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Valley of the sun-drenched parking space: The growth, extent, and implications of parking infrastructure in Phoenix

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ABSTRACT

There is little knowledge of how much parking infrastructure exists in cities despite clear evidence that abundant and underpriced parking has economic, environmental, and social consequences. Urban parking requirements are very precise and routinely enforced despite the fact that most cities have little to no knowledge about their own parking supply. To further explore these issues, a parking inventory for metropolitan Phoenix, Arizona, USA is developed by cross-referencing geospatial cadastral and roadway data with minimum parking requirements. Metropolitan Phoenix is chosen because it is relatively young, rapidly growing, highly sprawled, and car dependent. Historical growth of parking is also estimated by linking year of property development to required off-street and nearby on-street parking spaces. As of 2017, we estimate that there were 12.2 million parking spaces in the metropolitan region with 4.04 million inhabitants, 2.86 million registered personal vehicles, and 1.84 million jobs. Growth of parking in metro Phoenix has also been significant; since 1960, 10.9 million spaces have been added to the region compared to a population growth of 3.41 million, vehicle fleet growth of 2.63 million, and employment growth of 1.56 million jobs. Since the 2008 recession, parking growth in metro Phoenix has significantly slowed, but continued urban growth combined with substantial minimum parking requirements may promote more parking infrastructure than is needed. Planners and policy makers should value quantifying the growth and supply of parking in urban areas and consider reforming parking standards to promote sustainable urban growth.

1. Introduction

The evidence is clear that abundant and underpriced parking creates economic, environmental, and social problems (Chester, Fraser, Matute, Flower, & Pendyala, 2015; Manville & Shoup, 2005; Shoup, 1999; Weinberger, 2012; Willson, 1995). Yet less is known about the growth and extent of parking infrastructure. This is true at global, national, and local scales, and is especially problematic for US cities where minimum parking requirements are perhaps the most dominating force of determining why cities are so automobile oriented (Willson, 2013). Past parking estimates for the US claim between 105 million to 2 billion total spaces (or between one space per 40 m of roadway to one space per two meters of roadway; Chester, Horvath, & Madanat, 2010). While some recent studies quantify point-in-time parking supply (Davis, Pijanowski, Robinson, & Engel, 2010; Rutman, Darnell, Krantz, & Risse, 2013; Scharnhorst, 2018), there are few studies that quantify the intra-city growth and extent of parking infrastructure (one example is the Chester et al., 2015 study of Los Angeles). Without cities actively tracking and quantifying parking growth and supply, policy and land use planning towards density and non-automobile travel is blind.

Widespread automobile adoption revolutionized 20th century travel. Off-street parking facilities were initially intended to manage congestion by moving vehicles off-road when not in use (Ferguson, 2004). By the middle of the century, most cities had implemented minimum parking requirements to meet increasing demand. Parking requirements produced abundant and underpriced infrastructure, creating perverse incentives for automobile travel by shifting the costs of parking into other services (e.g., rental costs or the costs of groceries) thereby distorting modal choice (McDonnell, Madar, & Been, 2011; Shoup, 1999; Weinberger, 2012; Weinberger, Kaehny, & Rufo, 2010; Willson, 1995). Minimum parking requirements led to urban designs that favor the automobile by reducing density and increasing the frequency and distance of automobile trips (Weinberger et al., 2010; Willson, 1995). Accumulating evidence suggests that minimum parking requirements reinforce a cycle of auto-dependency and make transitions to public transit, biking, and walking more challenging.

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Cities are constantly developing a myriad of strategies to combat issues such as population growth, traffic congestion, pollution, and climate change. If cities are to promote sustainable development, lower housing costs, decreased air pollution, and improved public health through biking, walking, and transit, then estimates of urban parking supply are critical for establishing local and regional policy aimed at freeing land for more valuable uses and reducing incentives to drive. Requiring parking increases the incentive to drive by effectively subsidizing it (Willson & Shoup, 1990). Reducing parking availability through relaxing parking requirements is possible (Engel-Yan, Hollingworth, & Anderson, 2007), and would likely decrease automobile use (Weinberger, 2012).

Automobile dependence and oversupplied parking has many consequences that manifest to constrain urban development and sustainable growth. A parking space is often 'free' to use, at least in the sense that there is not direct payment. However, parking is not free when considering indirect costs, and there may be significant burdens associated with meeting minimum requirements (Manville & Shoup, 2005; McDonnell et al., 2011; McPherson, 2001). Typically, developers invest up-front for the required parking infrastructure, and the costs are passed to the parking space user through increased prices of goods or services (Shoup, 1997). Parking can cost tens of thousands of dollars per space constructed, leading to investments of tens to hundreds of billions of dollars collectively by developers in cities despite the value of land almost always being greater for something other than parking (Shoup, 1997; Willson, 1995). Scharnhorst's (2018) study of parking in five US cities estimates a high cost of parking: up to $118,000 per household for parking infrastructure in Jackson, Mississippi, USA and $35.8 billion to replace all parking in the City of Seattle, Washington, USA. These examples underscore the significant investment in infrastructure required by cities to support automobile dependence just through parking, and these estimates do not include the costs of maintenance. Building and maintaining parking infrastructure also requires large amounts of resources and land, and contributes non-trivial environmental life-cycle impacts to automobile travel (Chester et al., 2010). For cities with high automobile dependence, abundant and underpriced parking only adds fuel to the fire; urban pollution and urban heat are exacerbated by dense traffic and widespread automobile-related infrastructure (Allen, Lindberg, & Grimmond, 2011; Davis et al., 2010; Hart & Sailor, 2009; Kempton, Tomic, Letendre, Brooks, & Lipman, 2001; Van Bohemen & Van De Laak, 2003), and this cycle of automobile dependence is further cemented with each additional parking space paved.

