Habitat International 106 (2020) 102289

Contents lists available at ScienceDirect

Habitat International

journal homepage: http://www.elsevier.com/locate/habitatint

People or parking?

devin michelle bunten[a,*], Lyndsey Rolheiser[b,1]

[a] MIT, USA
[b] Ryerson University, Canada

ABSTRACT

Car-based transportation networks (as in Phoenix) necessitate parking at origin and destination in order to establish a link—but the space devoted to parking lowers its ability to provide housing and consumer amenities. Walking and transit networks (as in Manhattan) have no such tradeoff, and a city reliant on them will be able to make fuller use of its land for productive purposes like amenities and housing. However, they hinder mobility in other ways: walking does not get you far, and using transit requires adhering to the routes and stops the city's transit agency provides. In this paper, we develop and calibrate a spatial consumer city model to study what would happen if Phoenix *banned cars*, delineating the roles of parking conversion, of the light rail network, and of a last mile option. Together with a last mile option, Phoenix's current light rail line would be able to sustain a meaningful (if smaller) population—but only if Phoenix converts its current parking to other uses. We then ask the reverse: what would happen if Manhattan required parking? The model indicates the island would essentially empty, as the declining capacity of each block lowers the vibrancy of the city, inducing still more residents to leave. Altogether, these model outcomes tell a story of agglomeration through complementarities. The transportation network and incumbent land use must ensure a high degree of access to jobs and amenities in order for enough people to choose to live in the city and thereby support those amenities.

1. Introduction

Cities across the U.S. have responded to the COVID-19 pandemic by encouraging outdoor dining, even converting street and parking space into restaurant seating.[2] Restaurateurs face a tradeoff when pursuing customers: offer safe outdoor dining, or offer parking. Scaled to the city as a whole, this question remains salient even outside of pandemics. Should a city ensure that parking is readily available or ensure that more space is devoted to useful ends like amenities and housing? Manhattan has taken the latter choice, with plentiful amenities and dense housing throughout its 22.8 square miles. Phoenix, Arizona, has taken the first choice. Despite having the same population as Manhattan—1.6 million people—Phoenix covers 23 *times* more territory. It has approximately 50 square miles—more than two Manhattans—of parking, and another 130 square miles of roadways (Hoehne et al., 2019).

This car-oriented lifestyle socially and environmentally devastating. Cars kill 40,000 people on the streets (and sidewalks) of America every year; the air pollution generated by vehicles kills another 50,000 while also generating non-lethal health problems.[3] Remediating these harms—or, in countries where car use is rising, preventing them—is a central challenge for urban planners today. The heart of the challenge is the same as that facing restaurants: removing parking can make way for more useful activities, but this can only work if sufficient customers can visit without driving. In turn, this requires intense residential development (perhaps on other nearby parking lots), a mass transit option serving the area, or both.

In this paper, we investigate the dual roles of the transportation network and the land it uses. Phoenix's car-based network necessitates available parking at the origin and destination in order to establish a link between two locations. But setting aside that space for car storage requires lowering the capacity of the location to provide residential and commercial activity like retail amenities. An additional parking lot in Phoenix thus improves *mobility*, as drivers find it easier to move about the city, but diminishes *accessibility* by sacrificing space that could have

---

* Corresponding author.
E-mail address: dmbdmb@mit.edu (bunten).

[1] We are co-lead authors. We are grateful for helpful feedback from Jinhua Zhao, Siqi Zheng, Rucha Mehendale, Chris Severen, and three anonymous referees. We thank Rucha Mehendale, Devin Kelly, and Michelle Mueller Gámez for valuable research assistance. The title owes to a question posed by Toronto housing activist Mark Richardson as reported by the CBC. All remaining errors are our own.

[2] For example, Los Angeles (https://www.latimes.com/california/story/2020-08-02/dining-al-fresco-coronavirus-los-angeles-long-beach-burbank-pasadena-torrance)and New York (https://www.nytimes.com/2020/09/25/nyregion/nyc-outdoor-dining-restaurants.html).

[3] See https://www.nsc.org/road-safety/safety-topics/fatality-estimates for data on traffic fatalities, Caiazzo et al. (2013) for details on traffic-related pollution fatalities, and Kim et al. (2015) for more on the health impacts. Shill (2020) offers a useful overview of the this devestation in the context of the law and policy roots of "automobile supremacy".

https://doi.org/10.1016/j.habitatint.2020.102289
Received 16 September 2019; Received in revised form 13 October 2020; Accepted 6 November 2020

gone to amenities or housing.[4] Manhattan's train-based network, by contrast, requires little parking and thus leaves the land available for other uses. The resulting intensive residential and commercial development makes for easy access to most needs, despite the more-limited mobility provided by transit.

The dramatic divergence between the two city types suggests that the land used directly by transportation networks induces a complementarity between transportation mode and the land used *by* the vehicles for moving and for storage. In this paper, we investigate these complementarities and ask whether the space required by automobile parking limits the ability of a car-based city to provide a walkable and vibrant urban neighborhoods. To address this question, we develop a spatial consumer city model and embed a tradeoff: the use of a car-based network entails devoting a significant fraction of built-up space to parking, rather than to amenities or to residential space. In contrast, the use of a transit network entails no parking, but restricts mobility as households' long-distance travel becomes limited in practice to locations with transit stations.[5] Once we develop the model, we calibrate it to a pair of starkly contrasting geographies: a transit city calibrated to Manhattan data, and a driving city calibrated to Phoenix data.

We use the quantitative version of the model to address the importance of parking to urban vibrancy by jointly manipulating the transportation network and parking requirements, and evaluating the resulting equilibrium. With the Phoenix model, we begin by removing the possibility of car-based travel entirely. Conceptually, this frees up all parking-related land for other uses. From there, we change (1) the transportation network, (2) the land devoted to parking, or (3) both. While this counterfactual has the shape of a policy question, the inquiry is conceptual: We aim to bring the space used by cars into direct conversation with their mobility implications. To that end, we introduce scooters as a decentralized last-mile option that mimics the *anywhere-to-anywhere* mobility patterns of cars while requiring a tiny fraction of the storage space. Households in the model will leave this *open city* if its quality of life falls, making the new population our main outcome of interest in these counterfactuals.

We show that the mobility offered by the transportation network and the land that once went to parking are both essential, indicating a fundamental complementarity between transportation and land use. A car-free Phoenix will only retain a meaningful population if it retains its light rail network, adds a last-mile solution, and fills in its parking with new housing and amenities. If any one of those features is absent, the city will lose 90–99% of its population, signifying a collapse in the ability of the city to provide a meaningful standard of living.

In the first counterfactual, we investigate complementarities between Phoenix's existing light rail line and a last-mile option connecting light rail stops to surrounding locations.[6] This allows us to vary the scale of the mobility reduction implied by removal of the car network while still making fully available the land once used for parking cars.[7] We calibrate the last-mile option to the scooter, a low-cost option spreading in cities like Phoenix. Under our calibration, the last-mile option is a necessity: without it, a car-free Phoenix sees a 99% reduction in its population. While necessary, the scooter is insufficient alone. Without the existing train, scooters struggle to provide long-distance trips, limiting accessibility in all locations and inducing a 94% in population relative to the baseline.[8] In contrast, a city with trains, scooters, and densified parking spaces is able to retain about 300,000 residents, or over 20% of the baseline population. The importance of scooters in particular is a classic network effect: as new connections are made feasible, they serve as both a residential location for new residents as well as a new amenity destination for existing residents.

In the second counterfactual, we turn to the relevance of land devoted to parking. We investigate the resulting population if the city bans cars, installs scooters, keeps the light rail—but neglects to fill in the former parking spaces with residential or amenity uses. In this case, the city population plummets to essentially zero. Even with scooters, the transit network is incapable of sustaining a meaningful population in any location without the densification offered by former parking. This suggests that parking, while necessary to support a car-based lifestyle, is a tremendous deterrent to urban vibrancy. The exact same transportation network—scooters and a single train—is capable of providing for a small city, but *if and only if* the parking can be adapted to other uses.

We then investigate further complementarities embedded within the above scenarios. We show that filling in residential parking (but not at amenity destinations) is insufficient to provide for a meaningful population, as is the reverse. Instead, densification must be allowed to occur at both ends. Next, we investigate whether the last mile option is important for work trips, for amenity trips, or both. Again, the answer is both: although work trips are somewhat more important. In both cases the combined effect is multiplicative rather than merely additive. These multiplicative effects suggest complementary roles where two aspects are jointly central to supporting the outcome.

Finally, we investigate the opposite case: what happens if you require parking at residences and amenities in Manhattan? To a first order approximation, the city disappears: only 1000 residents are left in our calibration.[9] We also model the removal of the subway system from Manhattan. In this case, about 100,000 residents choose to remain even when forced to walk to work and amenities. This somewhat smaller decline highlights again the large relative effects of parking provision as a loss of useable space.

Contributions in context of the literature In this paper, we focus on parking as a way to understand the land use of transportation infrastructure, which we argue is central to a complementarity between land use and transport mode. The necessity of parking to facilitate mobility via cars introduces a fundamental mobility/access tradeoff in

---

[4] Ride hailing and autonomous vehicles may render the dependence of cars on *parking* moot—someday. But even these car-share options use a much larger amount of land than do trains, buses, or scooters—while the vehicle is in motion. In this paper, we do not model car congestion, and so we do not investigate the ability of car-share (or other interventions, like toll roads or congestion taxes) to reduce the land used by cars.

[5] We embed this tradeoff in an otherwise straightforward urban economic spatial model. Households commute to work in the central business district, and they value access to a variety of amenities dispersed throughout the city. Because households value variety in amenity experiences, they value access to a large number of locations. This contrasts with traditional urban models, wherein a household's sole trip is a commute to the same destination. The dispersed nature of amenities is thus important for the network analysis. Developers construct housing in competitive markets, and households are free to live in any location and are also free to leave the city entirely.

[6] Walking is always an option, but it is costly in terms of time taken.

[7] A city with somewhat more light rail and somewhat fewer cars—a more viable policy proposal, to be sure—continues to vary both aspects simultaneously, reducing insight for the sake of realism.

[8] In contrast to scooters, we could have explored introducing more transit lines. We pursued the scooter assumption for two reasons. Most fundamentally, we contrast Phoenix to Manhattan in this paper because Manhattan is a city with the same population built around a massive subway network and thus serves as the ultimate transit-oriented counterfactual. Second, the scooter is a straightforward way to vary the reduction in mobility while holding fixed the ability to re-use parking lots. Our goal is not to evaluate a promising policy proposal to ban cars in Phoenix, which would absolutely require investment in transit.

[9] Note that we don't model the introduction of a driving possibility—only the introduction of parking spaces—so this is somewhat of a lower bound. That said, Manhattan contains approximately 4% of the land area of car-based Phoenix, so this estimate may not be too far off.

cities organized around driving, in contrast to those organized primarily around transit and walking. These features are usually not considered simultaneously (e.g., Nelson et al. (2010)). We make this theoretical contribution in the context of the urban gravity models gaining popularity within economics (e.g., Ahlfeldt et al., 2015; Rossi-Hansberg, 2005; Tsivanidis, 2018). These models generally focus on commuting flows, and firm agglomeration, two features that tend to reflect urban spatial structure (Sohn, 2005). Like Allen et al. (2016), we consider trips to amenities, for which households value access to many locations(Deng & Srinivasan, 2016; Li et al., 2019).

Our paper builds on a growing literature investigating parking that regards parking "not as a residual space of our built world, but as an integral part of it" (Ben-Joseph, 2012). In a similar vein Crockett (2018) and Brinkman & Lin (2019) both investigate the land used directly by transportation infrastructure — in their case highways. Focusing on parking, Shoup (2005) finds that the availability of parking and bundled parking regulation skews mode choice towards driving, while Manville (2020), chap. 13 argues this is true even in dense cities. Parking policies are intimately related to retail productivity (Ersoy et al., 2016; Manville, 2020, chap. 13) as well as urban growth (Zacharias, 2012). Like our paper, Chester et al. (2015) suggest that parking infrastructure presents an opportunity for redevelopment to more attractive uses, although they emphasize the redevelopment option and possibility *per se*. We focus on the ensuing equilibrium after redevelopment, and so do not consider the option value of holding a parking lot for the point of optimal return. We add to this conversation by embedding parking within a more general model of transportation networks that connects parking with transportation issues like access to amenities and last mile solutions.

