.1 mi	0.1 mi
outer	5.2 mi	9.5 mi	13.1 mi	15.7 mi	17.6 mi	19.0 mi
Population Density (ths prs per sqmi)						
mean	1.7	2.5	4.0	6.2	9.6	14.3
inner	2.7	5.1	9.7	17.0	28.0	43.2
outer	1.1	1.1	1.1	1.1	1.1	1.1
Commute Time						
mean	12 min	15 min	20 min	25 min	31 min	36 min
inner	8 min	8 min	8 min	8 min	8 min	8 min
outer	14 min	21 min	29 min	39 min	50 min	60 min
Commute Speed						
mean	50 mph	43 mph	33 mph	25 mph	20 mph	17 mph
inner	50 mph	39 mph	27 mph	20 mph	15 mph	12 mph
outer	50 mph	50 mph	50 mph	50 mph	50 mph	50 mph

Table A.1: TFP, Metro Size, and Commuting. Table shows size and commuting outcomes when numeraire TFP varies across metros. Population is normalized to a span of 180°.

baseline	**@tfp 0.90**	**@tfp 0.95**	**@tfp 1.00**	**@tfp 1.05**	**@tfp 1.10**	**@tfp 1.15**
Population	**130,000**	**440,000**	**1,000,000**	**1,800,000**	**2,820,000**	**4,020,000**
Housing Price (index)						
mean	0.70	0.83	1.00	1.22	1.50	1.82
inner	0.86	1.16	1.58	2.11	2.77	3.55
outer	0.61	0.61	0.61	0.61	0.61	0.61
Housing Expenditure (index)						
mean	0.85	0.92	1.00	1.09	1.20	1.31
inner	0.93	1.06	1.22	1.39	1.59	1.79
outer	0.81	0.81	0.82	0.83	0.84	0.86
Land Price (index)						
mean	0.31	0.54	1.00	1.86	3.34	5.75
inner	0.56	1.30	2.95	6.23	12.11	21.84
outer	0.19	0.19	0.19	0.19	0.19	0.19

Table A.2: Summary, Residential Prices. Table shows residential prices when TFP varies across metros. Population is normalized to a span of 180°. Indexes are normalized to equal 1 at the mean value in the anchor metro.

baseline	**@tfp 0.90**	**@tfp 0.95**	**@tfp 1.00**	**@tfp 1.05**	**@tfp 1.10**	**@tfp 1.15**
Population	**130,000**	**440,000**	**1,000,000**	**1,800,000**	**2,820,000**	**4,020,000**
Numeraire Consumption (index)						
mean	0.95	0.97	1.00	1.03	1.06	1.09
inner	0.97	1.00	1.04	1.08	1.13	1.17
outer	0.94	0.95	0.97	0.98	0.99	1.00
Housing Consumption (index)						
mean	1.17	1.09	1.00	0.92	0.85	0.78
inner	1.03	0.87	0.74	0.63	0.55	0.48
outer	1.27	1.28	1.30	1.32	1.33	1.35
Leisure (includes from commuting)						
mean	57.0 hrs	56.8 hrs	56.6 hrs	56.4 hrs	56.2 hrs	56.1 hrs
inner	57.3 hrs	57.3 hrs	57.3 hrs	57.3 hrs	57.3 hrs	57.3 hrs
outer	56.9 hrs	56.5 hrs	56.1 hrs	55.6 hrs	55.2 hrs	54.8 hrs
Housing Expend Share						
mean	0.155	0.162	0.170	0.179	0.188	0.197
inner	0.165	0.178	0.194	0.209	0.224	0.239
outer	0.149	0.149	0.149	0.149	0.149	0.149

Table A.3: Consumption and Leisure. Table shows consumption and leisure when TFP varies across metros. Population is normalized to a span of 180°. Indexes are normalized to equal 1 at the mean value in the anchor metro. Leisure includes both explicit leisure time and leisure derived from commuting.

baseline	**@tfp 0.90**	**@tfp 0.95**	**@tfp 1.00**	**@tfp 1.05**	**@tfp 1.10**	**@tfp 1.15**
Population	**130,000**	**440,000**	**1,000,000**	**1,800,000**	**2,820,000**	**4,020,000**
Housing Structure Density (index)						
mean	0.36	0.58	1.00	1.73	2.92	4.74
inner	0.61	1.29	2.71	5.31	9.65	16.41
outer	0.23	0.23	0.23	0.23	0.23	0.23
Housing Services Density (index)						
mean	0.53	0.72	1.00	1.39	1.88	2.49
inner	0.76	1.25	1.98	2.99	4.26	5.79
outer	0.40	0.40	0.40	0.40	0.40	0.40
Land Factor Share of Housing						
mean	0.329	0.339	0.350	0.361	0.372	0.383
inner	0.343	0.362	0.381	0.399	0.415	0.430
outer	0.319	0.319	0.319	0.319	0.319	0.319
Housing Supply Elasticity						
mean	1.84	1.76	1.68	1.60	1.53	1.46
inner	1.72	1.58	1.46	1.35	1.27	1.19
outer	1.92	1.92	1.92	1.92	1.92	1.92

Table A.4: Housing Supply. Table shows measures of housing supply when TFP varies across metros. Population is normalized to a span of 180°. Indexes are normalized to equal 1 at the mean value in the anchor metro. Housing structure and housing services density are the respective ratios of housing capital and housing services to land area.

B Summary Tables of Alternative Scenarios

B.1 alternative parameterizations

Alternative Parameterizations	population					
	@tfp 0.90	**@tfp 0.95**	**@tfp 1.00**	**@tfp 1.05**	**@tfp 1.10**	**@tfp 1.15**
Baseline	**130,000**	**440,000**	**1,000,000**	**1,800,000**	**2,820,000**	**4,020,000**
Production						
α_L=0.004 (0.016; X, land factor share)	40,000	340,000	1,000,000	1,960,000	3,170,000	4,590,000
α_L=0.064 (0.016; X, land factor share)	380,000	640,000	1,000,000	1,470,000	2,040,000	2,720,000
σ_L=0.75 (0.90; H, CES K and L)	130,000	450,000	1,000,000	1,740,000	2,610,000	3,580,000
σ_L=1.05 (0.90; H, CES K and L)	130,000	430,000	1,000,000	1,890,000	3,160,000	4,880,000
$\bar{\mu}_{L,A}$=0.25 (0.35; H, L mean fctr shr in anchor)	120,000	400,000	1,000,000	2,010,000	3,470,000	5,730,000
$\bar{\mu}_{L,A}$=0.50 (0.35; H, L mean fctr shr in anchor)	130,000	460,000	1,000,000	1,700,000	2,500,000	3,390,000
Utility						
σ_h=0.50 (0.67; CES h and x)	130,000	450,000	1,000,000	1,760,000	2,680,000	3,730,000
σ_h=0.90 (0.67; CES h and x)	120,000	430,000	1,000,000	1,870,000	3,050,000	4,560,000
$\bar{\mu}_{h,A}$=0.14 (0.17; h mean expnd shr in anchor)	130,000	430,000	1,000,000	1,880,000	3,050,000	4,490,000
$\bar{\mu}_{h,A}$=0.22 (0.17; h mean expnd shr in anchor)	130,000	460,000	1,000,000	1,730,000	2,600,000	3,600,000
$\text{Frisch}_{\Lambda,1}$=0.10/$\sigma_l$=0.17 (0.20/0.34)	130,000	440,000	1,000,000	1,800,000	2,810,000	4,010,000
$\text{Frisch}_{\Lambda,1}$=0.40/$\sigma_l$=0.68 (0.20/0.34)	130,000	440,000	1,000,000	1,810,000	2,830,000	4,050,000
Commuting						
λ=1 (no time cost)	50,000	280,000	1,000,000	2,740,000	6,330,000	13,060,000
δ=0 (no distance cost)	20,000	300,000	1,000,000	1,850,000	2,820,000	3,920,000
λ=0 (no leisure content)	160,000	460,000	1,000,000	1,800,000	2,850,000	4,140,000
λ=½ (constant leisure content)	90,000	380,000	1,000,000	2,040,000	3,500,000	5,350,000
σV=0.90 (elas hwy cpcty, base=0.92)	130,000	450,000	1,000,000	1,730,000	2,600,000	3,570,000
σV=0.94 (elas hwy cpcty, base=0.92)	130,000	430,000	1,000,000	1,880,000	3,090,000	4,630,000