Where minimum parking requirements seem to have the greatest impact on land use and automobile dependence are in cities that have predominantly grown in the latter half of the twentieth century, an archetypal city being Phoenix, Arizona, USA. The metropolitan region of Phoenix is unique because it is relatively young, rapidly growing, highly sprawled, and car dependent. According to the US Census Bureau (CB), the City of Phoenix is the second fastest growing large US city behind San Antonio, Texas (US CB, 2018a), and the surrounding metropolitan region is projected to continue rapidly growing and expanding. According to the Maricopa Association of Governments, (the regional metropolitan planning organization of metro Phoenix), residential developed land in the region is projected to grow 480% (from 2100 km^2 to 10,000 km^2) by 2040 with population and employment growth of 150% (MAG, 2017). Much of this growth is due to lateral expansion into currently undeveloped peripheral land. Phoenix is also sprawling and automobile dependent. Hamidi and Ewing (2014) analyzed the 162 largest US urbanized areas (UZAs), and the Phoenix UZA was the 36th most sprawled, and the second most sprawled of the top 20 most populous UZAs. Of US UZAs with at least 2 million in population, Phoenix has the highest non-interstate per-capita vehicle miles traveled. Most cities in the Phoenix metropolitan region also have high vehicle ownership: cities in the region with household vehicle ownership above the national average of 91% include Gilbert (98%), Surprise (97%), Chandler (96%), Scottsdale (96%), Mesa (93%), and Phoenix (92%) (US CB, 2016). Yet, at the same time, the Phoenix metro region is heavily investing in high quality transit (namely a light rail network), is promoting infill development and densification, and is well-positioned to increase active transit given its active population and temperate non-summer climate.

In growing, sprawling, and hot cities like Phoenix, increasingly severe heat and pollution are two major threats to human health directly tied to urban automobile dependence. In the urban US, concrete and asphalt pavements account for approximately 30–40% of land cover (Akbari, Rose, & Taha, 2003; Rose, Akbari, & Taha, 2003), and may reach as high as 40–66% in non-residential areas (Akbari & Rose, 2001a, 2001b). This large amount of grey infrastructure, much of which supports automobility, is a primary contributing factor to urban heat island, where temperatures in urban regions are greater than rural regions and daily lows are increased. Additionally, automobiles themselves are a direct source of heat contributing 47% to 62% of urban anthropogenic heat during summer months (Sailor & Lu, 2004). Pollution from automobile travel is also problematic, and the Phoenix metropolitan region ranks 8th worst in the US for smog (American Lung Association, 2018). With the threat of increasingly severe urban heat due to climate change and urbanization (Luber & McGeehin, 2008; Stone, Hess, & Frumkin, 2010), cities (especially those with an already hot summer climate) may have increased incentives to shift away from automobile dependence and abundant and underpriced parking.

This research fills gaps in knowledge about the extent of parking infrastructure supplied in cities. Focusing on the metropolitan region of Phoenix, we aim to answer three research questions: 1) What is the current supply of parking?; 2) How has the parking supply grown?; and 3) What issues exist or may arise due to vast parking infrastructure in metropolitan regions like Phoenix?

2. Methodology

An inventory of on-street and off-street parking was developed for the Phoenix, Arizona metropolitan region. We define the Phoenix metropolitan region (hereafter, 'metro Phoenix') as the UZA of Maricopa County, Arizona, USA (note that this is not the same as the metropolitan statistical area, and excludes parts of urbanized Pinal County, sometimes considered part of the metro area). We choose this as the study region for two main reasons: 1) 94% of the Maricopa County population (approximately 4 million people in 2017) resides in the UZA (US CB, 2016); and 2) the vast extent of built infrastructure exists in the UZA. Fig. 1 shows the study area including significant highways, high capacity transit, and downtown areas. We define on-street parking as roadway shoulder space able to accommodate and legally park a vehicle. Off-street parking is defined as dedicated parking area located off the road network (e.g. residential driveways or non-residential parking lots). We started by assessing the extent of parking infrastructure (area and number of spaces by space type and location) and then conducted a time series analysis that links the initial age of land development to nearby parking spaces to develop an estimate of infrastructure growth. This methodology follows the approach established by Chester et al. (2015).

2.1. Estimating on-street parking

To estimate on-street parking, OpenStreetMap (OSM) geospatial road network data were cross-referenced with city-level on-street parking restrictions (OpenStreetMap contributors, 2017). As municipal codes in metro Phoenix prohibit on-street shoulder parking on arterials and highways, we only assign the functional road classes of 'residential' and 'unclassified' (i.e. local and collector roads) as permitted for on-street shoulder parking. We eliminated roadway space where obstructions prohibit or codes restrict parking including near intersections, in front of bus stops, crosswalks, and driveways, within tunnels, and on bridges. Remaining available space was then used to estimate available