Existing literature on the relationship between retail firm location and transportation infrastructure primarily concerns road networks treating proximity to major infrastructure as an exogenous amenity (Kawamura, 2001; Nilsson & Smirnov, 2016) or examining the role of traffic congestion on location decisions (Hou, 2016). Our model considers the impacts of both road and transit systems on household location decisions. Our focus on the different geographies generated by different transportation modes speaks to the effects of patterns of development on cost structures beyond the straightforward effects of density (Rolheiser & Dai, 2019, pp. 1–27). Our paper also relates to Anas and Kim (1996), who model the relationship between consumer amenities and the transportation network. They focus on firm decisions and their main transportation component is the incorporation of traffic congestion, while we focus on the land used by transportation and its implications for residential development and resultant amenity spillovers.[10]

Additionally, we connect to the literature on light rail, transit-oriented development (TOD), and parking (e.g. Baum-Snow et al., 2005, pp. 147–206; Ingvardson & Nielsen, 2018; Knowles & Ferbrache, 2016; Nilsson & Smirnov, 2016). A central question in this literature has been the effects of light rail on mode choice. In terms of traffic, decelerating increases in congestion have been observed (Bhattacharjee & Goetz, 2012; Ingvardson & Nielsen, 2018). The source of the new light rail ridership is contentious because it often runs alongside or replaces existing bus service (Werner et al., 2016; Lee & Senior, 2013). Lee et al. (2017) finds variable effects of light rail on bus ridership, and note that longer-term land use changes *could* sustain or further the observed shifts in mode choice. However, Severen (2019) argues that only limited shifts have taken place, a fact that bunten (2017) suggests is due to the political power of pre-existing residents. For non-work trip mode choice, factors include neighborhood land use and on-site parking supply (Cervero & Radisch, 1996; Weinberger, 2012). Kahn (2007) shows that park-and-ride stations are valued less than "walk-and-ride" stations. We emphasize the shortcomings of small light rail networks in providing access to a substantial range of urban amenities.

Finally, we contribute to an emerging literature on scooters (e.g. Aguilera-García et al., 2020; McKenzie, 2019) and the potential of shared mobility services to act as last-mile modes (DeMaio, 2009; Yan et al., 2019). Unlike cars, shared dockless scooters can readily be parked in large quantities at or near transit stations, making them a more space efficient last-mile mode choice (Shaheen & Chan, 2016). In contrast to most of this nascent literature, we emphasize the follow-on effects on land use that could result from the widespread adoption of scooters.

2. A spatial model of a consumer city

This section briefly describes our spatial consumer city model.[11] Following such lights as Fujita, Krugman, & Venables, 1999, we assume that households prefer to have a wide variety of consumer amenity experiences. To access these amenities and fulfill these preferences, and thus enjoy the abundance of urban joys, households must travel to a variety of locations. This stands in contrast to the classical urban models of Alonso (1964), Mills (1967), and Muth (1969). These classics model a *commuter* city: households take a single trip to work at a single central business district (CBD), and a single trip home. In these models, the "network" can be collapsed to a line segment. While our households also travel to work in a CBD, pulling focus from their trips to work onto their trips for amenities places the urban network *as a network* in sharper relief. A single transit line will impose strong restrictions on households' ability to access amenities in locations off the line, and lower their enjoyment of the city.

Constructing a model with a fully-fledged network requires specifying the network's different modes, such as cars, mass transit, walking, and scooters. These different modes have different requirements in terms of the land they use.[12] A driving city's flexible network is entailed with parking lots, which diminish the share of land available to amenities and to residential use. A transit city's more rigid and limited network, by contrast, enables the full use of land for either amenities or residential purposes—but may not reach as many locations.

Against the transportation network, we model a fairly traditional household. We assume households choose where to live, and that they have preferences over a basic consumption good, house size, and amenities. As with the classics, we model a single central employment district. Workers commute to the CBD, and they use the income they earn for travel (to work and to amenities), for consumption, and to purchase housing. Households living close to the CBD will have higher discretionary income for consumption, housing, and travel to amenities—and in equilibrium, these gains will be offset by higher rents.

We pursue a similarly straightforward approach to modeling amenities in each neighborhood. The amenity level of a location depends on three features. First, we assume that locations vary in their baseline ability to produce amenities; we use data to inform our calibration of these values (described in the next section). Then, we assume that amenities are subject to positive spillovers between locations within a short distance. Finally, we assume that this spillover relationship is

---

[10] It would be interesting to incorporate endogenous traffic congestion into our model. Indeed, congestion reflects the same complementarity between land use and transportation mode: the low threshold for congestibility of automobile traffic necessitates a tremendous amount of land being devoted to roadways—hence Phoenix's over 100 *square* miles of roadway. Low population density is a necessity for a car-based city not just because of parking, but because of congestion. Nevertheless, we view our channel as important and worth highlighting in its own right, especially given the theoretic and computation burden of incorporating congestion into the gravity model.

[11] The full model is detailed in the appendix.

[12] Of course, different modes and network structures will also make locations differentially attractive to investment, as in the traditional monocentric city model.

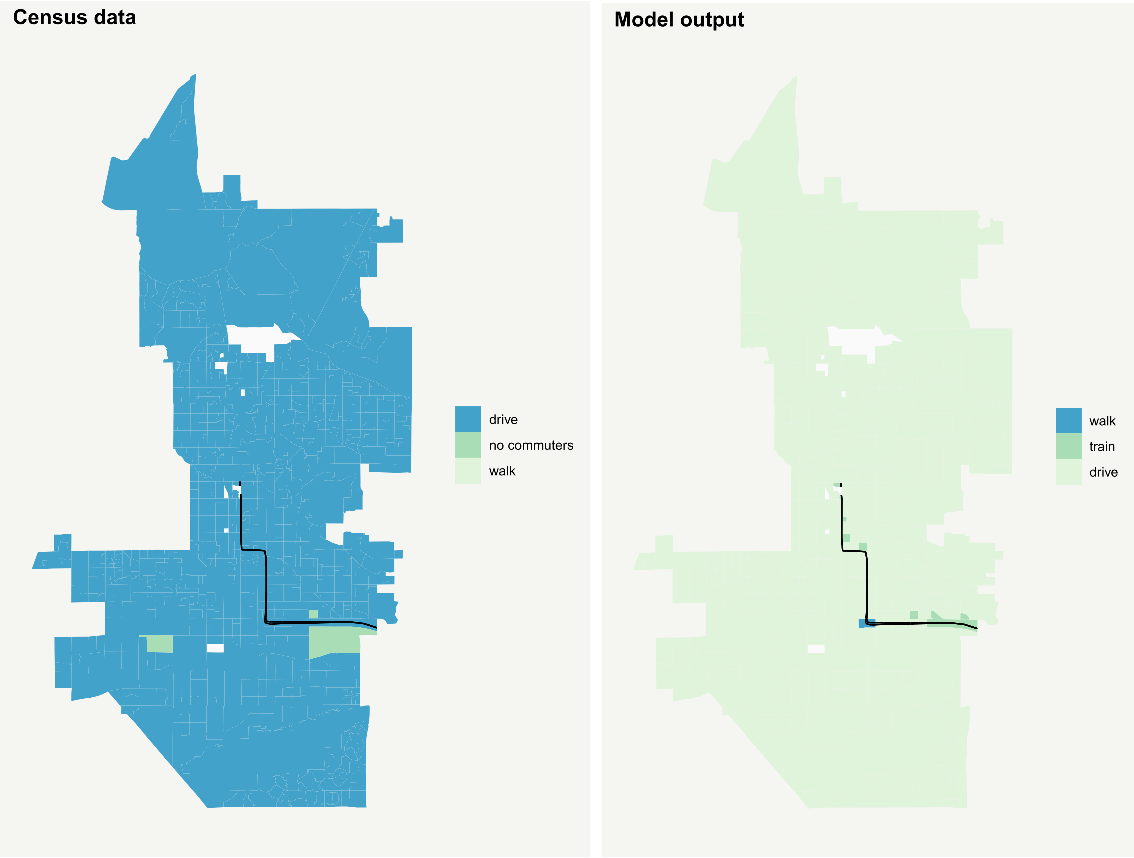


Fig. 1. Phoenix commuting mode choice.

stronger when the neighbouring location has a larger residential population.[13]

In the next section, we describe our calibration of key model elements: the transportation network itself, and the spatial distribution of amenities and construction productivity. We then study the equilibria that would emerge if the city modified its transportation network. Our focus is on the tradeoff between the ability of the network to provide widespread access and the amount of land devoted to transportation infrastructure, i.e. parking.

3. Data and calibration

The goal of the calibration is to build a quantitative version of the model that captures key features of the real world. This requires two steps. First, we try to identify as many model parameters either directly from the world or indirectly through existing empirical research. The former process includes the construction of transportation costs, which are directly measured. The latter process includes estimates of the housing cost function, which we take from existing research.

Note that we are unable to identify all model parameters in this fashion. Notably, location-specific parameters like construction productivity, which may vary according to regulatory or geographic factors, are unobservable. It is precisely these parameters that we seek to identify using our calibration. To perform the calibration, we identify a set of equations corresponding to the model's equilibrium. These equations provide relationships between our unknown parameters and observed equilibrium objects (such as population and housing square footage). By collecting data for the empirical counterparts of these equilibrium objects, we can use the equations to solve for the unknown parameters. This is the second step of our calibration process.

At the end of the process, we will have a quantitative value for every parameter in the model, whether by direct observation, by citation, or by calibration. We can then set about doing the interesting work: evaluating how the model equilibrium values change when you alter key parameters. In particular, we will investigate the change in population density across locations when the transportation network changes.

Explicit details regarding the data sources used in the construction of the travel cost parameters, the methodology used in the construction of the transportation networks for Phoenix and Manhattan, the description of additional variables required for calibration (population, income, housing and land use), and the steps of the calibration itself can be found in Appendix A and B. We omit the details here for brevity.

Using our simplified models of Phoenix and Manhattan, in the next section we explore how well the constructed transportation networks for each city models actual commuting mode choice and how well the residential rent outputted by the calibrated model matches rent observed in census data.

3.1. *Model output versus census data*

Beginning with commute mode, Figs. 1 and 2 present visual checks for how well the mode choices implied by the constructed travel cost matrices represent actual mode choice in Phoenix and Manhattan. Commute mode from the 2013–2017 American Community Survey based on the relative majority mode choice for each census block group is mapped next to least-cost commute mode based on the constructed travel cost matrix.

Phoenix is predominantly a driving city. This is well represented within the travel cost matrix. However, under the assumption of a single employment location, the travel cost matrix identifies walking as the

---

[13] This model feature captures the notion of an *amenity-* or *nightlife-district*, where the proximity to other consumers makes a place more attractive.

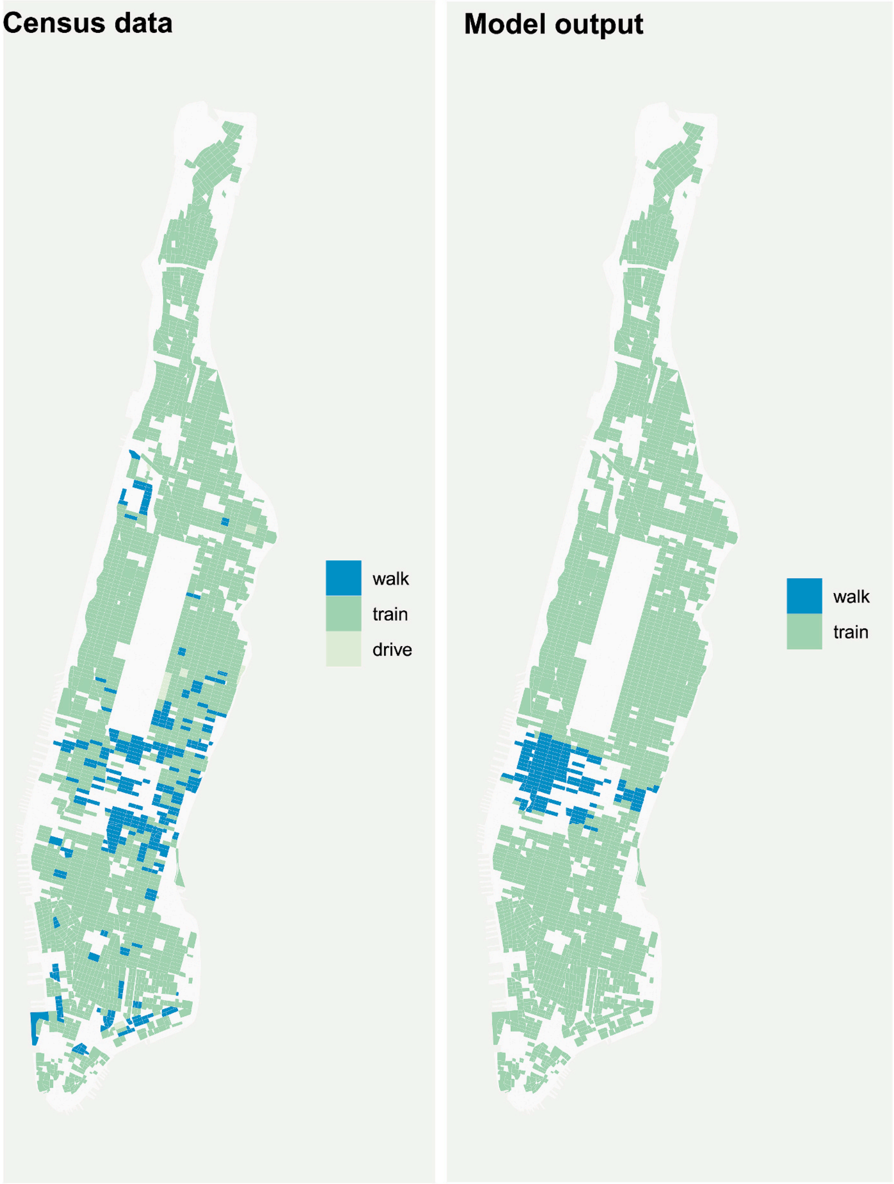


Fig. 2. Manhattan commuting mode choice.

least-cost mode choice at the CBD with the train as the mode choice for a few locations along the LRT line. From the census data, walking is the dominate mode choice for only one block group. This small block group is difficult to see in the figure; it is adjacent to the LRT line towards the northern end. Of the 40 commuters in this block group, 28 walk and 18 drive. Block groups with no commuters represent large commercial and industrial locations—the Phoenix International Airport, a medical center, a prison, and a large industrial park.