Table B.1: Alternative Parameterizations: Population versus TFP. Table shows metro population for alternative parameterizations of the process generating outcomes in all metros. Numbers in parentheses give baseline values. Population is normalized to a span of 180°.

Alternative Parameterizations	**mean commute distance** (miles)						**outer commute distance** (miles)					
	@tfp 0.90	**@tfp 0.95**	**@tfp 1.00**	**@tfp 1.05**	**@tfp 1.10**	**@tfp 1.15**	**@tfp 0.90**	**@tfp 0.95**	**@tfp 1.00**	**@tfp 1.05**	**@tfp 1.10**	**@tfp 1.15**
Baseline	**3.3**	**5.4**	**6.7**	**7.4**	**7.6**	**7.6**	**5.2**	**9.5**	**13.1**	**15.7**	**17.6**	**19.0**
Production												
α_L=0.004 (0.016)	1.6	4.9	6.7	7.4	7.6	7.6	2.4	8.5	13.1	16.1	18.1	19.5
α_L=0.064 (0.016)	5.1	6.0	6.7	7.2	7.5	7.6	9.0	11.1	13.1	14.8	16.2	17.5
σ_L=0.75 (0.90)	3.1	5.5	7.1	8.1	8.6	9.0	4.9	9.4	13.1	15.9	18.0	19.6
σ_L=1.05 (0.90)	3.4	5.3	6.3	6.6	6.4	5.9	5.6	9.7	13.1	15.5	17.1	18.3
$\bar{\mu}_{L,A}$=0.25 (0.35)	3.2	4.0	4.4	4.4	4.3	4.1	7.4	10.5	13.1	14.9	16.2	17.2
$\bar{\mu}_{L,A}$=0.50 (0.35)	2.9	5.7	7.7	8.9	9.7	10.1	4.4	9.1	13.1	16.1	18.5	20.3
Utility												
σ_h=0.50 (0.67)	3.3	5.4	6.8	7.6	8.0	8.2	5.2	9.5	13.1	15.7	17.7	19.2
σ_h=0.90 (0.67)	3.3	5.3	6.5	7.0	7.0	6.7	5.2	9.6	13.1	15.6	17.4	18.7
$\bar{\mu}_{h,A}$=0.14 (0.17)	3.4	4.9	5.8	6.1	6.2	6.0	6.1	9.9	13.1	15.3	17.0	18.1
$\bar{\mu}_{h,A}$=0.22 (0.17)	3.0	5.6	7.4	8.4	9.0	9.2	4.6	9.2	13.1	16.0	18.2	19.8
$\text{Frisch}_{A,1}$=0.10/σ_l=0.17	3.3	5.4	6.7	7.4	7.6	7.6	5.3	9.6	13.1	15.6	17.5	18.8
$\text{Frisch}_{A,1}$=0.40/σ_l=0.68	3.2	5.3	6.7	7.4	7.7	7.7	5.1	9.5	13.1	15.8	17.9	19.4
Commuting												
λ=1 (no time cost)	1.6	4.4	7.6	10.8	13.9	16.9	2.3	7.0	13.1	19.9	27.2	34.9
δ=0 (no distance cost)	0.8	4.7	8.2	9.5	9.9	9.8	1.1	7.0	13.1	16.6	18.9	20.4
λ=0 (no leisure)	3.7	5.1	5.9	6.4	6.6	6.6	6.7	10.2	13.1	15.3	17.0	18.3
λ=½ (constant leisure)	2.7	5.1	7.0	8.3	9.0	9.4	4.2	8.7	13.1	16.8	19.7	21.9
σ_V=0.90 (base=0.92)	3.2	5.4	6.8	7.3	7.4	7.3	5.1	9.5	13.1	15.5	17.2	18.3
σ_V=0.94 (base=0.92)	3.4	5.3	6.6	7.4	7.8	8.0	5.4	9.5	13.1	15.9	18.1	19.9

Table B.2: Alternative Parameterizations: Commute Distance versus TFP. Table shows commute distances for alternative parameterizations of the process generating outcomes in all metros. Numbers in parentheses give baseline values.