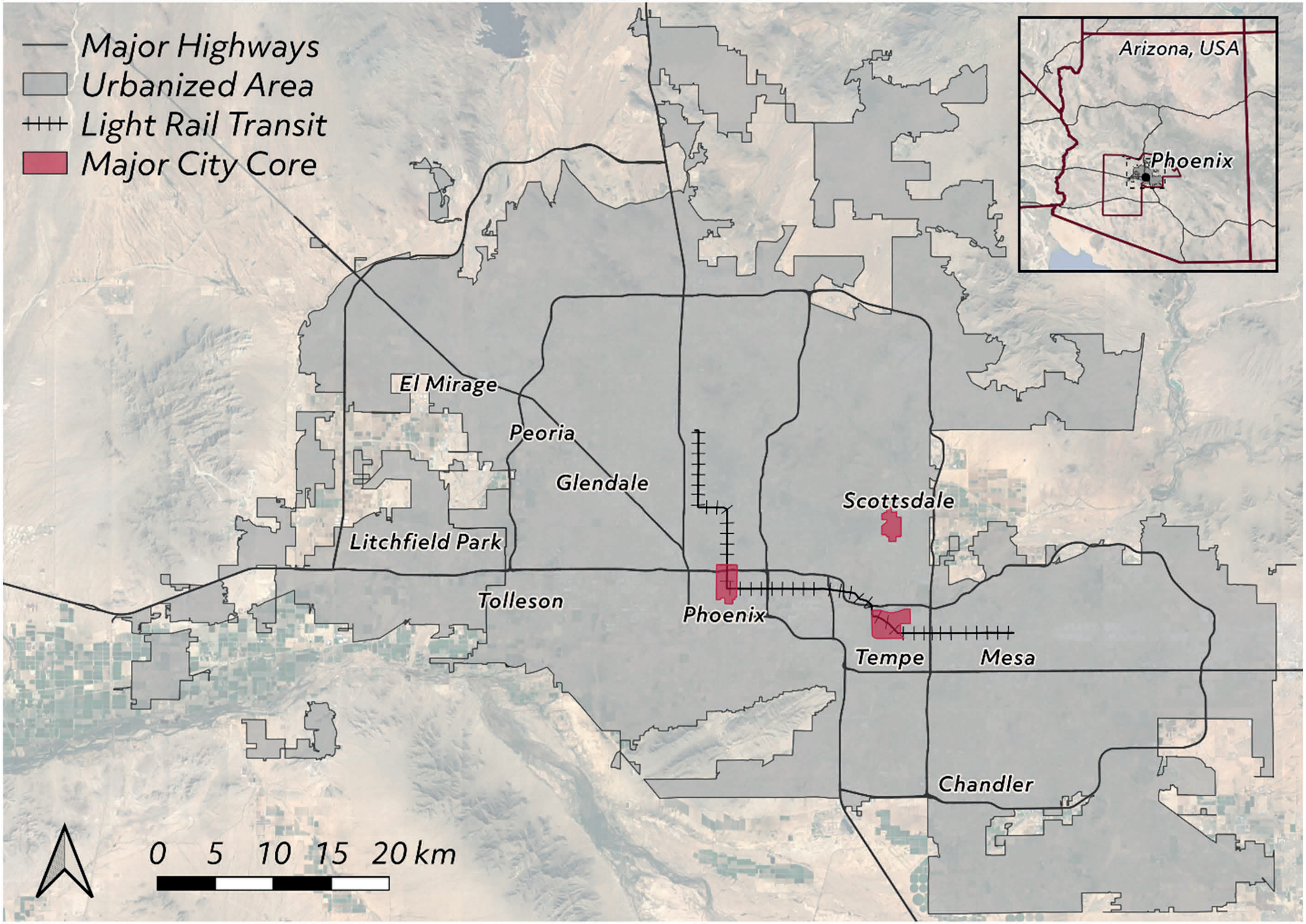

Fig. 1. Metro Phoenix including major highways, major downtowns, and the light rail transit. The study region is shown along with major highways, the main light rail transit line, and three primary downtown districts (red) of the Cities of Phoenix, Scottsdale, and Tempe. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

curbside parking, assuming a 6.7 m (22 ft) length and 2.6 m (8.5 ft) width per on-street space. Due to a lack of spatially explicit data regarding fire hydrant locations, we assumed the maximum allowed spacing between fire hydrants. This resulted in the loss of one parking space per 152 m (500 ft) of curb space. All other obstruction locations were modeled using OSM data.

Due to a lack of data, metered or marked on-street spaces were not distinctly estimated but were assumed to be captured because metered spaces either replace where an unmetered space would exist, or on-street metered spaces substitute for required off-street parking. Regardless, on-street metered spaces are likely an insignificant fraction of the total space estimates; the City of Phoenix operates approximately 2000 metered spaces (City of Phoenix, 2018b).

2.2. Estimating off-street parking

To estimate off-street parking, parcel-level cadastral data (the finest resolution of land delineation data in the U.S.) from the Maricopa County Assessor's Database was cross-referenced with municipal minimum parking requirements by property type as listed in each city's zoning regulations (Maricopa County Assessor's Office, 2017). A parcel is often equivalent to a building lot, but may sometimes contain multiple structures. Off-street minimum parking requirements were codified by jurisdiction with over 2000 property use codes across 33 cities and towns in the metro region. The number of parking spaces for each of the 1.6 million parcels in urbanized Maricopa County was modeled by cross-referencing codified minimum requirements in the jurisdiction of the parcel.

For the majority of non-residential property types, the required number of spaces is based on the total floor space of the building(s) at the parcel. Most jurisdictions have very similar requirements; for example, offices in nearly all cities in the metro region require one space per 28 m^2 (300 ft^2) of floor space (City of Phoenix, 2018a; City of Scottsdale, 2018; City of Tempe, 2011). In these cases, total required off-street parking is simply a product of total parcel floor space and the parking space per floor space factor from the parking code.

Residential and commercial lodging properties often require spaces based on the expected number of residents or the number of dwelling units rather than total floor space. In every municipality in the region, two spaces are required per single-family detached dwelling unit (i.e. single family home). For multi-family units, required spaces range from 1.0 to 2.5 spaces per dwelling unit. Due to a lack of consistent reporting of the total units per residential or commercial lodging facility, total spaces were estimated by one of two methods: when total units are reported, the total spaces equal total units times spaces required per unit; and when total units are not reported, typical dwelling unit floor space sizes are assumed (e.g. studio and 1-bed apartments, hospital rooms, hotel rooms, etc.) to estimate the number of units present in a multi-unit complexes. For apartment complexes, city-average apartment sizes were referenced for each municipality via RENTCafé (Yardi Systems Inc., 2018). For other multi-dwelling units, average unit sizes are assigned based on local, regional, or national averages. For details on specific assignments for residential and commercial lodging properties, see the Supplementary Information (Table S1).

To estimate total surface area dedicated to parking (coverage area), we assumed 31 m^2 (330 ft^2) of paved surface per off-street space to account for access ways, accessible parking, and excess residential driveway and garage space. This is equivalent to a parking lot density of 325 spaces per hectare, consistent with typical parking lot space densities (Holland, 2014; Manville & Shoup, 2005; VAA, 2018). For residential driveways, visible driveway areas were measured using satellite imagery and were found to be consistent with 61.5 m^2 (662 ft^2) for an average sized driveway (to accommodate at least two parked cars). Total surface area for on-street parking is allocated only by the size of the on-street space itself (17.4 m^2 or 187 ft^2). We also estimated roadway coverage area for the region using OSM data with standard lane and shoulder widths by functional class.

2.3. Estimating historical growth of parking

To assess the historical growth of parking, off-street and on-street spaces were assigned a construction year linked to the construction year of surrounding buildings. Specifically, each parcel of land has a construction year that corresponds to the first year the property was developed. This approach assumes that all off-street spaces currently present were constructed in the year the land was initially developed. On-street spaces were assigned the construction year of the average neighborhood parcel construction year minus one standard deviation following Chester et al. (2015). This assumes that nearby local and residential streets were constructed approximately when neighborhood property development started accelerating. We assume this to be generally true in that roads and other infrastructure for housing subdivisions and commercial districts are built in order to develop adjacent properties. There are times when this does not hold, where infrastructure was built and development did not follow, but based on consistent growth in the region, this is assumed to be rare.

2.4. Validation

We focused on validating off-street non-residential and off-street high-density residential parking spaces for two reasons: 1) these types of spaces had significantly higher variation at the parcel level, largely due to varied inter-city requirements for non-residential and mixed-use property types; and 2) manually validating in-situ parking is time intensive and therefore effort is concentrated on these high variance property types. Low variance in on-street parking and off-street low-density residential parking is predictable because on-street parking spaces are allocated using geospatially consistent inventories of roadways minus known obstructions, and low-density residential parcels consistently have a single off-street driveway per single family dwelling unit.