The central employment assumption is more applicable to Manhattan which has two main employment locations (Midtown and Downtown); Midtown being the larger of the two. We see this clearly displayed in the left panel of Fig. 2 with a large cluster of walking commuters in Midtown. This pattern is mimicked within the mode choices generated by the travel cost matrix. We do not model driving in Manhattan although there are a handful of high income block groups where driving is the dominant mode within the census data.

Median monthly gross rent at the block group level from the 2013–2017 ACS is mapped next to rent outputted by the model in Figs. 3 and 4.[14] Spatial rent patterns produced by the model follow closely with an expected rent gradient based on the monocentric city—highest rents at the CBD, decreasing towards the periphery. Again, monocentric city assumptions fail to capture the true rent pattern observed in Phoenix. Namely, higher rents exist in suburban and exurban block groups. Proximity to large nature preserves is also associated with higher rents.[15]

The overall spatial pattern of rent in Manhattan fits the census data quite well. However, the range of rents predicted by the model is much smaller. The lower rents present in the census are likely associated with rent control or subsidized rent. The extremely high rents may be associated with local amenity features our model is unable to capture.

At the aggregate level, the model fits the data relatively well. Mean gross rent across all block groups from the model output is $899 for

---

[14] Grey block groups represent missing rent data within the census.

[15] We do not model proximity to natural amenities given limited data availability with respect to park locations within Phoenix.

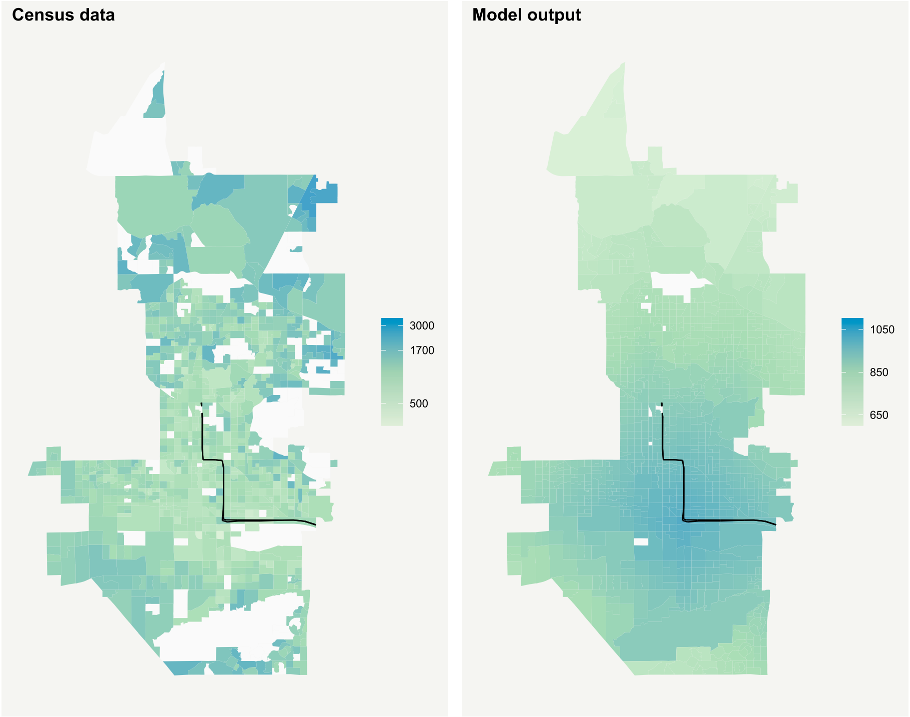


Fig. 3. Phoenix median residential rent per unit per month.

Phoenix and $1,658 for Manhattan. From the census data it is $1,153 and $1,977. Taking the ratio of Phoenix to Manhattan rent for both the output and the census gives ratios of 0.54 and 0.58. Thus, modelgenerated rents fairly accurately represent the overall rent differential between the two cities.

A supplementary investigation of spatial income gradients is included in Appendix C. Visual descriptives of the two cities highlight the model's ability to capture complex spatial patterns with respect to income net of commuting costs. Unsurprisingly, the gradient is relatively flat when driving is allowed in the Phoenix model. For Manhattan, the combination of the train network and walking produces a similarly flat gradient. Together, these images demonstrate the equitable accessibility provided by two very different networks in two very different cities. Removing these dominate transportation networks in each city highlights the difference in land use patterns: Manhattan as a relatively walkable compact city, Phoenix as a city with no meaningful alternative to driving to traverse it's expansive area. Specifically, removing driving from Phoenix produces a steep and concentrated gradient emanating from the light rail network. The gradient is dampened somewhat with the inclusion of scooters given their cheap anywhere-to-anywhere capabilities. Removing the train network from Manhattan, the gradient remains nearly identical for locations near Midtown at 42^{nd} Street and 6^{th} Avenue (Bryant Park) where households choose to walk regardless of the presence of a train network. Net incomes decline somewhat for those living downtown and more so for those living at the fringes of uptown.

4. Results

4.1. What happens if Phoenix bans cars?

In this section, we use the calibrated model to study what would happen if Phoenix removed its car-based transportation network and simultaneously allowed its parking lots and driveways to be used for amenity and residential purposes. To understand their effects, we vary each of these elements in turn.

Unsurprisingly, the city population falls under all scenarios. However, we show that the scale of the drop-off depends on the interplay between transportation modes and the land they require. Adding last-mile solutions to light rail *and* converting former parking into residential and amenity uses makes feasible the preservation of a meaningful population in the car-free city. Neither is sufficient alone. Instead, we find evidence that there are complementarities between transportation and land use. The scale of the transit network is insufficient to generate enough homes and amenities without converting parking to other uses. But densification is insufficient without ensuring that a wide range of places are reachable for commuting and shopping opportunities. Changes to both the network and the land use of transportation together are able to sustain a sizeable urban population in the absence of cars.

4.1.1. Last-mile problems: complementarities between scooters and light rail

Fig. 5 shows four maps of population density in Phoenix. The upper left panel shows the observed data, derived from a world where most people drive for most trips, although walking and light rail do exist. Moving to the upper right panel, we show the equilibrium population density in an alternative scenario where cars are no longer available, and residents rely on the light rail or their feet. Moving to the lower left panel, we show density under the scenario of scooters or walking only, but no light rail. Finally, the lower right panel introduces both changes: light rail and scooters can both be used, either alone or in tandem. In each of the three alternative scenarios, residential and amenity uses are now more productive: no space must be set aside for parking.

As noted above, the total city population declines in all cases. However, the magnitude of the decline depends on the scale of the transportation network. The current light rail alone covers a relatively small fraction of the territory of Phoenix, and at relatively low travel frequencies—compared to, say, the dense network of Manhattan. Relying on this alone, as in the upper right panel, means households choose to cluster mostly along the line. Similarly, relying on the scooter alone (bottom left panel), provides insufficient coverage to retain households throughout most of the city. In both cases, the decline is precipitous: a 95–99% decline in the urban population.

The combination of scooters with the light rail network leads to a different outcome (bottom right panel of Fig. 5). On the commuting side, scooters serve as a last-mile solution that extends the reach of the light

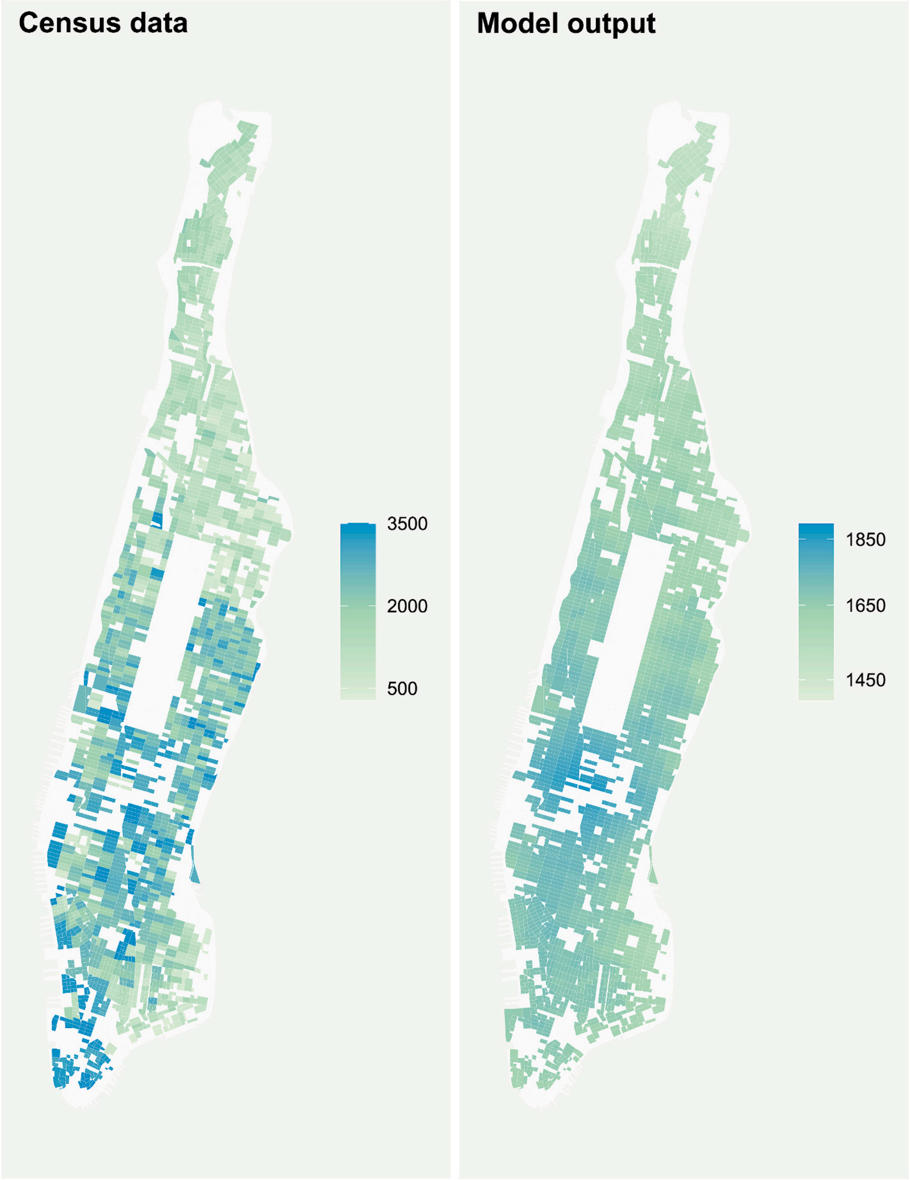


Fig. 4. Manhattan median residential rent per unit per month.

rail network beyond the extant line. This raises incomes net of commuting costs. However, the scooter also has an important effect on access to amenities. This is visible in (for instance) the densification of neighborhoods that are adjacent to light rail stops. Commuters are not taking the scooter there, but they are using it for some fraction of trips to amenities in locations that are beyond the reach of the train. Similarly, comparing the bottom two panels, densification of areas far from the rail road reflects the role the light rail plays in shopping trips even when scooters or walking are the commute mode. Altogether, this tells a story of agglomeration through complementarities: the transportation network must provide scale in job access to ensure scale in amenities.

4.1.2. Densification: complementarities between the network and land use of transportation

Next, we turn to the role of the land used in transportation. Specifically, we investigate conversion into residential and amenity uses of space that would have gone to parking in a car-based city. In terms of the model, we are varying ψ^{DR} from its baseline calibrated value of 0.65 and setting it equal to 1 in either residential construction, in amenity provision, or both.