Alternative Parameterizations	mean pop density (ths prs per sq mi)						inner pop density (ths prs per sq mi)					
	@tfp 0.90	@tfp 0.95	@tfp 1.00	@tfp 1.05	@tfp 1.10	@tfp 1.15	@tfp 0.90	@tfp 0.95	@tfp 1.00	@tfp 1.05	@tfp 1.10	@tfp 1.15
Baseline	**1.7**	**2.5**	**4.0**	**6.2**	**9.6**	**14.3**	**2.7**	**5.1**	**9.7**	**17.0**	**28.0**	**43.2**
Production												
α_L=0.004 (0.016)	1.3	2.2	4.0	6.7	10.9	16.7	1.7	4.4	9.7	18.6	32.1	51.1
α_L=0.064 (0.016)	2.3	3.0	4.0	5.3	7.0	9.3	4.7	6.7	9.7	13.8	19.5	26.9
σ_L=0.75 (0.90)	1.8	2.5	3.5	4.9	6.7	8.7	2.7	4.7	7.8	11.9	17.1	23.3
σ_L=1.05 (0.90)	1.5	2.5	4.5	8.6	16.6	31.8	2.7	5.7	12.5	26.8	55.3	109.7
$\bar{\mu}_{L,A}$=0.25 (0.35)	1.6	4.0	9.1	18.6	35.0	64.2	3.8	10.3	24.6	52.8	102.2	179.7
$\bar{\mu}_{L,A}$=0.50 (0.35)	2.0	2.4	3.1	4.0	5.1	6.5	2.6	3.9	6.1	9.0	12.8	17.4
Utility												
σ_h=0.50 (0.67)	1.7	2.5	3.8	5.6	8.0	11.1	2.7	5.0	8.8	14.4	21.9	31.4
σ_h=0.90 (0.67)	1.6	2.5	4.2	7.4	12.9	22.2	2.6	5.3	11.0	21.8	41.1	73.3
$\bar{\mu}_{h,A}$=0.14 (0.17)	1.5	2.8	5.3	9.5	15.9	25.2	3.0	6.7	14.1	26.9	46.9	75.9
$\bar{\mu}_{h,A}$=0.22 (0.17)	1.9	2.4	3.3	4.5	6.3	8.5	2.6	4.2	7.0	11.2	17.0	24.7
$\text{Frisch}_{A,1}$=0.10/σ_l=0.17	1.6	2.5	3.9	6.2	9.6	14.3	2.6	5.1	9.6	16.9	27.8	42.9
$\text{Frisch}_{A,1}$=0.40/σ_l=0.68	1.7	2.5	4.0	6.2	9.6	14.2	2.7	5.2	9.8	17.3	28.3	43.8
Commuting												
λ=1 (no time cost)	1.8	2.3	3.1	4.6	6.7	9.6	2.1	3.5	6.0	10.0	15.9	24.0
δ=0 (no distance cost)	2.2	2.3	2.9	4.0	5.8	8.4	2.2	2.8	5.1	9.4	16.3	26.3
λ=0 (no leisure)	1.7	2.9	5.0	8.2	12.7	18.9	3.4	6.9	12.8	22.3	36.1	55.1
λ=½ (constant leisure)	1.6	2.4	3.6	5.6	8.5	12.5	2.4	4.5	8.2	14.3	23.4	36.2
σ_V=0.90 (base=0.92)	1.7	2.5	3.9	6.1	9.4	13.8	2.7	5.1	9.6	17.0	28.2	43.7
σ_V=0.94 (base=0.92)	1.6	2.5	4.0	6.4	9.9	14.8	2.7	5.2	9.8	17.1	27.8	42.7

Table B.3: Alternative Parameterizations: Population Density versus TFP. Table shows population density for alternative parameterizations of the process generating outcomes in all metros. Numbers in parentheses give baseline values. Mean density is weighted by population.

Alternative Parameterizations	mean commute time (minutes)						outer commute time (minutes)					
	@tfp 0.90	@tfp 0.95	@tfp 1.00	@tfp 1.05	@tfp 1.10	@tfp 1.15	@tfp 0.90	@tfp 0.95	@tfp 1.00	@tfp 1.05	@tfp 1.10	@tfp 1.15
Baseline	**12**	**15**	**20**	**25**	**31**	**36**	**14**	**21**	**29**	**39**	**50**	**60**
Production												
α_L=0.004 (0.016)	10	14	20	26	32	38	11	19	29	41	53	64
α_L=0.064 (0.016)	15	17	20	23	27	30	20	24	29	35	42	49
σ_L=0.75 (0.90)	12	16	21	27	32	38	14	20	29	39	50	60
σ_L=1.05 (0.90)	12	15	20	24	28	32	15	21	29	39	49	59
$\bar{\mu}_{L,A}$=0.25 (0.35)	12	14	17	21	25	28	17	22	29	38	47	57
$\bar{\mu}_{L,A}$=0.50 (0.35)	11	16	21	28	34	40	13	20	29	40	50	61
Utility												
σ_h=0.50 (0.67)	12	16	21	26	32	37	14	21	30	39	50	60
σ_h=0.90 (0.67)	12	15	20	25	29	33	14	21	29	39	49	59
$\bar{\mu}_{h,A}$=0.14 (0.17)	12	15	19	24	28	33	15	21	29	39	49	59
$\bar{\mu}_{h,A}$=0.22 (0.17)	12	16	21	27	33	38	14	20	29	40	50	60
$\text{Frisch}_{A,1}$=0.10/σ_l=0.17	12	16	20	25	31	35	14	21	29	39	49	59
$\text{Frisch}_{A,1}$=0.40/σ_l=0.68	12	15	20	26	31	36	14	21	29	39	50	61
Commuting												
λ=1 (no time cost)	10	14	22	41	78	105	11	17	30	60	118	176
δ=0 (no distance cost)	9	14	23	32	39	44	9	17	31	45	58	69
λ=0 (no leisure)	12	15	19	24	29	34	16	22	29	38	48	58
λ=½ (constant leisure)	11	15	21	29	38	48	13	19	29	43	60	79
σ_V=0.90 (base=0.92)	12	15	20	26	32	37	14	20	29	39	50	60
σ_V=0.94 (base=0.92)	12	16	20	25	30	34	14	21	30	39	49	59

Table B.4: Alternative Parameterizations: Commute Time versus TFP. Table shows commute times for alternative parameterizations of the process generating outcomes in all metros. Numbers in parentheses give baseline values.

Alternative Parameterizations	**mean commute speed** (mph)						**inner commute speed** (mph)					
	@tfp 0.90	**@tfp 0.95**	**@tfp 1.00**	**@tfp 1.05**	**@tfp 1.10**	**@tfp 1.15**	**@tfp 0.90**	**@tfp 0.95**	**@tfp 1.00**	**@tfp 1.05**	**@tfp 1.10**	**@tfp 1.15**
Baseline	**50**	**42**	**31**	**24**	**19**	**15**	**50**	**39**	**27**	**20**	**15**	**12**
Production												
α_L=0.004 (0.016)	50	45	31	23	18	14	50	42	27	19	14	11
α_L=0.064 (0.016)	44	37	31	26	22	19	41	33	27	22	19	16
σ_L=0.75 (0.90)	50	43	32	25	20	17	50	39	28	21	17	14
σ_L=1.05 (0.90)	50	42	31	23	17	13	50	38	26	19	14	10
$\bar{\mu}_{L,A}$=0.25 (0.35)	50	39	27	19	14	11	50	35	23	15	10	10
$\bar{\mu}_{L,A}$=0.50 (0.35)	50	43	33	26	21	18	50	40	29	23	18	15
Utility												
σ_h=0.50 (0.67)	50	42	31	24	19	16	50	38	27	20	16	13
σ_h=0.90 (0.67)	50	43	32	24	18	14	50	39	27	20	15	11
$\bar{\mu}_{h,A}$=0.14 (0.17)	50	41	30	22	17	13	50	37	25	18	13	10
$\bar{\mu}_{h,A}$=0.22 (0.17)	50	43	33	25	21	17	50	40	29	22	17	14
$\text{Frisch}_{A,1}$=0.10/σ_l=0.17	50	42	31	24	19	15	50	39	27	20	15	12
$\text{Frisch}_{A,1}$=0.40/σ_l=0.68	50	42	31	24	19	15	50	39	27	20	15	12
Commuting												
λ=1 (no time cost)	50	47	31	19	11	10	50	45	27	16	10	10
δ=0 (no distance cost)	50	46	31	23	18	15	50	44	27	20	15	12
λ=0 (no leisure)	50	41	30	23	18	14	50	37	26	19	14	11
λ=½ (constant leisure)	50	44	32	23	17	13	50	41	28	19	14	10
σ_V=0.90 (base=0.92)	50	44	31	23	17	14	50	40	27	18	13	10
σ_V=0.94 (base=0.92)	50	40	31	25	21	17	49	37	28	22	18	15

Table B.5: Alternative Parameterizations: Commute Speed versus TFP. Table shows mean commute speed (aggregate miles divided by aggregate drive time) and speed through the innermost ring for alternative parameterizations of the process generating outcomes in all metros. Numbers in parentheses give baseline values.