To validate our estimate of parking supply, we first counted parking spaces using satellite imagery, and when available, verified with local inventory estimates via publicly available records. Then, researchers manually counted parking spaces using satellite imagery for eight representative census blockgroups with a diverse selection of property types and sizes. Some additional parcels with unique purposes and high parking estimates such as concert venues, convention centers, large higher education facilities, and hospitals were also chosen for individual validation. These results were compared against the required parking estimates. For surface lots, counting spaces was straightforward as individual stalls were clearly visible in the images. For above-ground parking structures, the total number of spaces were estimated by multiplying visible space on the top floor by the number of stories of the structure.

2.5. Supplementary data sources

We investigate the amount of urban parking compared to other urban statistics on automobile registrations, employment, and population. Passenger vehicle registration data are referenced from the Arizona Department of Transportation (ADOT, 2018) and Kenworthy et al. (1999). Non-farm employment data are referenced from the US Bureau of Labor Statistics (US BLS, 2018) and the Arizona Office of Economic Opportunity (AZ OEO, 2018a). Historical, current, and future population estimates are referenced from the US Census Bureau (US CB, 2018b) and the Arizona Office of Economic Opportunity (AZ OEO, 2018b, 2018c).

3. Results

3.1. Current parking inventory

In 2017, there were a total of over 12 million spaces and 4.0 million inhabitants in metro Phoenix, or approximately 3.0 parking spaces per person. For every registered non-commercial passenger vehicle there are 4.3 total parking spaces of which 1.3 are off-street residential spaces, 1.3 are off-street non-residential spaces, and 1.7 are on-street spaces. For every (non-farm) employed individual, there are 6.6 parking spaces, 2.1 of which are non-residential (on or off-street). Parking and roadway pavements have a coverage area of 36% of the metro's land area (10% parking and 26% roadway). This agrees with previous estimates of urban pavement land cover being between 30 and 40% (Akbari et al., 2003). Coverage area is defined as the total surface area of pavements including access ways, accessible parking spots, parking spaces located in parking garages, residential driveways, etc. Note that these estimates of coverage area are *not* land cover of roadway and parking pavements; parking spaces and roadways may occasionally be vertically stacked (e.g. parking garages). Also note we did not include coverage area of pedestrian or transit travel ways (e.g. sidewalks). Summary statistics of the parking inventory are displayed in Fig. 2 (for results in table format, see the Supplementary Information).

Parking density is highest in urban and commercial cores and lowest in the suburbs and natural preserve and park land. The entire metro Phoenix has a parking density of approximately 39 spaces per hectare. Spatial distribution of parking density is shown in Fig. 3. At the blockgroup level, median parking density is 48 total spaces per hectare, 25 off-street spaces per hectare, and 19 on-street spaces per hectare. The median parking coverage area per blockgroup is 12%. The downtown areas of Phoenix, Scottsdale, and Tempe, which are the three largest employment and activity centers, (see Fig. 1 for boundaries) have some of the highest density of parking in the region. Of the three, Downtown Scottsdale has the highest density of parking (127 spaces per hectare) compared to Downtown Tempe (113) and Downtown City of Phoenix (112).

Parking density in metro Phoenix is spatially heterogeneous and may vary significantly by parking space type. In addition to classifying parking spaces as on or off-street, spaces are also classified as residential or non-residential based on dominant surrounding property type and road classification. Spatial distribution of parking spaces by these four major types is shown in Fig. 4. On-street and residential parking appears relatively spatially homogenous due to the high amount of residentially zoned land in urban Phoenix; over two-thirds (67%) of urban parcels are designated as single family residential (SFR) dwellings. Residential and off-street parking are the dominant types of parking; residential parking (on and off-street) accounts for 69% of total spaces, and off-street parking (residential and non-residential) accounts for 60% of total spaces. Conversely, off-street and non-residential parking is highly concentrated around major travel ways and centered on downtown Phoenix.

3.2. Historical parking growth

Since the middle of the 20th century, parking supply has grown rapidly in metro Phoenix, but since the 2008 recession, growth has significantly slowed. This is consistent with infrastructure maturation theory (Chester & Allenby, 2018) and infrastructure results for other cities (Chester et al., 2015; Chester & Cano, 2016). Before 1960, there was less than one off-street parking space per resident, and the majority of available parking was on-street. Since 1960, metro Phoenix has seen an increase of 11 million parking spaces, 3.4 million residents, 2.6 million personal and non-commercial vehicles, and 1.6 million non-farm jobs (Fig. 5). The volume of parking space growth has been driven by residential and off-street additions, but the densest growth occurred in downtown and commercial areas with significant parking growth around metro Phoenix's light rail corridor (Fig. 6). Since the 2008 recession, parking space additions have slowed significantly. From 1960 until 2000, there was an average parking space growth rate of 5.2% per year. From 2000 to 2008, the parking growth rate declined all but one year from 3.8% to 1.3%. Since 2008, growth of parking spaces has dramatically slowed with an average growth of 0.44% spaces per year.

There is a wide range of possibilities when considering future growth of parking in metro Phoenix. Recent trends allude to a significant slowing in parking growth. However, if the development and parking growth in metro Phoenix returns to 2000–2008 rates (2.8% average growth per year), as many as 3.9 million spaces could be added in the next 10 years, and current parking capacity could nearly double by 2040 to 23 million spaces. Conversely, if post-2008 trends hold, roughly 1.1 million spaces would be added by 2040. For comparison, urbanized Maricopa County is projected to add 1.2 to 2.1 million residents by 2040 (AZ OEO, 2018c).

3.3. Comparing Phoenix and Los Angeles parking

To further evaluate parking in metro Phoenix, we compare results of this analysis with a past analysis of parking in Los Angeles, California (Chester et al., 2015). These regions have many similarities including that the bulk of their growth occurred in the latter half of the 20th century, although Los Angeles developed well before Phoenix. A statistical comparison is shown in Fig. 7 (for results in table format, see the Supplementary Information).

Notable differences and similarities arise when comparing the parking in the metros of the Phoenix and Los Angeles. First, it should be noted that the boundaries of comparison between these studies are slightly different: we assess the urbanized area of Maricopa County and Chester et al. assess parking throughout the whole County of Los Angeles. While these boundaries are different, both capture significant portions of each metro region including the densest areas of population and employment. Los Angeles County had a greater amount of parking in 2010 compared to urbanized Maricopa County now (Fig. 7). This is expected as Los Angeles is arguably the most extreme case of urban parking prevalence with more space dedicated to parking than any other city in the world (Shoup, 1997). Overall, urbanized Los Angeles was denser in 2010 compared to urbanized Maricopa County in 2017; 2702 people per square kilometer in urbanized Los Angeles compared to 1276 in urbanized Phoenix. Hamidi and Ewing (2014) also found that Los Angeles is denser than Phoenix for the county and metropolitan statistical area (MSA) across multiple metrics including land use mix, activity centering, and street connectivity.