We show population density under these different scenarios in Fig. 6. In all four panels, we use the transportation network with both scooters and light rail. The degree of parking conversion is the only variable changing across the four panels. In the upper left panel, we show population densities in a city where parking spaces are retained at both residential and amenity locations—despite the switch to light rail and scooters. Under this scenario, the city is effectively empty. In the upper right panel, we set $\psi^{DR} = 1$ for residential uses only; in the bottom left panel, we set $\psi^{DR} = 1$ for amenities only. In both of these cases, the new city population is less than 1% of the baseline scenario. The bottom right panel repeats the previous figure: $\psi^{DR} = 1$ for both uses alongside a scooter-and-train transportation network.

Only this final case corresponds to a meaningful population still remaining in the city: 348,000. This is an order of magnitude (or more) larger than the other three scenarios. This difference is driven not by land availability *per se*, but rather by a positive feedback loop between land availability, population, and urban amenities.[16] The presence of more land for population and amenities encourages growth in both. This growth increases the attractiveness of the city still more, until eventually the costs of construction are sufficiently high to quell the feedback loop. This scenario points towards an important complementarity between the urban amenities that enable population growth and the land *used by* transportation for parking.

4.1.3. Complementarities between last-mile solutions for work and for amenities

Next, we investigate whether the role of the last-mile transportation solution is important because it brings more locations into feasible commuting distance, feasible amenity-shopping distance, or both. In line with the previous cases, the answer is a clear both—and both together have a greater impact than either alone. These scenarios are shown in Fig. 7.

Starting from the top left, this first panel reproduces the outcome with trains (and walking) but no parking provided. There is substantial densification around a few light-rail stations, but the overall effect is a 99% decline in population for the city as a whole. Moving across to the top-right panel, we introduce the option of using a scooter as a last-mile solution—but only for shopping trips. Moving to the bottom-left panel, we can see that the introduction of last-mile options for commuting plays a much larger role. In both cases, scooters for one type of trip are able to offer a meaningful expansion of population.

Moving to the bottom right panel, we see repeated the case where scooters (and trains) are available for both kinds of trip. This panel makes clear there remains a strong role for complementarities between last-mile solutions for work and for amenity access. The effect of the scooters for shopping and for commuting are much larger than additive.

4.2. Manhattan

To further investigate the role of parking, we now consider three scenarios with our Manhattan model, calibrated to data from Manhattan. First is the baseline scenario. In this model, the baseline includes transit and walking options, and no parking is required at either residential or amenity uses. Second, we consider the effects of eliminating the subway system, while still allowing walking and requiring no parking. Finally, we consider a scenario with the baseline transit network, but now with parking requirements: $\psi_A = \psi_b = 0.65$, as in the calibrated Phoenix model. In line with the scenarios in Phoenix, this last counterfactual highlights the role of parking in reducing the capacity of a city block in providing residential and amenity space.[17] These scenarios are shown in Fig. 8.

The left panel shows the baseline population density observed in the world. Of course, densities are quite high in Manhattan.[18] The middle panel shows the population densities under a no-subway scenario, where walking is the only means of transportation for both commuting and shopping. In contrast to Phoenix, there are enough blocks within close range of Midtown Manhattan—and baseline incomes are high enough—that the city still retains a small population. The population is clustered around the business district, with essentially zero residents remaining in northern Manhattan neighborhoods like Inwood.[19]

The right panel shows the final counterfactual: what if residential and amenity uses in Manhattan were burdened with the provision of parking, as they are in Phoenix? This highlights the key question of this paper in a new way: what are the land-use implications of different transportation modes? Even retaining the high-quality subway network of Manhattan, the devotion of space to parking more than decimates the urban population. In this scenario, Manhattan is empty. The provision of parking would be so detrimental to life in Manhattan that the lowered density would start a vicious cycle of declining amenities and then declining population that would only stabilize after most of the population was elsewhere.[20]

5. Conclusions

The evidence we provide of complementaries hints at open planning possibilities. Indeed, planning is necessary: transforming parking into homes and shops will reduce mobility—unless transit fills in the gaps. Building transit while retaining parking means insufficient use to capitalize on the investment (see Severen, 2019).

In our paper, we focus on the outcomes of several counterfactuals oriented around a single possibility: banning cars from Phoenix, reverting to a transit (and scooter) network, and densification of former parking spaces. We pursue this stylized scenario as it places land use/transportation complementarities into stark relief. The counterfactuals are not intended as a policy recommendation.[21]

And yet. We do not attempt a full accounting of the benefits of a city

---

[16] Note that the income (net of commuting costs) of each location is identical across all four scenarios.

[17] Of course, parking can also improve access by car-driving households; we do not model this feature in Manhattan.

[18] As before, the grey-colored blocks are those with zero residential population and/or zero residential building square footage. These areas are principally parks or business districts.

[19] As of 1790, the walking city of New York—although clustered around downtown, not midtown—had a population of 30,000.

[20] Granted, we don't figure in the possibility that declining traffic makes it easier to get around by car than by subway. Our finding overstates the decline. However, a decline sufficient to bring Phoenix population densities to Manhattan would still leave the population of the island with about 4% of its original inhabitants—a few tens of thousands. Although, the limited geography of the city would mean car mobility would not be as attractive as in Phoenix, providing access to only 23 square miles of destinations rather than 517; this would push down on the likely population in a car-based counterfactual.

[21] While policies of banning cars (or at least, private automobiles) have been pursued in several major cities (e.g. https://www.businessinsider.com/cities-going-car-free-ban-2017-8), these policies generally are accompanied by existing and new interventions supplementing non-car transportation. Abandoning cars without building new transit in Phoenix would not be supportive of continued human habitation in the Valley of the Sun.

[16] Note that the income (net of commuting costs) of each location is identical across all four scenarios.

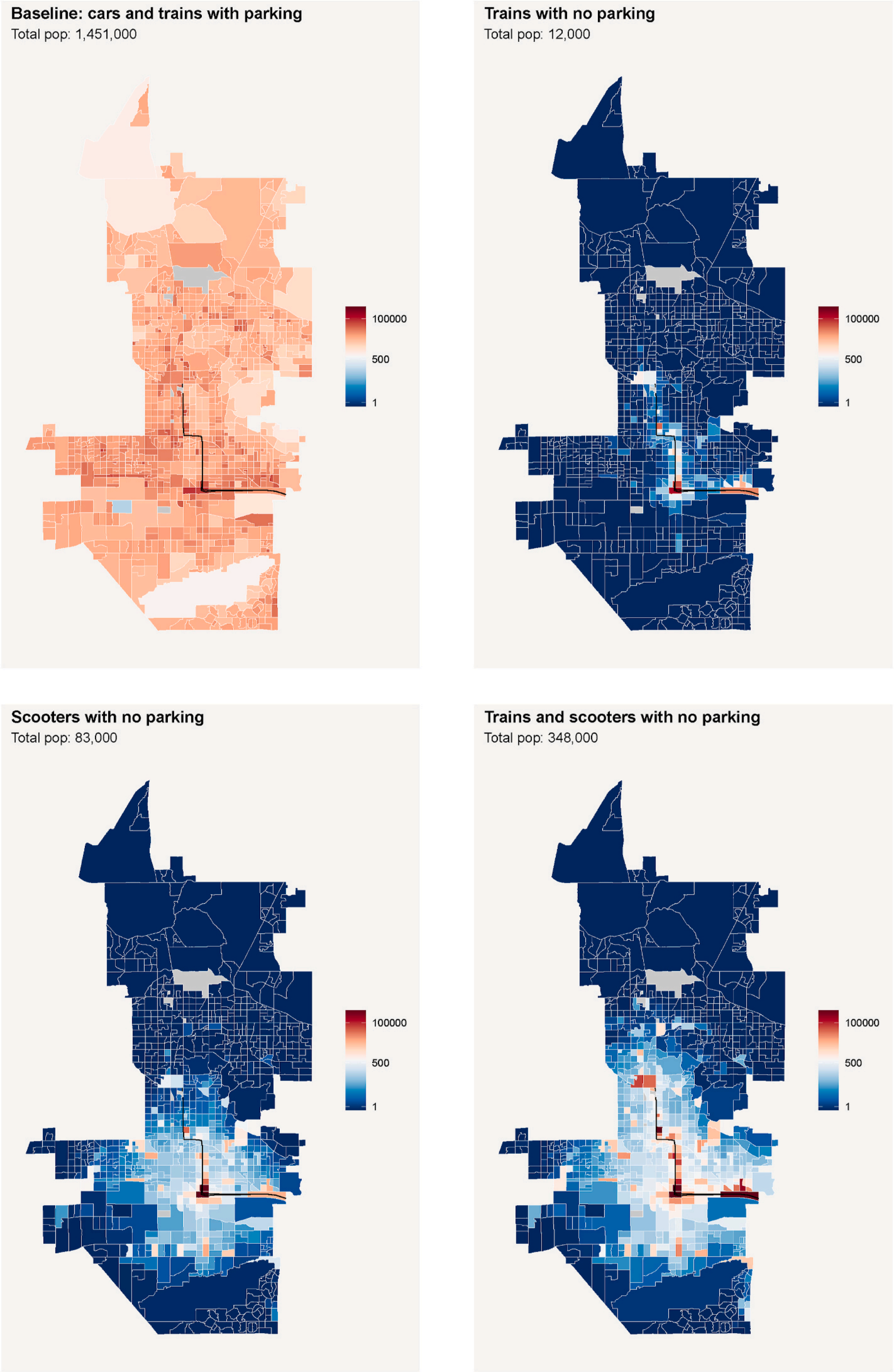
[17] Of course, parking can also improve access by car-driving households; we do not model this feature in Manhattan.

[18] As before, the grey-colored blocks are those with zero residential population and/or zero residential building square footage. These areas are principally parks or business districts.

[19] As of 1790, the walking city of New York—although clustered around downtown, not midtown—had a population of 30,000.

[20] Granted, we don't figure in the possibility that declining traffic makes it easier to get around by car than by subway. Our finding overstates the decline. However, a decline sufficient to bring Phoenix population densities to Manhattan would still leave the population of the island with about 4% of its original inhabitants—a few tens of thousands. Although, the limited geography of the city would mean car mobility would not be as attractive as in Phoenix, providing access to only 23 square miles of destinations rather than 517; this would push down on the likely population in a car-based counterfactual.

[21] While policies of banning cars (or at least, private automobiles) have been pursued in several major cities (e.g. https://www.businessinsider.com/cities-going-car-free-ban-2017-8), these policies generally are accompanied by existing and new interventions supplementing non-car transportation. Abandoning cars without building new transit in Phoenix would not be supportive of continued human habitation in the Valley of the Sun.



Baseline: cars and trains with parking
Total pop: 1,451,000

Trains with no parking
Total pop: 12,000

Scooters with no parking
Total pop: 83,000

Trains and scooters with no parking
Total pop: 348,000

Fig. 5. Phoenix density under the baseline and counterfactuals. In the baseline case, densities are uniformly above 500 people per square mile. In the other cases, densities in outlying areas are essentially zero while densities at the CBD and, in some cases, along the light-rail line are well above 500 people per square mile.

shifting from driving to transit, but some benefits of doing so are quite plain. One such dimension is environmental. Glaeser and Kahn (2010), among others, provide evidence that denser urban areas, with their associated smaller apartments and smaller share of driving trips, enjoy lower greenhouse gas emissions that more sprawling suburban areas. But the flip side of the spatial concentration of productive land use in car cities is that ambient air pollution ($PM_{2.5}$) is more concentrated (Carozzi & Roth, 2018). A good deal of this $PM_{2.5}$ comes not from cars' exhaust but from their toxic tire and break pad dust (Fang et al., 2017). This dust and soot is associated with lower levels of life expectancy, infant mortality, and emergency room visits resulting in substantial public health costs.

Densifying a car city is insufficient for local respiratory health: a transition towards modes that pollute far less (rather than towards electric vehicles, which still use brakes) is necessary. Such a transition would also ease the global burdens of climate change. The power of the parking lot is to close the loop on this transition: the space wasted on parking today can become tomorrow's homes and shops, filling out the missing pieces of our new transit- and walking-accessible neighborhoods.