Alternative Parameterizations	mean price of housing services						inner price of housing services					
	@tfp 0.90	**@tfp 0.95**	**@tfp 1.00**	**@tfp 1.05**	**@tfp 1.10**	**@tfp 1.15**	**@tfp 0.90**	**@tfp 0.95**	**@tfp 1.00**	**@tfp 1.05**	**@tfp 1.10**	**@tfp 1.15**
Baseline	**0.70**	**0.83**	**1.00**	**1.22**	**1.50**	**1.82**	**0.86**	**1.16**	**1.58**	**2.11**	**2.77**	**3.55**
Production												
α_L=0.004 (0.016)	0.64	0.79	1.00	1.27	1.59	1.97	0.72	1.08	1.58	2.21	2.99	3.92
α_L=0.064 (0.016)	0.81	0.89	1.00	1.13	1.29	1.47	1.11	1.32	1.58	1.89	2.27	2.71
σ_L=0.75 (0.90)	0.72	0.84	1.00	1.20	1.44	1.73	0.87	1.17	1.59	2.14	2.81	3.62
σ_L=1.05 (0.90)	0.68	0.81	1.00	1.25	1.57	1.96	0.85	1.15	1.56	2.08	2.70	3.44
$\bar{\mu}_{L,A}$=0.25 (0.35)	0.62	0.79	1.00	1.26	1.56	1.96	0.82	1.11	1.49	1.97	2.56	3.25
$\bar{\mu}_{L,A}$=0.50 (0.35)	0.75	0.85	1.00	1.19	1.42	1.70	0.88	1.18	1.61	2.17	2.86	3.68
Utility												
σ_h=0.50 (0.67)	0.70	0.83	1.00	1.21	1.44	1.72	0.87	1.17	1.58	2.07	2.65	3.31
σ_h=0.90 (0.67)	0.70	0.82	1.00	1.25	1.58	2.02	0.85	1.14	1.58	2.18	2.97	4.01
$\bar{\mu}_{h,A}$=0.14 (0.17)	0.60	0.77	1.00	1.30	1.67	2.11	0.81	1.17	1.67	2.34	3.18	4.21
$\bar{\mu}_{h,A}$=0.22 (0.17)	0.79	0.88	1.00	1.15	1.33	1.55	0.91	1.14	1.45	1.85	2.31	2.85
$\text{Frisch}_{A,1}$=0.10/σ_l=0.17	0.70	0.82	1.00	1.22	1.50	1.82	0.86	1.16	1.58	2.11	2.77	3.55
$\text{Frisch}_{A,1}$=0.40/σ_l=0.68	0.70	0.83	1.00	1.22	1.49	1.81	0.86	1.16	1.57	2.11	2.76	3.54
Commuting												
λ=1 (no time cost)	0.79	0.87	1.00	1.18	1.41	1.68	0.85	1.06	1.37	1.76	2.24	2.81
δ=0 (no distance cost)	0.88	0.91	1.00	1.15	1.35	1.60	0.89	0.99	1.30	1.77	2.36	3.07
λ=0 (no leisure)	0.64	0.79	1.00	1.25	1.55	1.89	0.88	1.21	1.64	2.19	2.85	3.64
λ=½ (constant leisure)	0.72	0.84	1.00	1.21	1.47	1.77	0.85	1.12	1.50	1.99	2.60	3.32
σ_V=0.90 (base=0.92)	0.71	0.83	1.00	1.22	1.48	1.79	0.87	1.16	1.58	2.12	2.79	3.59
σ_V=0.94 (base=0.92)	0.69	0.82	1.00	1.23	1.51	1.84	0.86	1.16	1.57	2.10	2.74	3.50

Table B.6: Alternative Parameterizations: Housing Price versus TFP. Table shows the price of housing services for alternative parameterizations of the process generating outcomes in all metros. Numbers in parentheses give baseline values.

Alternative Parameterizations	mean price of land services						inner price of land services					
	@tfp 0.90	@tfp 0.95	@tfp 1.00	@tfp 1.05	@tfp 1.10	@tfp 1.15	@tfp 0.90	@tfp 0.95	@tfp 1.00	@tfp 1.05	@tfp 1.10	@tfp 1.15
Baseline	**0.31**	**0.54**	**1.00**	**1.86**	**3.34**	**5.75**	**0.56**	**1.30**	**2.95**	**6.23**	**12.11**	**21.84**
Production												
α_L=0.004 (0.016)	0.23	0.47	1.00	2.06	3.97	7.13	0.32	1.05	2.95	7.02	14.62	27.49
α_L=0.064 (0.016)	0.50	0.69	1.00	1.47	2.17	3.19	1.15	1.83	2.95	4.72	7.45	11.50
σ_L=0.75 (0.90)	0.34	0.57	1.00	1.70	2.77	4.28	0.60	1.35	2.90	5.60	9.86	16.06
σ_L=1.05 (0.90)	0.28	0.50	1.00	2.10	4.48	9.41	0.52	1.23	3.01	7.17	16.35	35.46
$\bar{\mu}_{L,A}$=0.25 (0.35)	0.12	0.36	1.00	2.47	5.54	12.01	0.32	1.06	3.15	8.23	19.11	39.63
$\bar{\mu}_{L,A}$=0.50 (0.35)	0.53	0.70	1.00	1.46	2.14	3.09	0.74	1.31	2.39	4.19	6.95	10.95
Utility												
σ_h=0.50 (0.67)	0.32	0.55	1.00	1.78	3.02	4.89	0.58	1.34	2.95	5.93	10.89	18.49
σ_h=0.90 (0.67)	0.30	0.52	1.00	1.99	3.95	7.62	0.53	1.24	2.95	6.73	14.42	28.99
$\bar{\mu}_{h,A}$=0.14 (0.17)	0.19	0.44	1.00	2.15	4.28	7.93	0.43	1.22	3.18	7.40	15.52	29.70
$\bar{\mu}_{h,A}$=0.22 (0.17)	0.47	0.66	1.00	1.57	2.47	3.82	0.69	1.31	2.56	4.77	8.42	14.06
$\text{Frisch}_{A,1}$=0.10/σ_l=0.17	0.31	0.54	1.00	1.86	3.35	5.77	0.56	1.30	2.96	6.24	12.14	21.90
$\text{Frisch}_{A,1}$=0.40/σ_l=0.68	0.31	0.54	1.00	1.85	3.32	5.69	0.56	1.30	2.95	6.20	12.04	21.70
Commuting												
λ=1 (no time cost)	0.47	0.64	1.00	1.66	2.76	4.51	0.58	1.11	2.23	4.35	8.00	13.87
δ=0 (no distance cost)	0.68	0.75	1.00	1.57	2.64	4.49	0.70	0.94	2.02	4.55	9.43	17.92
λ=0 (no leisure)	0.24	0.49	1.00	1.92	3.49	5.98	0.55	1.36	3.08	6.39	12.21	21.70
λ=½ (constant leisure)	0.35	0.56	1.00	1.80	3.17	5.37	0.56	1.23	2.70	5.58	10.77	19.45
σ_V=0.90 (base=0.92)	0.32	0.55	1.00	1.84	3.30	5.66	0.57	1.30	2.97	6.34	12.43	22.56
σ_V=0.94 (base=0.92)	0.30	0.53	1.00	1.88	3.38	5.81	0.55	1.29	2.93	6.11	11.75	21.01