Despite the greater overall parking supply and density in Los Angeles, we estimate that metro Phoenix has 36% more on-street parking, largely driven by increased residential on-street parking space. Although Los Angeles appears denser in nearly all apparent metrics, there is not a significant difference in the density of total roadway miles in the urbanized areas of Los Angeles and Maricopa County (urbanized Los Angeles County roadway density: 12.47 km roadway/km^2 urbanized area; urbanized Maricopa County roadway density: 12.45 km roadway/km^2 urbanized area). Although the roadway density is not significantly different between the two regions, Los Angeles parcels are smaller on average, and the road network is more connected. The mean parcel density in Los Angeles County in 2010 was 870 parcels/km^2 compared to 512 parcels/km^2 in urbanized Maricopa County in 2017. The mean intersection density in Los Angeles County was 89 intersections per square kilometer compared to 63 for Maricopa County in 2010 (Fraser et al., 2016), and the street connectivity score was 154 for Los Angeles MSA compared to 111 for the Phoenix MSA (a higher score equates to higher street connectivity; Hamidi & Ewing, 2014). As a result, there is less curb space for on-street parking in Los Angeles per ‘parkable roadway length’ due to increased obstructions from intersections and driveways due to higher intersection and parcel density. Additionally, there may be higher density of other obstructions like fire

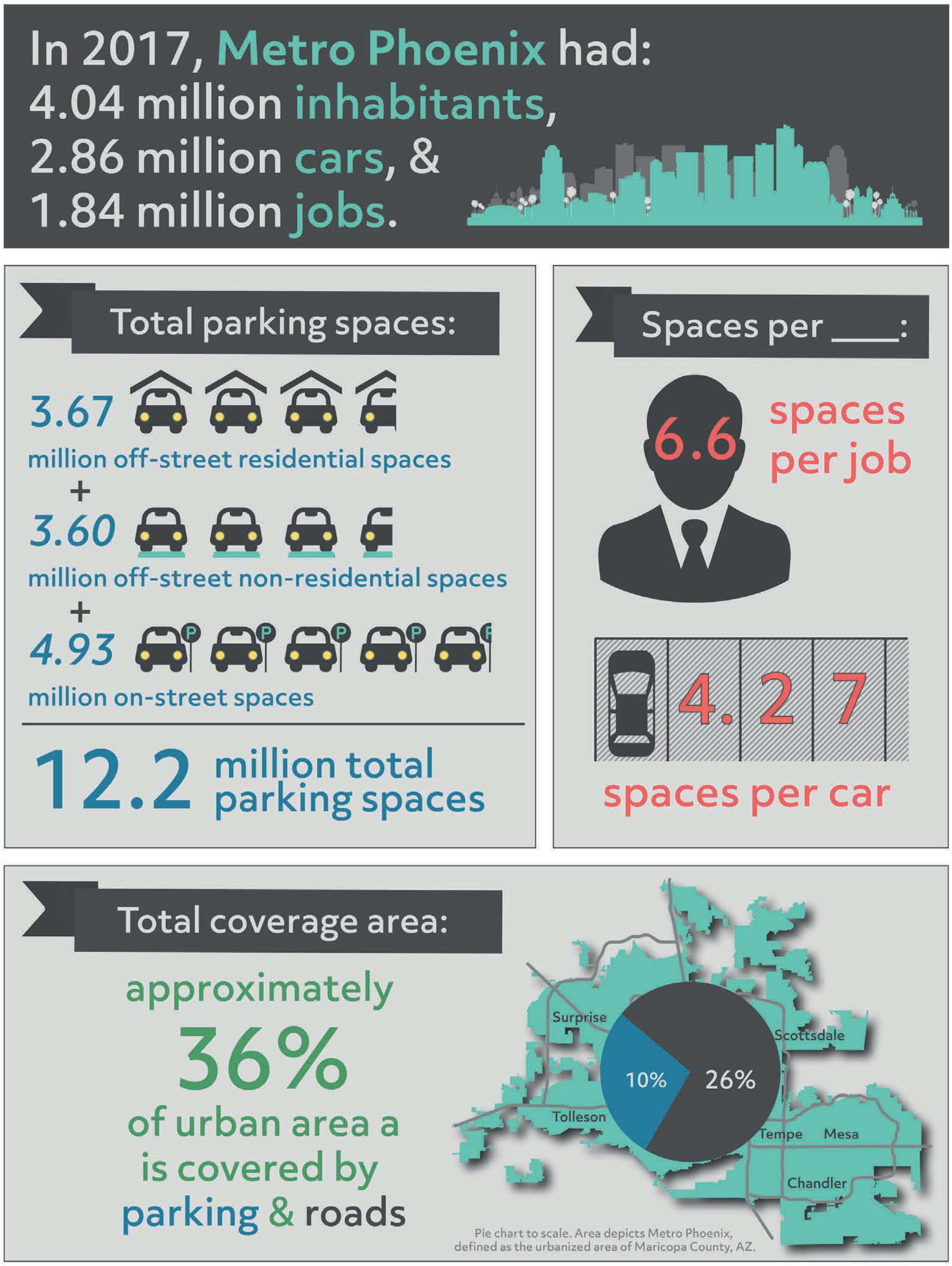

Fig. 2. Summary statistics for metro Phoenix in 2017. All values are for the UZA of Maricopa County only. "Cars" are defined as all registered non-commercial passenger vehicles in the region; "jobs" are defined as all non-farm employment in the region. Note that coverage area is an estimate that includes excess space needed to maneuver and space within parking garages.

hydrants and bus stops given the higher density of parcels and travel demand. Despite the higher availability of on-street parking in Phoenix, it is likely that on-street parking in Los Angeles has higher utilization due to fewer spaces per vehicle and a greater travel density.

3.4. Validation results

Over 22,000 parking spaces were manually counted using satellite imagery across 585 non-residential and high density residential parcels. Co-located parcels were often grouped by neighborhood to ameliorate issues such as shared parking in commercial developments. Percent error in estimated spaces versus counted spaces varied from +110% to −73%, but the highest errors occurred at individual parcels or small groupings of parcels. For all parcels validated, the total error was 6.2% more spaces predicted than counted, and the median error across the grouped parcels was 1.1% more spaces predicted per parcel.