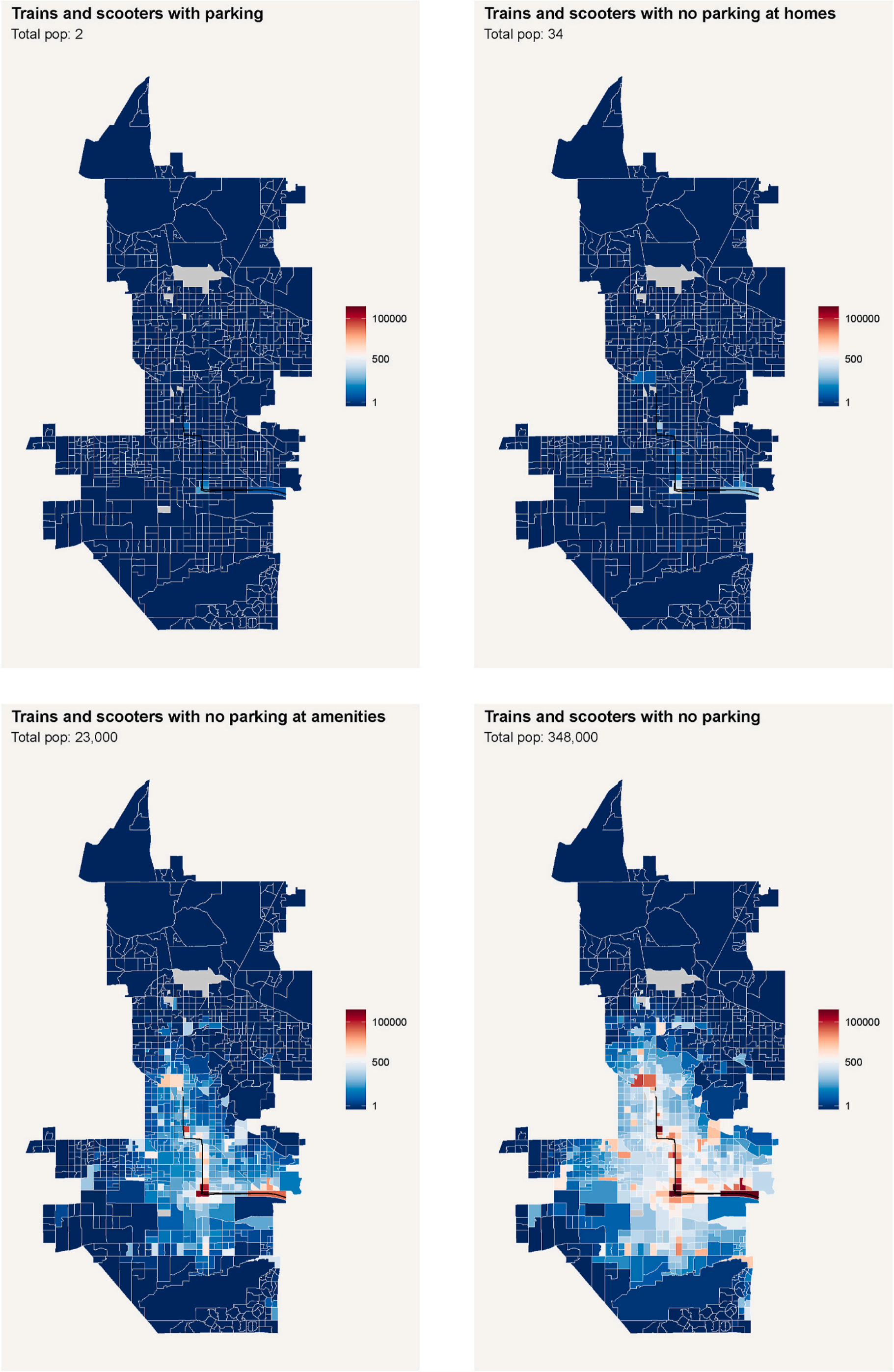


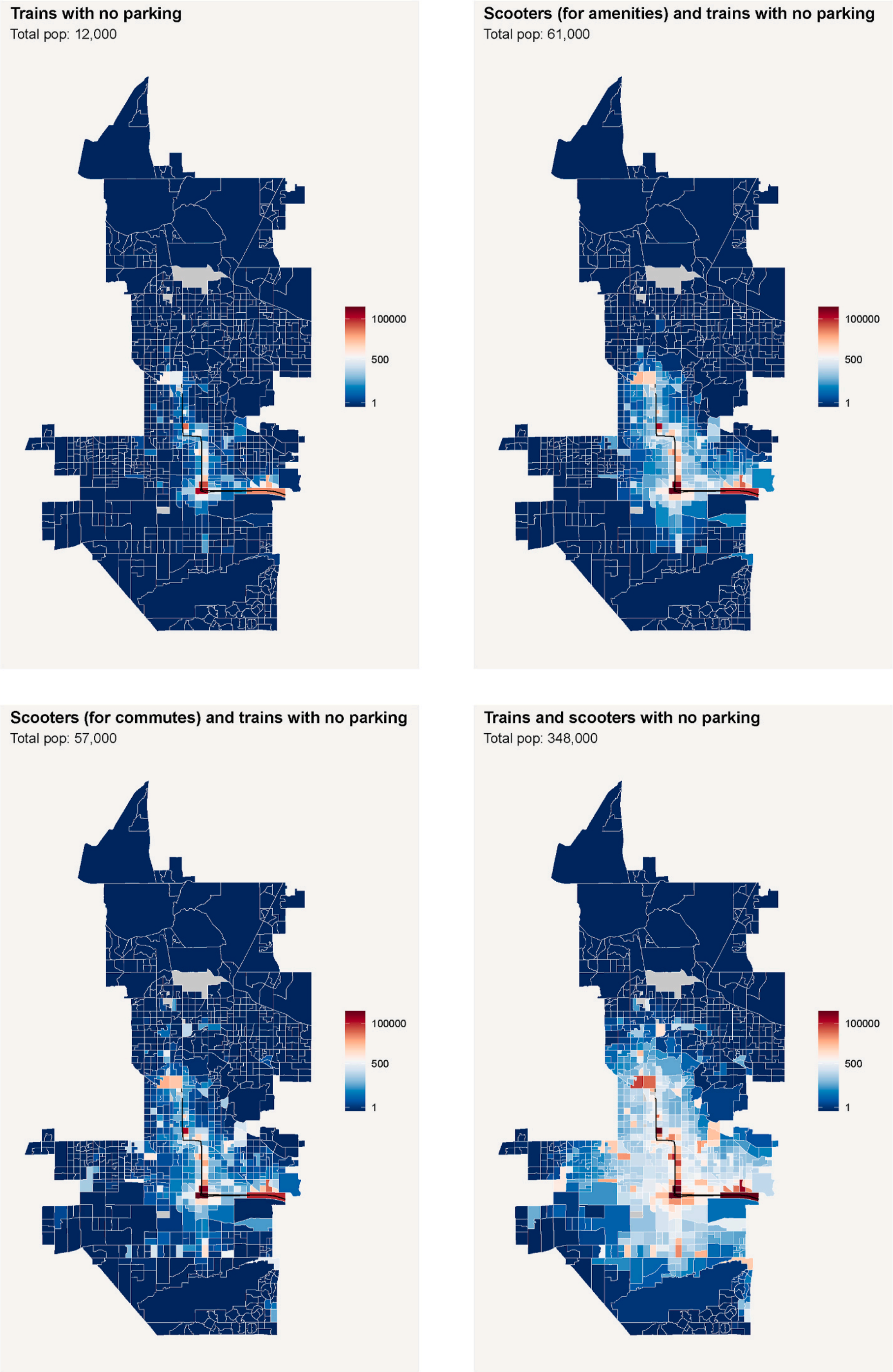
Fig. 6. Phoenix density under counterfactuals. In the upper two panels, densities are essentially zero everywhere. In the lower two panels, densities in outlying areas are essentially zero while densities at the CBD and, in some cases, along the light-rail line are well above 500 people per square mile.

Appendix A. Spatial Model of a Consumer City

This section describes our spatial consumer city model.

A.1. Geography

The city consists of N discrete locations given by the set $1, 2, \ldots, N$. Each location $i \in N$ is endowed with a measure L_i of land. Locations are connected by transportation networks that can involve walking, driving, and transit. We consider two types of network structures that we call the *transit city* and the *driving city*. These are described by the travel cost matrices τ_{ij}^{Tr} and τ_{ij}^{D}.


Trains with no parking
Total pop: 12,000

Scooters (for amenities) and trains with no parking
Total pop: 61,000

Scooters (for commutes) and trains with no parking
Total pop: 57,000

Trains and scooters with no parking
Total pop: 348,000

Fig. 7. Phoenix density under counterfactuals. Densities in outlying areas are essentially zero while densities at the CBD and, in some cases, along the light-rail line are well above 500 people per square mile.

A.2. Agents and their problems

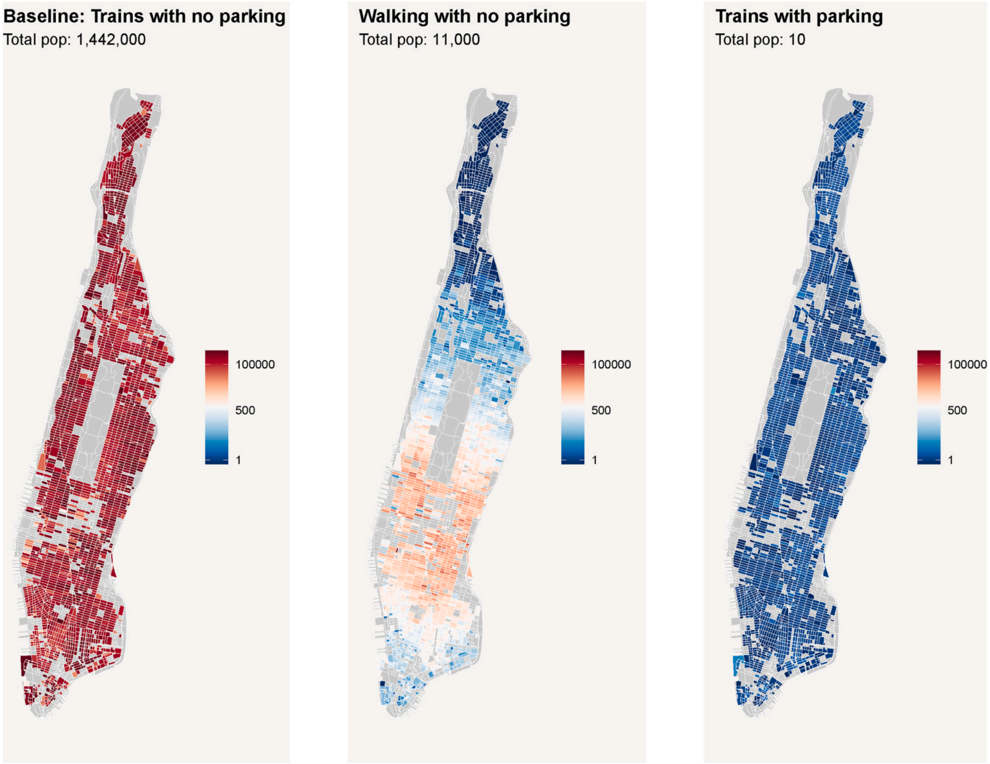
A.2.1. Preferences and the household problem

The model economy contains a measure Ω of households. These households choose which location $i \in N$ to live in. Household ω residing in location i receives a location-specific endowment y_i.[22]

Households have preferences over locations, and we use u_i to signify the exogenous amenity generated by location i. Households also receive utility from housing, and we let $h_i(\omega)$ denote the housing demand of household ω in location i. The rent they pay is denoted r_i. Residents also consume a numeraire consumption good, and we use $c_i(\omega)$ to signify purchases of this good.

---

[22] The location dependence may reflect access to job centers: higher in places with shorter average commuting costs, and vice versa. These effects may be idiosyncratic, as different households may value various job clusters differently from one another.



Baseline: Trains with no parking
Total pop: 1,442,000

Walking with no parking
Total pop: 11,000

Trains with parking
Total pop: 10

Fig. 8. Manhattan density under baseline and counterfactuals. In the baseline case, densities are well above 500 people per square mile everywhere. In the middle panel, densities are above 500 near Midtown but below 500 near the top and bottom of the island. In the right panel, densities are essentially zero everywhere.

Households gain utility through visiting neighborhoods and experiencing the amenities that are offered. We write as $q_{ik}(\omega)$ as the number of amenities experienced in location k by household ω living in location i. Traveling from i to k for these amenities has a multiplicative cost $\tau_{ik} \geq 1$, where $\tau_{ii} = 1$ for all i. Locations vary in the quality of the amenities, which is given by A_k. Households have constant elasticity of substitution (CES) preferences over varieties of amenities given by

$$Q_i(\omega) = \left(\sum_{k \in N} (A_k) q_{ik}(\omega)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}.$$

Here, $\sigma > 1$ captures the elasticity of substitution.

Households have Cobb-Douglas preferences over housing, $h_i(\omega)$, the numeraire good $c_i(\omega)$, and the aggregate amount of amenity experiences $Q_i(\omega)$. The corresponding exponents are given β_h, β_c, and β_a and we assume $\beta_h + \beta_c + \beta_a = 1$. The location-specific exogenous amenity u_i enters multiplicatively, so that utility for household ω locating in i is given

$$u(\omega) = u_i \times Q_i(\omega)^{\beta_a} \times c_i(\omega)^{\beta_c} \times h_i(\omega)^{\beta_h}.$$

Solving the household's problem We can state the problem of household ω as

$$\max_i \left[\max_{Q_i(\omega), c_i(\omega), h_i(\omega)} u_i \times Q_i(\omega)^{\beta_a} \times c_i(\omega)^{\beta_c} \times h_i(\omega)^{\beta_h} \right],$$

subject to the budget constraint

$$\sum_{k \in N} \tau_{ik} q_{ik}(\omega) + c_i(\omega) + r_i h_i(\omega) = y_i(\omega).$$

We solve the inside maximization problem—how much to spend on housing, consumption, and amenity experiences—and then the exterior problem of where to live.