Table B.7: Alternative Parameterizations: Land Price versus TFP. Table shows the price of land services for alternative parameterizations of the process generating outcomes in all metros. Numbers in parentheses give baseline values.

B.2 alternative assumptions, metros, and unanchored systems

Alternative Assumptions, Metros, and Unanchored Systems	**population**					
	@tfp 0.90	**@tfp 0.95**	**@tfp 1.00**	**@tfp 1.05**	**@tfp 1.10**	**@tfp 1.15**
Baseline	**130,000**	**440,000**	**1,000,000**	**1,800,000**	**2,820,000**	**4,020,000**
Alternative Assumptions						
fixed workhours, $\text{Frisch}_{\Lambda,1}$=0.20	130,000	460,000	1,000,000	1,740,000	2,820,000	3,630,000
fixed workhours, $\text{Frisch}_{\Lambda,1}$=0.10	170,000	500,000	1,000,000	1,630,000	2,350,000	3,130,000
rebate H (per capita H factor income in anchor)	160,000	480,000	1,000,000	1,720,000	2,620,000	3,670,000
rebate X+H (per capita L+K income in anchor)	250,000	560,000	1,000,000	1,580,000	2,280,000	3,070,000
endog CBD radius (constant land price ratio)	80,000	430,000	1,000,000	1,740,000	2,620,000	3,600,000
Alternative Metros						
minimum speed 27 mph (min in anchor)	130,000	440,000	1,000,000	2,020,000	3,900,000	7,060,000
constant speed 27 mph (min in anchor)	90,000	320,000	830,000	1,870,000	3,760,000	6,920,000
constant speed 33 mph (mean in anchor)	100,000	360,000	970,000	2,220,000	4,500,000	8,390,000
constant speed 50 mph (max in anchor)	130,000	480,000	1,340,000	3,170,000	6,630,000	12,700,000
σ_V=0.94 (0.92 in anchor metro)	130,000	460,000	1,140,000	2,240,000	3,830,000	5,910,000
σ_V=0.90 (0.92 in anchor metro)	130,000	420,000	870,000	1,450,000	2,110,000	2,970,000
4-day workweek	160,000	570,000	1,260,000	2,240,000	3,460,000	4,900,000
telecommute 1 day per week	160,000	590,000	1,340,000	2,420,000	3,770,000	5,380,000
distance cost 50% above anchor (per mile)	100,000	330,000	780,000	1,470,000	2,400,000	3,540,000
metro boundary at anchor radius	-	-	1,000,000	1,730,000	2,680,000	3,830,000
perimeter land price five times that of anchor	30,000	220,000	750,000	1,570,000	2,620,000	3,860,000
TFP varies for X and H	90,000	400,000	1,000,000	1,930,000	3,170,000	4,720,000
TFP varies for H only	840,000	920,000	1,000,000	1,080,000	1,170,000	1,260,000
Unanchored Systems						
λ=¾ (self-driving cars I)	70,000	340,000	1,000,000	2,240,000	4,150,000	6,860,000
λ=1@50→½@10mph (self-driving cars II)	70,000	360,000	1,000,000	2,020,000	3,380,000	5,030,000
σ_L=1.5, $\bar{\mu}_{L,A}$=0.35 (multifamily housing I)	100,000	370,000	1,000,000	2,700,000	12,550,000	134,900,000
σ_L=1.5, $\bar{\mu}_{L,A}$=0.35, min spd 5mph (mf II)	100,000	370,000	1,000,000	2,700,000	11,700,000	122,100,000

Table B.8: Population versus TFP. Alternative metro scenarios apply only to one or a handful of metros. Unanchored scenarios lack observed outcomes to which to be calibrated. Population is normalized to a span of 180°.

Alt Assumptions, Metros, and Unanchored	mean commute distance (miles)						outer commute distance (miles)					
	@tfp 0.90	@tfp 0.95	@tfp 1.00	@tfp 1.05	@tfp 1.10	@tfp 1.15	@tfp 0.90	@tfp 0.95	@tfp 1.00	@tfp 1.05	@tfp 1.10	@tfp 1.15
Baseline	**3.3**	**5.4**	**6.7**	**7.4**	**7.6**	**7.6**	**5.2**	**9.5**	**13.1**	**15.7**	**17.6**	**19.0**
Alt Assumptions												
fixed wrkhrs, $\text{Frisch}_{A,1}$=0.20	3.3	5.4	6.6	7.1	7.1	6.9	5.4	9.7	13.1	15.5	17.3	18.0
fixed wrkhrs, $\text{Frisch}_{A,1}$=0.10	3.9	5.5	6.1	6.1	5.7	5.2	6.7	10.5	13.1	14.4	14.8	14.6
rebate H factor incm	3.6	5.6	6.9	7.6	8.0	8.1	5.8	9.8	13.1	15.6	17.6	19.0
rebate X+H factor incm	4.3	6.0	7.3	8.2	8.8	9.1	6.9	10.2	13.1	15.5	17.5	19.1
endog CBD radius	2.9	5.4	6.7	7.4	7.8	7.9	4.4	9.5	13.1	15.7	17.6	19.0
Alternative Metros												
minimum speed 27 mph	3.3	5.4	6.7	7.6	8.6	9.6	5.2	9.5	13.1	16.3	19.7	23.1
constant speed 27 mph	2.5	4.1	5.6	6.9	8.1	9.3	4.1	7.5	11.0	14.6	18.1	21.6
constant speed 33 mph	2.7	4.6	6.2	7.8	9.2	10.6	4.4	8.2	12.2	16.3	20.3	24.4
constant speed 50 mph	3.3	5.6	7.8	9.9	12.0	13.9	5.2	9.9	15.1	20.4	25.9	31.5
σ_V=0.94 (0.92 in anchor)	3.3	5.5	7.2	8.3	8.9	9.3	5.2	9.8	13.9	17.4	20.2	22.5
σ_V=0.90 (0.92 in anchor)	3.3	5.2	6.2	6.6	6.6	6.4	5.2	9.3	12.2	14.2	15.5	16.5
4-day workweek	3.9	6.4	7.8	8.5	8.8	8.7	6.2	11.2	15.2	18.1	20.1	21.6
telecommute 1 day per wk	3.9	6.5	8.1	8.9	9.2	9.2	6.2	11.4	15.7	18.8	21.1	22.7
dist cost 50% above base	2.6	4.3	5.8	6.2	6.6	6.7	4.2	7.7	11.8	13.4	15.3	16.8
grwth bndry at anchor rad	-	-	6.7	6.7	6.6	6.5	-	-	13.1	13.1	13.1	13.1
perim L price 5x anchor	0.5	2.4	4.4	5.6	6.3	6.6	0.7	3.6	7.1	9.9	12.0	13.5
TFP varies for X & H	2.9	5.3	6.7	7.3	7.4	7.2	4.5	9.2	13.1	15.8	17.6	18.8
TFP varies for H only	6.7	6.7	6.7	6.7	6.7	6.7	12.7	12.9	13.1	13.2	13.4	13.5
Unanchored Systems												
λ=¾ (self-driving cars I)	2.2	4.8	7.3	9.1	10.4	11.2	3.3	8.0	13.1	17.7	21.7	25.0
λ=1@50→½@10mph (II)	2.1	5.0	7.4	8.8	9.6	9.9	3.2	8.1	13.1	17.0	19.9	22.1
σ_L=1.5, $\bar{\mu}_{L,A}$=0.35 (mf I)	3.3	5.2	5.7	4.3	1.5	0.3	5.2	9.6	13.1	15.1	15.8	16.0
σ_L=1.5,$\bar{\mu}_{L,A}$=0.35,5mph (mf II)	3.3	5.2	5.7	4.3	1.5	0.3	5.2	9.6	13.1	15.1	15.8	15.9