Due to limited historical satellite imagery available at high resolution and almost no other attempts to inventory parking in Phoenix, it is difficult to validate our historical parking growth approach. However, a few data points from a past synthesis of transportation statistics in major cities are useful: Kenworthy et al. (1999) estimated parking densities in downtown areas of major cities in 1960, 1970, 1980, and 1990, and there were 36, 57, 69, and 81 spaces per hectare respectively in the downtown City of Phoenix. We estimate 47, 56, 67, and 79 spaces per hectare for the same four years. These estimates are remarkably close, indicating that this historical approach is likely reasonable.

The high variance in actual versus predicated spaces at fine resolution may result from many cases such as: shared parking lots in

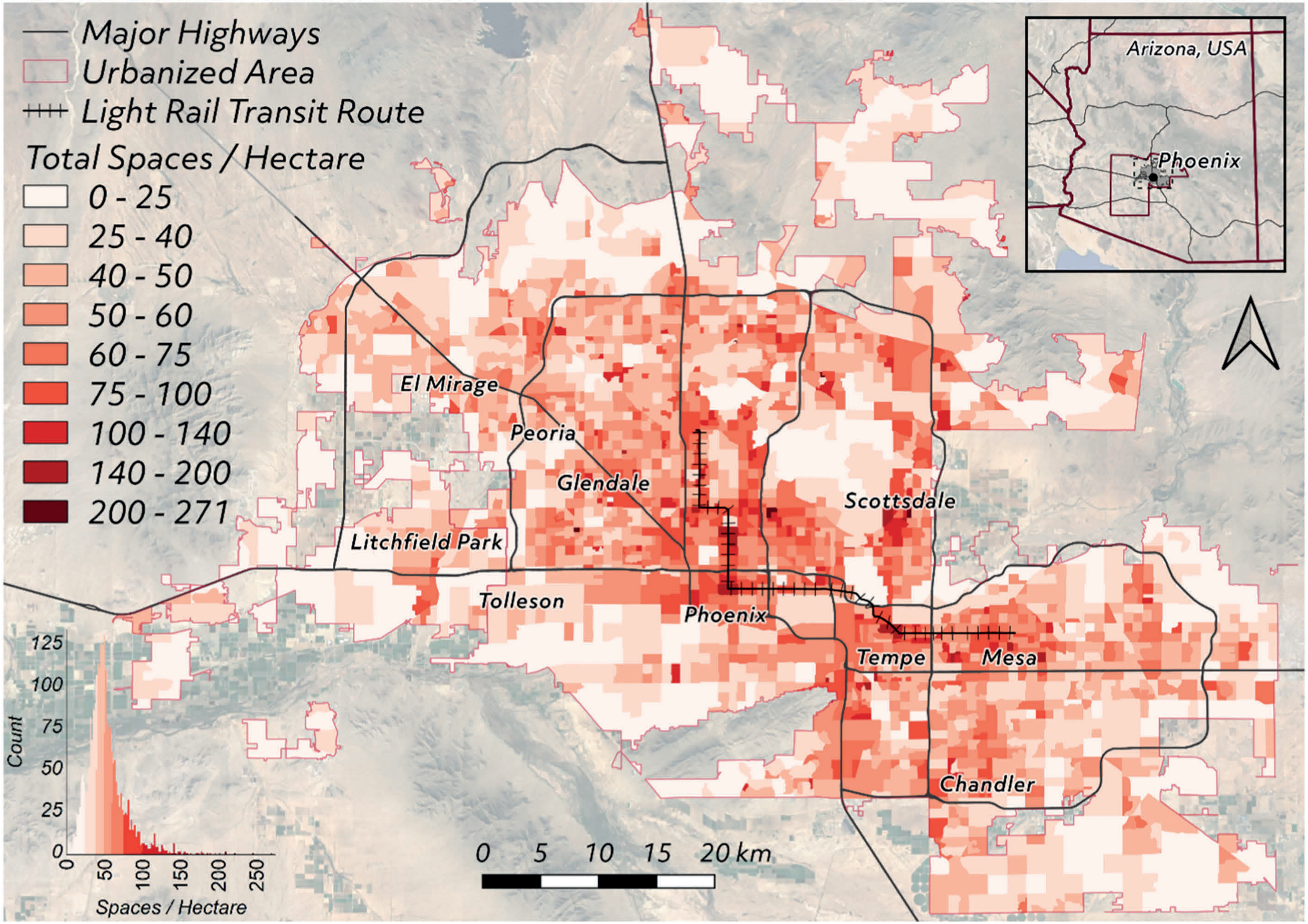

Fig. 3. Total parking density in metro Phoenix by census blockgroup. The distribution of parking space density by blockgroup is located in the bottom left. Estimates are for the UZA of Maricopa County only. Corresponding parking coverage area (%) can be approximated by multiplying total spaces per hectare by 0.3 (e.g. the first bin is 0% to 7.5% coverage area).