Housing expenditure The Cobb-Douglas utility function implies that agents spend a constant fraction of income β_a on amenity experiences, a fraction β_c on numeraire consumption, and a fraction β_h on housing. Thus total housing expenditure is given

$$r_i h_i = \beta_h y_i. \tag{1}$$

Amenity experience expenditure Household ω in location i has the following first order condition for amenity experiences in location k, where $\mu_i(\omega)$ is the Lagrange multiplier on the budget constraint when choosing to live in location i:

$$A_k q_{ik}(\omega)^{\frac{\sigma-1}{\sigma}-1} \times \beta_a u_i Q_i(\omega)^{\frac{1}{\sigma}+\beta_a-1} c_i(\omega)^{\beta_c} h_i(\omega)^{\beta_h} = \mu(\omega) \tau_{ik}.$$

Next we take the ratio between the first order conditions for window shopping in locations k and k', respectively. Simplifying, we have

$$\left(\frac{q_{ik'}(\omega)}{q_{ik}(\omega)}\right)^{-1/\sigma} = \frac{A_k \tau_{ik'}}{A_{k'} \tau_{ik}}.$$

We can rearrange this to solve for $q_{ik'}(\omega)$:

$$q_{ik'}(\omega) = q_{ik}(\omega)\left(\frac{A_k \tau_{ik'}}{A_{k'} \tau_{ik}}\right)^{-\sigma}.$$

Next, we multiply through by $\tau_{ik'}(\omega)$ to get total expenditure on the amenity experiences in k':

$$\tau_{ik'} q_{ik'}(\omega) = q_{ik}(\omega)\left(\frac{\tau_{ik}}{A_k}\right)^{\sigma} (A_{k'})^{\sigma} \tau_{ik'}^{1-\sigma}.$$

Next, we sum over k'. On the left hand side, this leaves us with total expenditure by household ω on amenity experiences, which we know to be $\beta_a y_i(\omega)$. Then, we have:

$$\beta_a y_i(\omega) = q_{ik}(\omega)\left(\frac{\tau_{ik}}{A_k}\right)^{\sigma} \sum_{k' \in N} (A_{k'})^{\sigma} \tau_{ik'}^{1-\sigma}$$

It is useful to define location-specific consumer price index:

$$P_i^{1-\sigma} = \sum_{k \in N} (A_k)^{\sigma} \tau_{ik}^{1-\sigma}. \tag{2}$$

This price index captures the aggregate value of amenities accessible to a household in location *i*, weighted by the cost of accessing those amenities. To interpret the relationships, recall that $\sigma > 1$, implying that changes that *increase* the magnitude of the right-hand side will *lower* the price index experienced by consumers in a location. A larger A_k—that is, a high-quality amenity experience—will tend to lower the price index in location *i*. On the other hand, a larger travel cost τ_{ik} will *raise* the price index in location *i*.

With this definition, we can simplify the right-hand side to

$$\beta_a y_i(\omega) = q_{ik}(\omega)\left(\frac{\tau_{ik}}{A_k}\right)^{\sigma} P_i^{1-\sigma}.$$

Rearranging, this gives us expenditure by household ω in location *i* on travel for amenity experiences in location *k*:

$$\tau_{ik} q_{ik}(\omega) = \beta_a y_i(\omega) \frac{A_k^{\sigma} \tau_{ik}^{1-\sigma}}{P_i^{1-\sigma}}.$$

Summing over *k*, we have

$$\begin{aligned}\sum_{k \in N} \tau_{ik} q_{ik}(\omega) &= \sum_{k \in N} \beta_a y_i(\omega) \tfrac{A_k^{\sigma} \tau_{ik}^{1-\sigma}}{P_i^{1-\sigma}} \\ &= \beta_a y_i(\omega) \frac{\sum_{k \in N} A_k^{\sigma} \tau_{ik}^{1-\sigma}}{P_i^{1-\sigma}} \\ &= \beta_a y_i(\omega) \frac{P_i^{1-\sigma}}{P_i^{1-\sigma}} \\ &= \beta_a y_i(\omega).\end{aligned}$$

Thus, each household spends a fraction β_a on amenity experiences.

Indirect utility function Taking the equilibrium spending shares for consumption and housing, plugging them into the utility function, and simplifying, we can define indirect utility as

$$v_i(\omega) = B \times u_i \times \frac{y_i(\omega)}{P_i^{\beta_a} r_i^{\beta_h}}.$$

For household ω, the location decision amounts to choosing *i* to maximize $v_i(\omega)$. The indirect utility form will be useful in deriving the spatial equilibrium where the constant $B = \beta_a^{\beta_a} \times \beta_c^{\beta_c} \times \beta_h^{\beta_h}$.

A.2.2. Construction

Each location contains a representative real estate firm. These firms are endowed with land L_i, and they combine land with building materials M_i to produce floor space H_i according to the production function

$$H_i = \psi_b b_i L_i^{\eta} M_i^{1-\eta}.$$

Here, b_i is the location-specific construction productivity, while $\psi_b \in [0,1]$ captures the square footage available after accounting for parking. As with parking for consumer amenities, $\psi_b = 1$ implies no floorspace is lost to parking, while $\psi_b < 1$ means that some floorspace must be devoted to parking and is unavailable for household consumption in other ways. Developers purchase building materials at price *s*. The cost of producing H_i units of floor space is thus

$$sM_i = s\left(\frac{H_i}{\psi_b b_i}\right)^{1/(1-\eta)} L_i^{-\eta/(1-\eta)}.$$

Rent received from the household is r_i. Their profits are given

$$r_iH_i - s\left(\frac{H_i}{\psi_b b_i}\right)^{1/(1-\eta)} L_i^{-\eta/(1-\eta)}.$$

They choose the level of output H_i that maximize profits. Rearranging the first order condition of this problem yields gives

$$H_i = \left(r_i\frac{1-\eta}{s}\right)^{(1-\eta)/\eta} (\psi_b b_i)^{1/\eta} L_i. \tag{3}$$

Firm profits are retained by capitalists outside the model.

A.2.3. Aggregation

Income and floor space Denote Ω_i as the set of households living in location i. Then, total income Y_i of households living in i is given $Y_i = \int_{\omega\in\Omega_i} y_i(\omega)d\omega = y_i\Omega_i$. Similarly, total housing consumption of households in location i is given $H_i^R = \int_{\omega\in\Omega_i} h_i(\omega)d\omega = h_i\Omega(i)$. Given the consumption decisions analyzed above we have

$$r_iH_i^R = \beta_h Y_i. \tag{4}$$

The floor space market clears when construction sector output H_i is equal to demand:

$$H_i = h_i\Omega_i. \tag{5}$$

Spillovers We allow there to be spatial spillovers affecting the utility terms A_k. This reflects a common feature of locations with amenities: they become more fun with others. Realized utility terms A_k are thus the result of the process

$$A_k = \psi_A \overline{A}_k \sum_{i\in N} K_{ik}\Omega_i^{\zeta}. \tag{6}$$

Here, K_{ik} is the spillover matrix linking locations i and k, while $\zeta \in [0,1]$ governs the strength of spillovers.[23] The term $\overline{A}$ captures an underlying exogenous amenity of each location. The matrix K_{ik} is strictly diminishing in travel costs τ_{ik}. Specifically, we set $K_{ik} = 1/\tau_{ik}^{0.5}$. This implies a 50% increase in travel cost decreases the effect of the population size in i on A_k by about 20%. Note that we considered a range of exponents on the τ_{ik} term (0.25–0.75). Results are broadly similar.

Here, $\psi^A \in [0,1]$ accounts for the decline in consumer amenity values owing to the necessity of parking. We interpret this as the share of retail space devoted to parking. If $\psi_A = 1$, no land is lost to parking and the consumer experiences the full amenity value of the location. If $\psi_A < 1$, then some square footage is devoted to parking and the value of the amenities are diminished correspondingly.

Spatial Equilibrium In the spatial equilibrium, households receive the outside option at each location:

$$W = B \times u_i \times \frac{y_i}{P_i^{\beta_a} r_i^{\beta_h}}. \tag{7}$$

A.3. Equilibrium & Calibration

A.3.1. Definition of Equilibrium

An equilibrium of the model is a set of populations Ω_i, residential space H_i, rents r_i, price indices P_i, and endogenous amenities A_k that satisfy (1) the household's utility-maximization problem, (2) the spatial equilibrium condition, (3) the construction firm's profit-maximization function, (4) the definition of the price index, and (5) the amenity spillover equation.

A.3.2. Constructing an equilibrium

The following describes an algorithm for calculating the equilibrium, given parameters, data for land area L_i & travel times τ_{ik}, and spillover matrix K_{ik} & amenity terms u_i and $\overline{A}_k$.

1. Begin with an initial guess for the set of populations Ω_i.
2. Combined with equation (6), the Ω_i yield realized amenity quality A_k.
3. Combined with equation (2), the A_k yield prices P_i.
4. Combined with equation (7), the P_i yield rents r_i.
5. Combined with equations (4) and (3), this gives h_i and H_i.
6. Dividing H_i/h_i gives an updated set of populations Ω_i.

Steps 2–6 define a contraction that will converge to the equilibrium values of the population. Upon convergence, the set of values A_k, P_i, r_i, h_i, H_i, and Ω_i constitute the equilibrium of this parameterization of the model.

A.3.3. Calibrating amenities from the data

We use data to calibrate the values of the local amenities u_i. In particular, we collect data for

---

[23] Spillovers are increasing in population, but there are diminishing returns associated with congestion.

- travel times τ_{ik},
- residential square footage H_i,
- residential land area L_i
- retail space which is normalized to produce A_k
- local income (net of commute costs) y_i,
- and local populations Ω_i.

We normalize the outside option W.[24] We combine these variables with calibrated parameters and various equilibrium conditions to immediately obtain the following:

- From the definition of total income, we have total income $Y_i = y_i\Omega_i$.
- From equation (4), we have rent $r_i = \beta_h Y_i / H_i^R$.
- From equation (3), we have real estate productivity $b_i = (H_i/L_i)^\eta / \left(r_i \frac{1-\eta}{s} \right)^{1-\eta}$.
- From equation (2), we have $P_i = \left(\sum_{k \in N} A_k^\sigma \tau_{ik}^{1-\sigma}\right)^{1/(1-\sigma)}$.
- From equation (7), we have $u_i = \frac{W P_i^{\beta_a} r_i^{\beta_h}}{B y_i}$.
- From equation (6), we have $\overline{A}_k = A_k \left(\psi_A \sum_{i \in N} K_{ik} \Omega_i^\zeta\right)^{-1}$.

A.4. Calibration and model targets

Table 1 provides details on the parameters chosen for the calibrated model.

Table 1
Targets and sources for calibration.

Household Components				
Parameter	Description	Value		Target/Source
σ	Elasticity of substitution	3		
β_a	Cobb-Douglas	0.40		Shopping share
β_h	Cobb-Douglas	0.35		Housing share
Transportation & Construction Components				
Parameter	Description	Value		Target/Source
ζ	Spillover strength	0.02		Allen et al. (2016)
S	Cost of construction materials	\$150		ProMatcher (2020)
H	Land share in production	0.2		Albouy and Ehrlich (2018)
City-Specific Components				
Parameter	Description	Value		Target/Source
		Phoenix	Manhattan	
ψ_A	Non-parking share of amenity space	0.65	1	Hoehne et al. (2019)
ψ_B	Non-parking share of residential space	0.65	1	No parking

Appendix B. Data and Transporation Network Details

B.1. Travel times

We start by describing the calibration procedure in terms of the construction of the travel cost matrix τ_{ij} from observable transportation information and the selection of key parameters in the model which are derived from observed data for both Manhattan and Phoenix.

First, we construct the transportation networks for both Phoenix and Manhattan. These networks consist of road, light-rail, and subway networks. Centerline road shapefiles are retrieved from NYC Open Data and City of Phoenix Open Data for Manhattan and Phoenix respectively (City of Phoenix Open Data, 2020; NYC Open Data, 2020). General Transit Feed Specification (GTFS) data for both Manhattan and Phoenix are used to construct the transit networks (OpenMobilityData, 2020a,b). GTFS data contains data pertaining to the transit schedule, fares, geographical transit information, arrival predictions, vehicle positions, and service advisories. The format of these data are consistent across transit agencies which allows for ease of use in geographic software.