Table B.9: Commute Distance versus TFP. Alternative metro scenarios apply only to one or a handful of metros. Unanchored scenarios lack observed outcomes to which to be calibrated.

Alternative Assumptions and Metros	**mean pop density** (ths prs per sq mi)						**inner pop density** (ths prs per sq mi)					
	@tfp 0.90	**@tfp 0.95**	**@tfp 1.00**	**@tfp 1.05**	**@tfp 1.10**	**@tfp 1.15**	**@tfp 0.90**	**@tfp 0.95**	**@tfp 1.00**	**@tfp 1.05**	**@tfp 1.10**	**@tfp 1.15**
Baseline	**1.7**	**2.5**	**4.0**	**6.2**	**9.6**	**14.3**	**2.7**	**5.1**	**9.7**	**17.0**	**28.0**	**43.2**
Alt Assumptions												
fixed wrkhrs, $\text{Frisch}_{A,1}$=0.20	1.7	2.6	4.1	6.5	11.2	15.6	2.8	5.4	10.1	17.9	32.2	45.5
fixed wrkhrs, $\text{Frisch}_{A,1}$=0.10	1.7	2.8	4.7	8.1	13.4	21.2	3.1	6.3	12.1	21.4	35.2	54.4
rebate H factor incm	1.8	2.6	3.8	5.5	8.0	11.4	2.9	5.2	8.9	14.6	22.8	33.7
rebate X+H factor incm	2.1	2.6	3.4	4.4	5.7	7.3	3.4	5.0	7.4	10.5	14.7	19.9
endog CBD radius	1.5	2.5	4.0	6.1	9.1	13.0	2.4	5.1	9.7	16.7	26.7	40.3
Alternative Metros												
minimum speed 27 mph	1.7	2.5	4.0	6.5	10.3	15.4	2.7	5.1	9.7	16.6	26.3	39.3
constant speed 27 mph	1.8	2.8	4.5	7.1	10.8	15.8	2.9	5.6	10.1	16.9	26.5	39.5
constant speed 33 mph	1.7	2.7	4.3	6.8	10.3	15.1	2.9	5.4	9.7	16.3	25.6	38.2
constant speed 50 mph	1.7	2.5	4.0	6.2	9.4	13.8	2.7	5.0	9.0	15.1	23.7	35.4
σ_V=0.94 (0.92 in anchor)	1.7	2.5	3.9	6.2	9.5	14.1	2.7	5.1	9.4	16.2	26.4	40.5
σ_V=0.90 (0.92 in anchor)	1.7	2.5	3.9	6.2	9.6	14.9	2.7	5.2	10.0	17.8	29.4	45.4
4-day workweek	1.6	2.4	3.8	6.0	9.3	13.8	2.6	5.0	9.5	16.8	27.7	42.9
telecommute 1 day per wk	1.6	2.4	3.8	6.0	9.2	13.6	2.6	4.9	9.3	16.5	27.3	42.2
dist cost 50% above base	1.7	2.7	5.1	6.8	10.4	15.3	2.9	5.6	12.6	17.7	28.7	43.9
grwth bndry at anchor rad	-	-	4.0	6.9	10.9	16.3	-	-	9.7	17.2	28.2	43.5
perim L price 5x anchor	4.2	4.8	6.0	8.2	11.5	16.0	4.4	6.2	10.4	17.5	28.3	43.4
TFP varies for X & H	1.5	2.3	4.0	6.8	11.5	18.7	2.2	4.6	9.7	18.8	33.9	56.9
TFP varies for H only	3.3	3.6	4.0	4.3	4.7	5.0	7.8	8.7	9.7	10.7	11.7	12.9
Unanchored Systems												
λ=¾ (self-driving cars I)	1.7	2.3	3.4	5.1	7.6	11.3	2.3	4.0	7.2	12.4	20.2	31.2
λ=1@50→½@10mph (II)	1.8	2.3	3.3	4.9	7.4	10.8	2.2	3.9	7.0	12.4	20.6	32.2
σ_L=1.5, $\bar{\mu}_{L,A}$=0.35 (mf I)	1.3	2.2	6.1	47.5	3,053	131,686	2.1	5.5	22.3	202.8	6,654	150,535
σ_L=1.5,$\bar{\mu}_{L,A}$=0.35,5mph (mf II)	1.3	2.2	6.1	47.5	3,047	132,104	2.1	5.5	22.3	202.8	6,497	143,557

Table B.10: Population Density versus TFP. Alternative metro scenarios apply only to one or a handful of metros. Unanchored scenarios lack observed outcomes to which to be calibrated. Mean density is weighted by population.