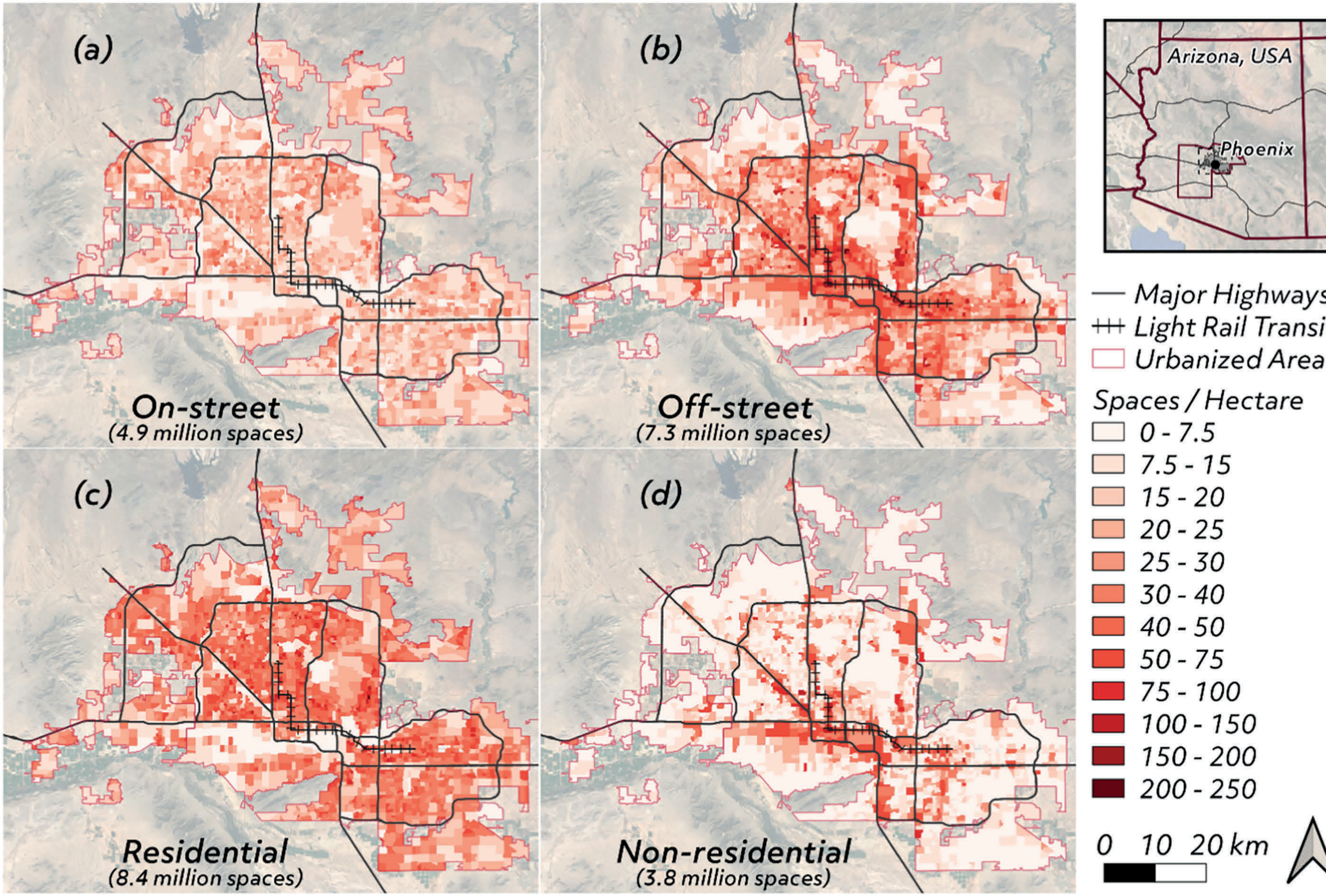

Fig. 4. Parking density in metro Phoenix by type at the census blockgroup level. Four types of parking classification are shown with total spaces in parenthesis below type name. Note that types are only mutually exclusive between on and off-street and between residential and non-residential (e.g. on-street spaces can be residential or non-residential). Estimates are for the UZA of Maricopa County only.

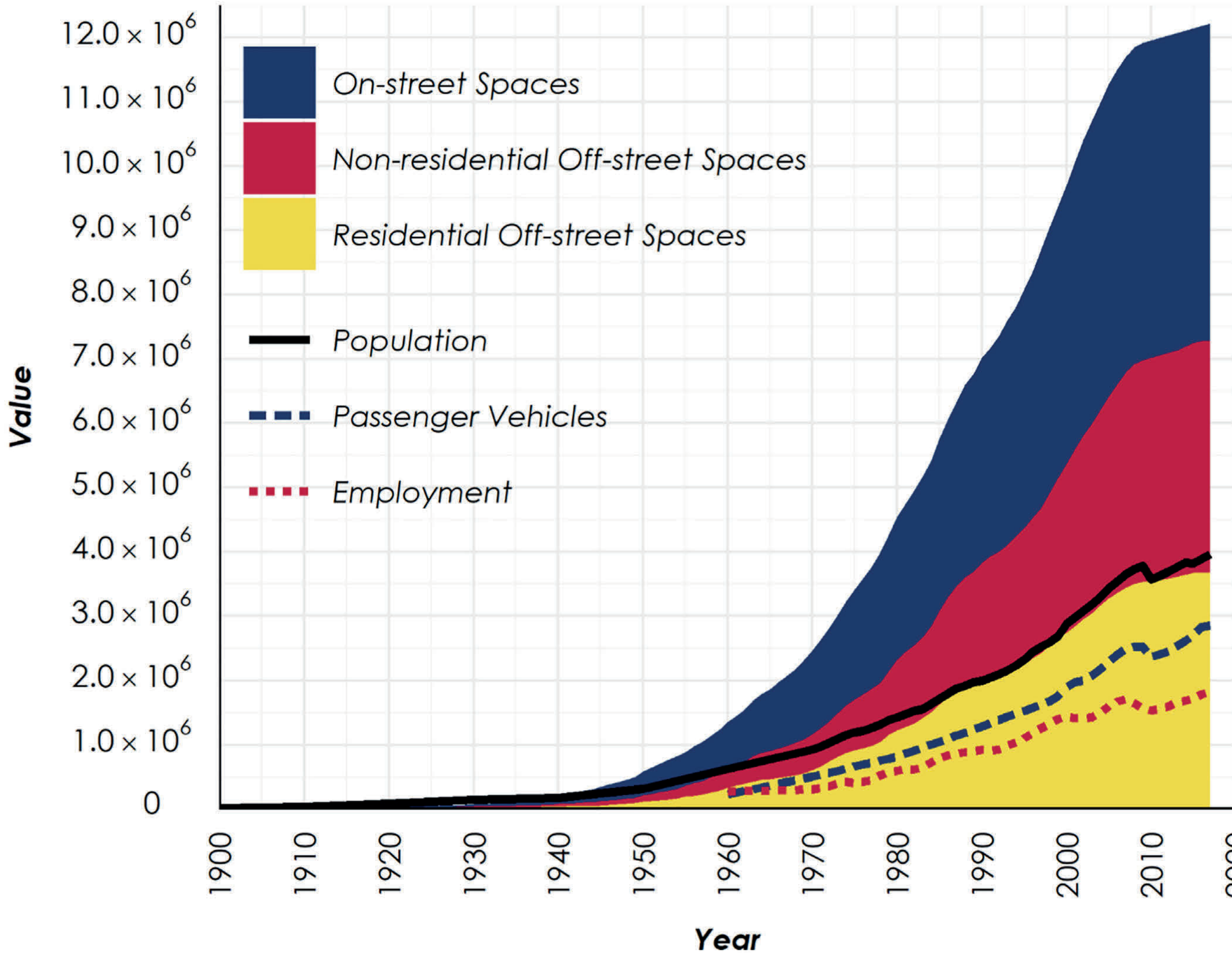

Fig. 5. Growth of parking, population, vehicles, and employment in metro Phoenix, 1900–2017. Parking growth is shown in stacked area. All values are estimates for the UZA of Maricopa County only. "Passenger Vehicles" include registered vehicles only and exclude commercial vehicles, non-motorized vehicles, recreational vehicles, and heavy duty vehicles. "Employment" excludes farm-related employment.

commercial zones; exceptions in special cases; discrepancies in reported versus existing property characteristics; and, developers building beyond minimum requirements. Despite the high variance at a fine resolution, our methods are aimed at accurately estimating parking at a neighborhood level, and given the more reasonable variance at a neighborhood scale, this indicates our approach is reasonable. For more details on the validation results, see the Supplementary Information (Table S4). For discussion of parking inventory limitations and sensitivity, see the Supplementary Information Section S1.