We combine the road and transit data within ArcGIS to create a Network Dataset that can be used to construct least-cost routes for origin/destination pairs. In Manhattan, these pairs consist of census block centroids, in Phoenix they are census block group centroids. Locations without residential populations are omitted from the network construction. We consider 2356 census blocks in Manhattan resulting in 5,550,736 origin/destination pairs. For the City of Phoenix, we consider 964 census block groups which result in 929,296 origin/destination pairs.[25] The minimum travel time for each pair along the network is computed using Dijkstra's algorithm. An origin/destination least-cost matrix in units of minutes results.

Multiple origin/destination cost matrices are constructed for each city based on mode. Using the road networks for each city, we construct cost

---

[24] The calibration of the remaining parameters (such as σ, β_h, etc) is done in the next section.

[25] There are approximately 30,000 census blocks within Phoenix proper. This is a computationally burdensome amount; therefore, we opt to use block groups in the Phoenix setting.

matrices for walking only, scooting only, and driving only given their various speeds—where driving only is considered for Phoenix but not Manhattan. We assume a walk speed of 83 m/min (5 km/h). Scooter speed is estimated at 250 m/min (15 km/h).[26] Driving speed in Phoenix varies with road type. We make a coarse categorization of local versus major arterial roads with speeds of 800 m/min (48 km/h) and 1333 m/min (80 km/h) respectively. We also construct matrices for combined mode use: walking and subway; walking, scooting, and subway/light-rail. Here the algorithm searches across the full network of roads and transit lines given mode speed on the road and the transit travel time between stations provided by the GTFS data.

Travel costs in the model are fully converted to dollar values. This conversion enables the combination of travel time costs with monetary costs (e.g., fares). We do this conversion by multiplying travel times by an estimate of median hourly earnings for Phoenix ($18) and for Manhattan ($32). For driving, we also add 3 min (multiplied by $18/hr) for parking itself.[27] The estimates are taken by dividing annual median earnings from the 2018 American Community Survey by 2000 h. Multiplying through the times by these figures, we then sum appropriately any monetary costs. For car-based trips, we add $0.50 per mile driven. For transit-based trips, we use the published fares of $2 each direction in Phoenix and $2.75 each direction in Manhattan. For scooters, we use a $1 base charge plus $0.20 per minute. We also add a 5-min cost to scooter trips to capture search and unlock times; we convert this time cost to a monetary cost as above.

Finally, we construct a travel cost matrix that combines the Phoenix transit network with the possibility of using a scooter as a *last mile* option, connecting users from their origin to the train station and/or the train station to their destination. We construct the network as follows. For each origin/destination pair, we calculate the three nearest train stations at each end. For each pair, this gives us nine ($= 3 \times 3$) possible transit routes. For each of these nine routes, we use the walking and scooter travel cost matrices to calculate the lowest-cost mode for the trips between the origin and the starting train station as well as for the ending train station to the destination. Next, for each of the nine routes, we sum the costs of each of the three trip segments: origin to train station, on the train, and train station to destination. Lastly, we take the minimum of these nine routes. This is our final travel cost for the scooter-plus-train transportation network.

B.2. Population, income, housing, and land data

For the full calibration of the model, we require population, building and land use information at the census block and census block group level. All households have identical income within the two cities which we set to the median earnings from the 2013–2017 American Community Survey. The values are $64,659 for Manhattan and $36,508 for Phoenix. The 2010 Census provides population data at the block level for Manhattan and block group level for Phoenix. Observed retail and residential square footage per parcel along with residential lot area is provided by New York City Department of Planning and Maricopa County Assessors (NYC Department of Planning, 2020; Maricopa County Assessor's Office, 2020). We aggregate the parcel-level square footage to the block or block group level.

Missing residential multifamily rental square footage is a concern for the Phoenix parcel data set. Upon close review, the residential parcel data omits some but not all multifamily rental buildings. Unfortunately, we can not be certain exactly how many of these buildings are omitted from the parcel data without resorting to a parcel by parcel inspection. We adjust for this missing data issue by estimating a lower bound for the residential square footage and residential lot area based on block group population, block group land area, census counts of various housing structures (detached, multifamily, etc.), and distance from the block group centroid to the CBD. Separate OLS regressions are run for both residential square footage and residential lot area using interactions of the listed explanatory variables. R-squared for the residential square footage and residential lot area regressions are reasonably high at 58% and 59% respectively. The residential square footage and residential lot area for each block group to be used in the model is then taken as the maximum between the predicted value from these regressions and the value observed in the parcel data.

Table 2
Summary Statistics

	Variable	Min.	p25	Median	p75	Max.	Std. Dev.
Manhattan	Pop.	1	271	525	853	4067	459
	Retail Sqft	0	7770	18,414	39,199	1,309,061	57,345
	Res. Sqft	791	164,253	290,641	493,329	8,367,942	353,223
	Res. Lot Area Sqft	735	40,808	67,647	100,841	2,675,000	97,304
	Res. FAR	0.032	3.105	4.043	6.224	38.529	3.376
Phoenix	Pop.	16	1130	1449	1810	4340	554
	Retail Sqft	0	0	18,245	78,772	3,514,788	213,133
	Res. Sqft	4316	603,348	836,664	1,149,640	6,169,659	575,728
	Res. Lot Area Sqft	282,039	2,494,394	3,844,895	5,007,289	58,043,928	3,937,948
	Res. FAR	0.012	0.182	0.220	0.289	1.696	0.146

Table 2 presents the summary statistics for the model inputs for Manhattan and Phoenix. We also include the residential floor-to-area ratio (FAR) for comparison purposes. Typically block groups are larger in area than blocks. This difference is kept in mind in the following comparisons. Beginning with population, the median population of a Manhattan block is roughly a third of the median population of a Phoenix block group. However, maximum values are similar highlighting the higher population density that exists in Manhattan. While the median for retail square footage for Manhattan and Phoenix is nearly identical at 18,414 and 18,245 respectively, the upper half of the Phoenix distribution quickly increases. Zero retail square footage for the 25*th* percentile in Phoenix indicates there are many block groups with no retail square footage at all. This is in contrast to Manhattan where the 25*th* percentile contains 7770 square feet. Median residential square footage for Manhattan is just over a third of the median for Phoenix. However, the maximum residential square footage in Manhattan is over 2,000,000 square feet more than in Phoenix. This is despite the size difference in blocks versus block groups. This fact and the lower levels of residential lot area square footage for Manhattan than Phoenix hint at the much greater residential density in Manhattan. The summary statistics for residential FAR clearly indicate this difference. The median residential FAR in Manhattan is 4.043 compared to

---

[26] Scooters have a similar travel speed to bicycles. For bike share systems, the non-time costs are similar as well. For these reasons, we choose to focus solely on scooters, a possibly more attractive option in a hot environment. However, the results should be similar if we incorporated a bicycling option.

[27] The transit travel time data already includes periods like wait times.

0.220 in Phoenix. The maximum FAR in Phoenix does not surpass Manhattan's 25^{th} percentile of 3.105. Residential square footage is brought directly into the model. Retail square footage is first divided by 1.4M; this variable is used directly as our measure of amenity A_k.

Appendix C. Spatial Income Gradients

Here, we provide figures of take-home income net of commuting costs across locations. These figures are akin to spatial income gradients, where the variation follows from the cost of commuting. In particular, we assume that each household earns their city's median annual earnings. Next, for each location, we calculate the commute cost using the same methodology described above for other trips. Finally, we multiply this round-trip cost by 250 working days per year, and subtract this total from the median annual earnings. Variation in spending power across locations thus comes exclusively from variation in commuting cost. We show these figures here for the various commute possibilities under study.

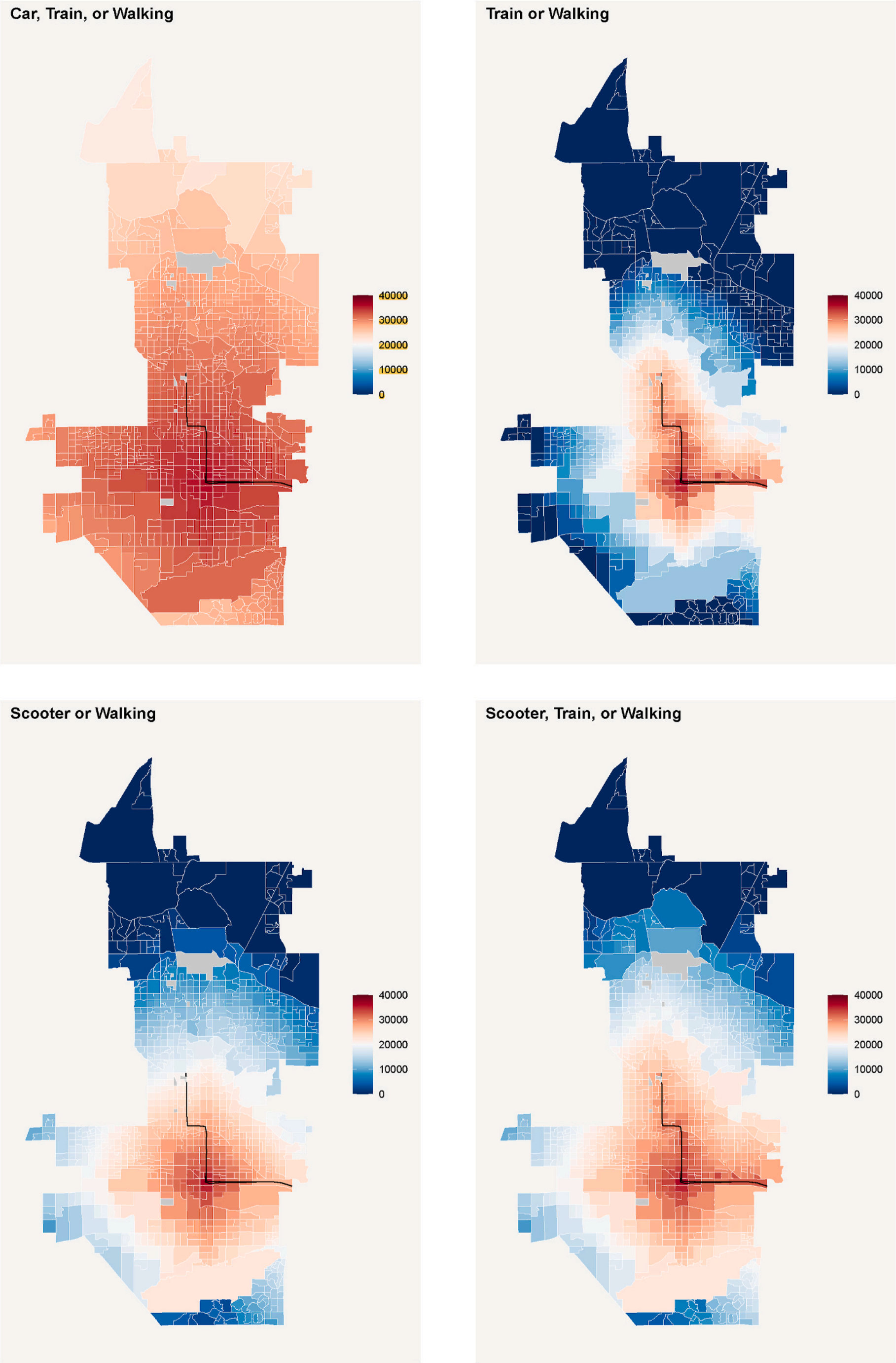


Fig. 9. Phoenix median earnings net of calibrated commuting costs. In the baseline case, net earnings are above $20,000 everywhere. In the other cases, net earnings are above $20,000 near the center but essentially zero near the city fringes.

Fig. 9 shows the spatial income gradients under four different calibrated transportation networks in Phoenix. Here, the central business district is at the intersection of Washington Street and Central Avenue.[28] The upper left panel shows net income when households can drive, take the train, or walk to work at the central business district.[29] The upper right panel takes away the option to drive to work. In turn, outlying areas and those places far from the train line see substantial declines in their net income. The bottom left panel further removes trains, but adds the option to take a scooter to work. This mode is a bit more symmetric, although the higher time costs imposed by the lower speeds than driving are readily apparent. Finally, the bottom right panel shows net income when the transportation network allows trains, scooters, and multi-modal trips. Scooters are available both as the main mode and as a last-mile option for light rail trips.

Fig. 10 shows the spatial income gradients for two different calibrated transportation networks in Manhattan. Here, the central business district is in Midtown Manhattan at 42nd Street and 6th Avenue (Bryant Park). The left panel shows incomes net of commuting costs to Bryant Park in the baseline city: households can walk or take the subway. The right panel shows net incomes when only walking is available. For some locations near midtown, the pictures are identical. In those places, households already chose to walk. Farther uptown and downtown, however, incomes are lower—much lower. In those places, walking to midtown would represent a real challenge to households.