Alternative Assumptions and Metros	**mean commute time** (minutes)						**outer commute time** (minutes)					
	@tfp 0.90	**@tfp 0.95**	**@tfp 1.00**	**@tfp 1.05**	**@tfp 1.10**	**@tfp 1.15**	**@tfp 0.90**	**@tfp 0.95**	**@tfp 1.00**	**@tfp 1.05**	**@tfp 1.10**	**@tfp 1.15**
Baseline	**12**	**15**	**20**	**25**	**31**	**36**	**14**	**21**	**29**	**39**	**50**	**60**
Alt Assumptions												
fixed wrkhrs, $\text{Frisch}_{A,1}$=0.20	12	16	20	24	29	31	14	21	29	38	48	53
fixed wrkhrs, $\text{Frisch}_{A,1}$=0.10	13	16	20	22	24	25	16	22	30	36	40	43
rebate H factor incm	12	16	21	26	31	36	15	21	30	39	49	59
rebate X+H factor incm	13	17	21	26	31	36	16	22	29	37	46	55
endog CBD radius	11	15	20	25	30	35	13	21	29	39	48	58
Alternative Metros												
minimum speed 27 mph	12	15	20	24	26	29	14	21	29	38	46	54
constant speed 27 mph	14	17	20	23	26	28	17	24	32	40	48	55
constant speed 33 mph	13	16	19	22	25	27	16	23	30	38	45	53
constant speed 50 mph	12	15	17	20	22	25	14	20	26	33	39	46
σ_V=0.94 (0.92 in anchor)	12	15	19	23	28	32	14	20	28	37	46	56
σ_V=0.90 (0.92 in anchor)	12	16	22	27	33	38	14	21	31	42	52	63
4-day workweek	13	18	24	31	37	44	15	24	35	48	61	74
telecommute 1 day per wk	13	17	23	30	37	43	15	23	34	47	60	73
dist cost 50% above base	11	13	19	21	26	31	13	18	27	32	41	51
grwth bndry at anchor rad	-	-	20	24	28	32	-	-	29	35	41	48
perim L price 5x anchor	9	11	15	21	27	32	9	12	19	28	38	49
TFP varies for X & H	11	15	20	26	31	37	13	20	29	40	51	62
TFP varies for H only	19	20	20	21	21	21	28	29	29	30	31	32
Unanchored Systems												
λ=¾ (self-driving cars I)	11	14	21	33	48	64	12	18	30	49	75	105
λ=1@50→½@10mph (II)	11	15	22	31	40	50	12	19	30	46	63	81
σ_L=1.5, $\bar{\mu}_{L,A}$=0.35 (mf I)	12	15	18	19	13	9	14	20	28	37	43	44
σ_L=1.5,$\bar{\mu}_{L,A}$=0.35,5mph (mf II)	12	15	18	19	14	10	14	20	28	37	43	45

Table B.11: Commute Time versus TFP. Alternative metro scenarios apply only to one or a handful of metros. Unanchored scenarios lack observed outcomes to which to be calibrated.

Alternative Assumptions and Metros	mean commute speed (mph)						inner commute speed (mph)					
	@tfp 0.90	@tfp 0.95	@tfp 1.00	@tfp 1.05	@tfp 1.10	@tfp 1.15	@tfp 0.90	@tfp 0.95	@tfp 1.00	@tfp 1.05	@tfp 1.10	@tfp 1.15
Baseline	**50**	**42**	**31**	**24**	**19**	**15**	**50**	**39**	**27**	**20**	**15**	**12**
Alt Assumptions												
fixed wrkhrs, $\text{Frisch}_{A,1}$=0.20	50	42	31	24	19	16	50	38	27	20	15	13
fixed wrkhrs, $\text{Frisch}_{A,1}$=0.10	50	39	30	24	20	17	49	35	26	20	16	13
rebate H factor incm	50	41	31	24	20	16	50	38	27	21	16	13
rebate X+H factor incm	49	40	33	27	22	19	47	37	29	23	19	15
endog CBD radius	50	42	31	24	20	16	50	39	27	20	16	13
Alternative Metros												
minimum speed 27 mph	50	42	31	28	28	28	50	39	27	27	27	27
constant speed 27 mph	27	27	27	27	27	27	27	27	27	27	27	27
constant speed 33 mph	33	33	33	33	33	33	33	33	33	33	33	33
constant speed 50 mph	50	50	50	50	50	50	50	50	50	50	50	50
σ_V=0.94 (0.92 in anchor)	50	46	38	31	26	22	50	44	35	28	23	19
σ_V=0.90 (0.92 in anchor)	50	38	26	19	14	12	50	34	21	15	11	10
4-day workweek	50	39	28	21	17	14	50	35	24	18	13	11
telecommute 1 day per wk	50	41	30	23	18	15	50	38	26	19	15	12
dist cost 50% above base	50	46	32	27	21	17	50	43	27	22	17	13
grwth bndry at anchor rad	-	-	31	24	19	15	-	-	27	21	16	13
perim L price 5x anchor	50	49	35	25	19	15	50	48	31	22	16	13
TFP varies for X & H	50	43	31	23	18	14	50	40	27	19	14	11
TFP varies for H only	34	33	31	30	29	28	30	29	27	26	25	24
Unanchored Systems												
λ=¾ (self-driving cars I)	50	45	31	21	15	11	50	42	27	18	12	10
λ=1@50→½@10mph (II)	50	45	31	22	17	13	50	42	27	19	14	11
σ_L=1.5, $\bar{\mu}_{L,A}$=0.35 (mf I)	50	44	32	21	12	10	50	41	27	16	10	10
σ_L=1.5,$\bar{\mu}_{L,A}$=0.35,5mph (mf II)	50	44	32	21	9	5	50	41	27	16	6	5

Table B.12: Commute Speed versus TFP. Alternative metro scenarios apply only to one or a handful of metros. Unanchored scenarios lack observed outcomes to which to be calibrated. Mean commute speed is calculated as aggregate miles divided by aggregate drive time.