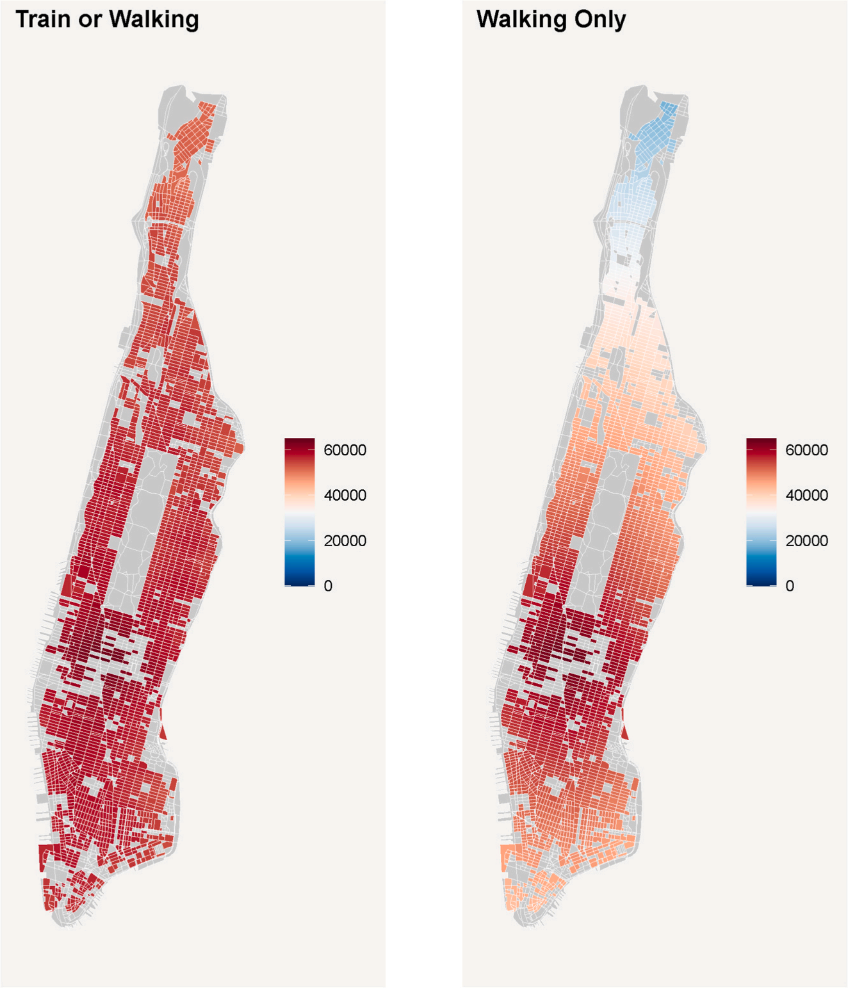


Fig. 10. Manhattan median earnings net of calibrated commuting costs. In the baseline case, net earnings are above $40,000 everywhere. In the walking-only case, net earnings fall below $40,000 near the top of the island.

References

Aguilera-García, Á., Gomez, J., & Sobrino, N. (2020). Exploring the adoption of moped scooter-sharing systems in Spanish urban areas. *Cities, 96*, 102424.

Ahlfeldt, G. M., Redding, S. J., Sturm, D. M., & Wolf, N. (2015). The economics of density: Evidence from the Berlin Wall. *Econometrica, 83*(6), 2127–2189.

Albouy, D., & Ehrlich, G. (2018). Housing productivity and the social cost of land-use restrictions. *Journal of Urban Economics, 107*, 101–120.

Allen, T., Arkolakis, C., & Li, X. (2016). *Optimal city structure*. Manuscript.

Alonso, W. (1964). *Location and Land Use: Toward a General Theory of Land Rent.* Publications of the Joint Center for Urban Studies of the Massachustts Institute of Technology and Harvard University. Harvard University Press.

Anas, A., & Kim, I. (1996). General equilibrium models of polycentric urban land use with endogenous congestion and job agglomeration. *Journal of Urban Economics, 40* (2), 232–256.

Baum-Snow, N., Kahn, M. E., & Voith, R. (2005). *Effects of urban rail transit expansions: Evidence from Sixteen cities, 1970–2000*. Brookings-Wharton Papers on Urban Affairs.

Ben-Joseph, E. (2012). *ReThinking a Lot: The Design and Culture of Parking*. MIT Press.

Bhattacharjee, S., & Goetz, A. R. (2012). Impact of light rail on traffic congestion in Denver. *Journal of Transport Geography, 22*, 262–270.

Brinkman, Jeffrey, & Lin, Jeffrey (2019). *Freeway Revolts!* Federal Reserve Bank of Philadelphia. Working Paper 19-29.

---

[28] Visually, the CBD is at the pivot of light-rail network's broadly L-shaped route through the city.

[29] Note that walking is allowed under all scenarios, so the labels focus on the modes that are not uniformly available.

bunten, d.m. (2017). *Is the Rent Too High? Aggregate Implications of Local Land-Use Regulation*. Working Paper 2017-06. Board of Governors of the Federal Reserve System.

Caiazzo, F., Ashok, A., Waitz, I. A., Yim, S. H., & Barrett, S. R. (2013). Air pollution and early deaths in the United States. Part I: Quantifying the impact of major sectors in 2005. *Atmospheric Environment, 79*, 198–208.

Carozzi, F., & Roth, S. (2018). *Dirty density: Air quality and the density of American cities*. Center for Economic Performance. Technical Report 1635.

Cervero, R., & Radisch, C. (1996). Travel choices in pedestrian versus automobile oriented nighborhoods. *Transport Policy, 3*(3), 127–141.

Chester, M., Fraser, A., Matute, J., Flower, C., & Pendyala, R. (2015). Parking infrastructure: A constraint on or opportunity for urban redevelopment? A study of Los Angeles county parking supply and growth. *Journal of the American Planning Association, 81*(4), 268–286.

City of Phoenix Open Data. (2020). *Street Centerline file*. http://mapping-phoenix.opendata.arcgis.com/datasets/street-centerline. (Accessed February 2020).

Crockett, Karilyn (2018). *People Before Highways*. Amherst and Boston: University of Massachusetts Press.

DeMaio, P. (2009). Bike-Sharing: History, impacts, models of provision, and future. *Journal of Public Transportation, 12*(4), 3.

Deng, Y., & Srinivasan, S. (2016). Urban land use change and regional access: A case study in Beijing, China. *Habitat International, 51*, 103–113.

Ersoy, F. Y., Hasker, K., & Inci, E. (2016). Parking as a loss leader at shopping malls. *Transportation Research Part B: Methodological, 91*, 98–112.

Fang, T., Guo, H., Zeng, L., Verma, V., Nenes, A., & Weber, R. J. (2017). Highly acidic ambient particles, soluble metals, and oxidative potential: A link between sulfate and aerosol toxicity. *Environmental Science & Technology, 51*(5), 2611–2620.

Fujita, M., Krugman, P. R., & Venables, A. (1999). *The Spatial Economy: Cities, Regions, and International Trade*. MIT Press.

Glaeser, E. L., & Kahn, M. E. (2010). The greenness of cities: Carbon dioxide emissions and urban development. *Journal of Urban Economics, 67*(3), 404–418.

Hoehne, C. G., Chester, M. V., Fraser, A. M., & King, D. A. (2019). Valley of the sun-drenched parking space: The growth, extent, and implications of parking infrastructure in phoenix. *Cities, 89*, 186–198.

Hou, Y. (2016). Traffic congestion, polycentricity, and intraurban firm location choices: A nested logit model for the los angeles metropolitan area. *Journal of Regional Science, 56*(4), 683–716.

Ingvardson, J. B., & Nielsen, O. A. (2018). Effects of new bus and rail rapid transit systems–an international review. *Transport Reviews, 38*(1), 96–116.

Kahn, M. E. (2007). Gentrification trends in new transit-oriented communities: Evidence from 14 cities that expanded and built rail transit systems. *Real Estate Economics, 35*(2), 155–182.

Kawamura, K. (2001). Empirical examination of relationship between firm location and transportation facilities. *Transportation Research Record, 1747*(1), 97–103.

Kim, K.-H., Kabir, E., & Kabir, S. (2015). A review on the human health impact of airborne particulate matter. *Environment International, 74*, 136–143.

Knowles, R. D., & Ferbrache, F. (2016). Evaluation of wider economic impacts of light rail investment on cities. *Journal of Transport Geography, 54*, 430–439.

Lee, J., Boarnet, M., Houston, D., Nixon, H., & Spears, S. (2017). Changes in service and associated ridership impacts near a new light rail transit line. *Sustainability, 9*(10), 1827.

Lee, S. S., & Senior, M. L. (2013). Do light rail services discourage car ownership and use? Evidence from census data for four English cities. *Journal of Transport Geography, 29*, 11–23.

Li, H., Wei, Y. D., & Wu, Y. (2019). Urban amenity, human capital and employment distribution in shanghai. *Habitat International, 91*, 102025.

Manville, M. (2020). Los Angeles, United States. In D. Pojani, J. Corcoran, N. Sipe, I. Mateo-Babiano, & D. Stead (Eds.), *Parking: An international perspective* (pp. 229–243). Elsevier (chapter 13).

Maricopa County Assessor's Office. (2020). *Secured master data*. Last accessed January 2020 https://www.mcassessor.maricopa.gov/.

McKenzie, G. (2019). Spatiotemporal comparative analysis of scooter-share and bike-share usage patterns in Washington, DC. *Journal of Transport Geography, 78*, 19–28.

Mills, E. S. (1967). An aggregative model of resource allocation in a metropolitan area. *The American Economic Review*, 197–210.

Muth, R. F. (1969). *Cities and Housing: The Spatial Pattern of Urban Residential Land Use*. University of Chicago Press, 1969.

Nelson, J. D., Wright, S., Masson, B., Ambrosino, G., & Naniopoulos, A. (2010). Recent developments in flexible transport services. *Research in Transportation Economics, 29*(1), 243–248.

Nilsson, I. M., & Smirnov, O. A. (2016). Measuring the effect of transportation infrastructure on retail firm co-location patterns. *Journal of Transport Geography, 51*, 110–118.

NYC Department of Planning. (2020). *PLUTO and MapPLUTO*. Last accessed March 2020 https://www1.nyc.gov/site/planning/data-maps/open-data/dwn-pluto-mappluto.page.

NYC Open Data. (2020). *NYC street Centerline (CSCL)*. Last Accessed February 2020 https://data.cityofnewyork.us/City-Government/NYC-Street-Centerline-CSCL-/exjm-f27b.

OpenMobilityData. (2020a). *MTA Manhattan GTFS*. Last accessed July 2020 https://openmobilitydata.org/p/mta/82?p=7.

OpenMobilityData. (2020b). *Valley Metro GTFS*. Last accessed July 2020 https://openmobilitydata.org/p/valley-metro/68.

ProMatcher. (2020). *Phoenix home construction costs & prices*. Last accessed March 2020 https://home-builders.promatcher.com/cost/phoenix-az-home-builders-costs-prices.aspx.

Rolheiser, L. A., & Dai, C. (2019). *Beyond density: Municipal expenditures and the shape and location of development*. Urban Geography.

Rossi-Hansberg, E. (2005). A spatial theory of trade. *The American Economic Review, 95*(5), 1464–1491.

Severen, C. (2019). *Commuting, labor, and housing market effects of mass transportation: Welfare and identification*. Federal Reserve Bank of Philadelphia. Working Paper 18-14.

Shaheen, S., & Chan, N. (2016). Mobility and the sharing economy: Potential to facilitate the first-and last-mile public transit connections. *Built Environment, 42*(4), 573–588.

Shill, G. H. (2020). Should law subsidize driving? *New York University Law Review, 95*(2).

Shoup, D. C. (2005). *The high cost of free parking*. Planners Press, American Planning Association.

Sohn, J. (2005). Are commuting patterns a good indicator of urban spatial structure? *Journal of Transport Geography, 13*(4), 306–317.

Tsivanidis, N. (2018). *The aggregate and distributional effects of urban transit infrastructure: Evidence from Bogotá's TransMilenio*. Unpublished manuscript.

Weinberger, R. (2012). Death by a thousand curb-cuts: Evidence on the effect of minimum parking requirements on the choice to drive. *Transport Policy, 20*, 93–102.

Werner, C. M., Brown, B. B., Tribby, C. P., Tharp, D., Flick, K., Miller, H. J., Smith, K. R., & Jensen, W. (2016). Evaluating the attractiveness of a new light rail extension: Testing simple change and displacement change hypotheses. *Transport Policy, 45*, 15–23.

Yan, X., Levine, J., & Zhao, X. (2019). Integrating ridesourcing services with public transit: An evaluation of traveler responses combining revealed and stated preference data. *Transportation Research Part C: Emerging Technologies, 105*, 683–696.

Zacharias, J. (2012). Resisting motorization in guangzhou. *Habitat International, 36*(1), 93–100.