Alternative Assumptions and Metros	mean price of housing services						inner price of housing services					
	@tfp 0.90	**@tfp 0.95**	**@tfp 1.00**	**@tfp 1.05**	**@tfp 1.10**	**@tfp 1.15**	**@tfp 0.90**	**@tfp 0.95**	**@tfp 1.00**	**@tfp 1.05**	**@tfp 1.10**	**@tfp 1.15**
Baseline	**0.70**	**0.83**	**1.00**	**1.22**	**1.50**	1.82	**0.86**	**1.16**	**1.58**	**2.11**	**2.77**	3.55
Alt Assumptions												
fixed wrkhrs, $\text{Frisch}_{A,1}$=0.20	0.69	0.82	1.00	1.24	1.61	1.91	0.86	1.16	1.58	2.12	2.93	3.57
fixed wrkhrs, $\text{Frisch}_{A,1}$=0.10	0.65	0.79	1.00	1.28	1.65	2.11	0.85	1.18	1.62	2.18	2.87	3.69
rebate H factor incm	0.74	0.85	1.00	1.18	1.41	1.67	0.91	1.19	1.55	1.99	2.53	3.16
rebate X+H factor incm	0.82	0.90	1.00	1.12	1.25	1.41	1.01	1.22	1.47	1.76	2.09	2.47
endog CBD radius	0.68	0.82	1.00	1.21	1.45	1.73	0.82	1.16	1.58	2.09	2.70	3.41
Alternative Metros												
minimum speed 27 mph	0.70	0.83	1.00	1.25	1.56	1.92	0.86	1.16	1.58	2.08	2.68	3.36
constant speed 27 mph	0.72	0.86	1.06	1.31	1.61	1.95	0.90	1.21	1.61	2.10	2.69	3.37
constant speed 33 mph	0.71	0.85	1.04	1.28	1.57	1.91	0.89	1.19	1.58	2.06	2.63	3.30
constant speed 50 mph	0.70	0.83	1.01	1.23	1.50	1.82	0.86	1.15	1.52	1.98	2.52	3.16
σ_V=0.94 (0.92 in anchor)	0.70	0.83	1.00	1.23	1.50	1.82	0.86	1.15	1.55	2.06	2.68	3.42
σ_V=0.90 (0.92 in anchor)	0.70	0.82	1.00	1.22	1.49	1.84	0.86	1.17	1.60	2.16	2.85	3.65
4-day workweek	0.70	0.81	0.98	1.20	1.47	1.78	0.85	1.15	1.56	2.09	2.75	3.53
telecommute 1 day per wk	0.70	0.81	0.98	1.20	1.46	1.77	0.85	1.14	1.55	2.08	2.73	3.50
dist cost 50% above base	0.72	0.85	1.04	1.28	1.56	1.89	0.90	1.20	1.62	2.15	2.81	3.58
grwth bndry at anchor rad	-	-	1.00	1.30	1.63	2.00	-	-	1.58	2.12	2.78	3.56
perim L price 5x anchor	1.06	1.12	1.25	1.44	1.68	1.98	1.08	1.27	1.63	2.14	2.79	3.56
TFP varies for X & H	0.76	0.85	1.00	1.20	1.45	1.76	0.90	1.18	1.58	2.09	2.73	3.49
TFP varies for H only	1.05	1.02	1.00	0.98	0.96	0.94	1.61	1.59	1.58	1.56	1.55	1.53
Unanchored Systems												
λ=¾ (self-driving cars I)	0.75	0.85	1.00	1.20	1.44	1.74	0.85	1.10	1.45	1.90	2.47	3.15
λ=1@50→½@10mph (II)	0.77	0.86	1.00	1.19	1.43	1.71	0.85	1.09	1.45	1.92	2.52	3.25
σ_L=1.5, $\bar{\mu}_{L,A}$=0.35 (mf I)	0.66	0.79	1.00	1.36	1.92	2.23	0.81	1.09	1.46	1.86	2.17	2.27
σ_L=1.5,$\bar{\mu}_{L,A}$=0.35,5mph (mf II)	0.66	0.79	1.00	1.36	1.91	2.23	0.81	1.09	1.46	1.86	2.17	2.27

Table B.13: Housing Prices versus TFP. Alternative metro scenarios apply only to one or a handful of metros. Unanchored scenarios lack observed outcomes to which to be calibrated. For each scenario, the population-weighted mean price of housing in the anchor metro is normalized to 1.

Alternative Assumptions and Metros	mean price of land services						inner price of land services					
	@tfp 0.90	**@tfp 0.95**	**@tfp 1.00**	**@tfp 1.05**	**@tfp 1.10**	**@tfp 1.15**	**@tfp 0.90**	**@tfp 0.95**	**@tfp 1.00**	**@tfp 1.05**	**@tfp 1.10**	**@tfp 1.15**
Baseline	**0.31**	**0.54**	**1.00**	**1.86**	**3.34**	**5.75**	**0.56**	**1.30**	**2.95**	**6.23**	**12.11**	**21.84**
Alt Assumptions												
fixed wrkhrs, $\text{Frisch}_{A,1}$=0.20	0.30	0.53	1.00	1.91	4.03	6.38	0.55	1.29	2.95	6.25	13.80	22.03
fixed wrkhrs, $\text{Frisch}_{A,1}$=0.10	0.24	0.48	1.00	2.06	4.09	7.64	0.52	1.29	3.01	6.43	12.56	22.69
rebate H factor incm	0.37	0.59	1.00	1.69	2.82	4.56	0.67	1.40	2.86	5.49	9.92	16.92
rebate X+H factor incm	0.52	0.71	1.00	1.42	2.02	2.85	0.94	1.58	2.59	4.15	6.45	9.73
endog CBD radius	0.28	0.53	1.00	1.80	3.09	5.05	0.48	1.28	2.95	6.07	11.40	19.89
Alternative Metros												
minimum speed 27 mph	0.31	0.54	1.00	1.95	3.58	6.12	0.56	1.30	2.95	6.04	11.18	19.23
constant speed 27 mph	0.34	0.62	1.17	2.15	3.77	6.30	0.63	1.46	3.14	6.18	11.28	19.32
constant speed 33 mph	0.33	0.59	1.11	2.03	3.56	5.94	0.61	1.39	2.98	5.89	10.76	18.44
constant speed 50 mph	0.31	0.54	1.00	1.81	3.15	5.25	0.56	1.26	2.69	5.30	9.70	16.65
σ_V=0.94 (0.92 in anchor)	0.31	0.54	0.99	1.84	3.27	5.58	0.56	1.27	2.83	5.86	11.21	20.02
σ_V=0.90 (0.92 in anchor)	0.31	0.54	1.00	1.87	3.39	6.14	0.56	1.32	3.08	6.61	12.96	23.38
4-day workweek	0.30	0.51	0.95	1.77	3.19	5.51	0.53	1.25	2.87	6.11	11.95	21.63
telecommute 1 day per wk	0.30	0.51	0.94	1.74	3.14	5.40	0.53	1.23	2.82	5.98	11.69	21.17
dist cost 50% above base	0.33	0.60	1.12	2.07	3.68	6.24	0.62	1.43	3.18	6.56	12.53	22.35
grwth bndry at anchor rad	-	-	1.00	2.05	3.83	6.60	-	-	2.95	6.30	12.25	22.05
perim L price 5x anchor	0.99	1.18	1.64	2.53	4.04	6.48	1.06	1.67	3.24	6.47	12.31	22.02
TFP varies for X & H	0.28	0.50	1.00	2.03	4.02	7.58	0.47	1.17	2.95	6.90	14.75	29.03
TFP varies for H only	0.84	0.92	1.00	1.09	1.18	1.27	2.37	2.65	2.95	3.27	3.60	3.95
Unanchored Systems												
λ=¾ (self-driving cars I)	0.39	0.59	1.00	1.74	3.01	5.12	0.56	1.17	2.51	5.11	9.80	17.60
λ=1@50→½@10mph (II)	0.43	0.61	1.00	1.73	2.99	5.06	0.57	1.16	2.52	5.31	10.44	19.14
σ_L=1.5, $\bar{\mu}_{L,A}$=0.35 (mf I)	0.27	0.44	1.00	4.55	86	1,246	0.43	0.98	2.98	15.22	172	1,416
σ_L=1.5,$\bar{\mu}_{L,A}$=0.35,5mph (mf II)	0.27	0.44	1.00	4.55	86	1,265	0.43	0.98	2.98	15.22	169	1,372

Table B.14: Land Prices versus TFP. Alternative metro scenarios apply only to one or a handful of metros. Unanchored scenarios lack observed outcomes to which to be calibrated. For each scenario, the population-weighted mean price of land in the anchor metro is normalized to 1.