4. Discussion

It is clear there is an abundant supply of parking in metro Phoenix. Shoup (1997) estimated that automobiles are parked 95% of the time, and following Shoup's methodology, which used the National Household Travel Survey, we estimate that the average private automobile in metro Phoenix is parked approximately 98% of the time (USDOT and FHWA, 2017). As a result, 23% of available parking spaces contain a parked private vehicle on average, but without further understanding of the parking demand, it is difficult to conclude if parking is oversupplied. Conversely, it is reasonable to conclude that a residential parking imbalance exists in metro Phoenix given that private vehicle registrations are a reasonable estimate for residential parking space demand. For every private vehicle in Phoenix there is approximately 1.3 off-street residential spaces and 1.7 on-street residential spaces. Comparing to Los Angeles in 2010, there was approximately one off-street residential space per private vehicle and 27% less total on-street spaces. Another specific instance where there is a significant supply-demand imbalance for parking is along the light rail transit corridor between Downtown Tempe and Downtown Phoenix. Along this corridor, there are between four to six off-street residential parking spaces per household vehicle (US CB, 2016). Whether this imbalance is caused by economic reasons, the proximity of a high quality transit, or other reasons, it implies that minimum parking requirements have led to a local oversupply, potentially hindering redevelopment in the area. Regardless of demand, this supply side estimate supports the notion that additional spaces may not be required for urban infill development.

Given the abundant and underpriced parking in metro Phoenix, and the many consequences tied to automobile dependence, planners and policymakers should consider reform of minimum requirements as well as opportunities for improved parking management and parking space repurposing. At a minimum, the precision with which parking regulations force developers to build new parking should reflect the amount of parking that is already built and promote opportunities to share existing spaces. One example in metro Phoenix could be to address the residential parking imbalance by reforming or even removing residential minimum parking requirements. Identifying current and future areas where excess parking could be repurposed will become increasingly

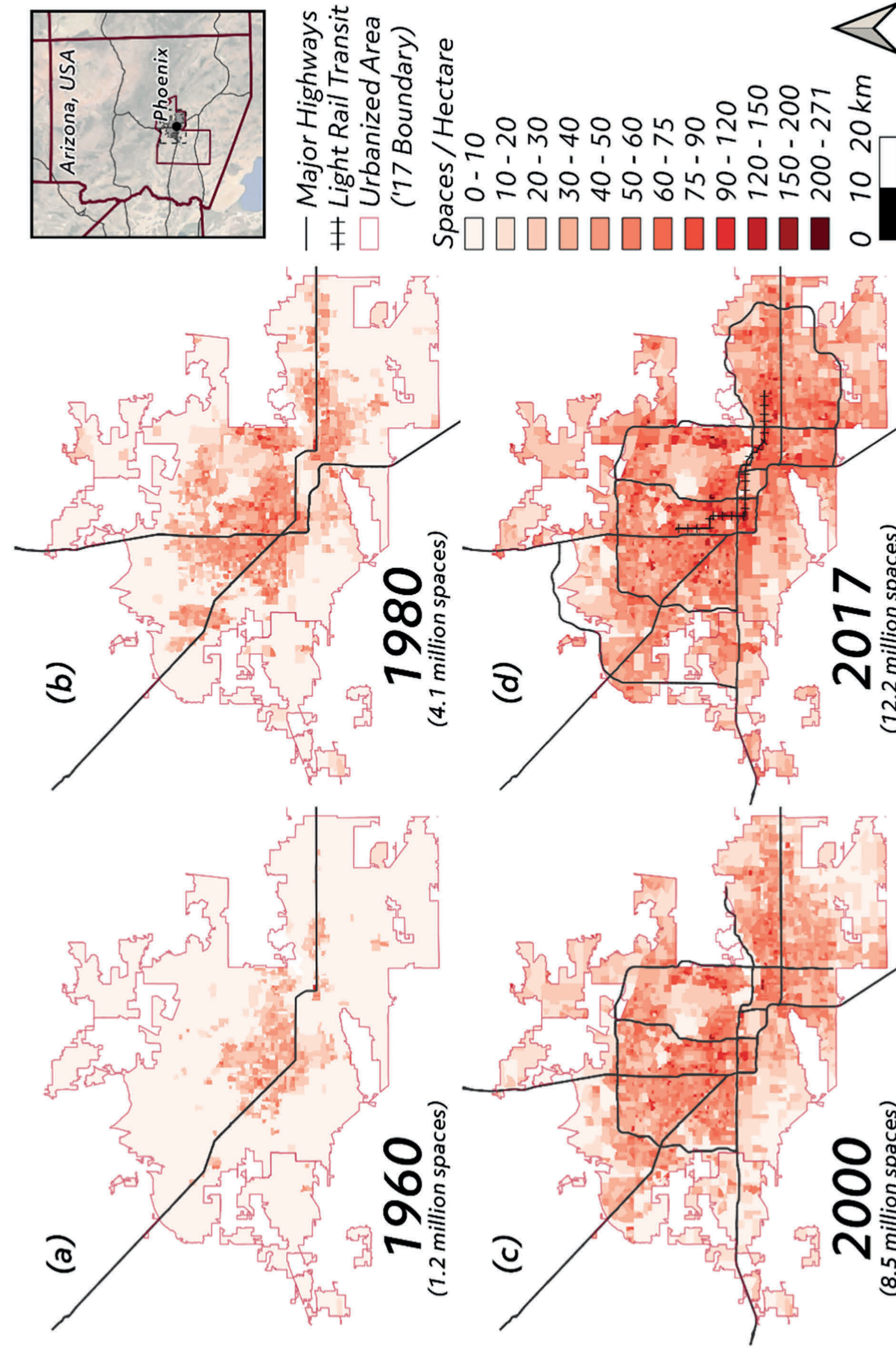

Fig. 6. Parking Growth in metro Phoenix, 1960–2017. Historical parking growth is shown for the 2017 urbanized area boundary in Maricopa County at four points in time. Note that the growth of major highways and the addition of the light rail transit line is captured.

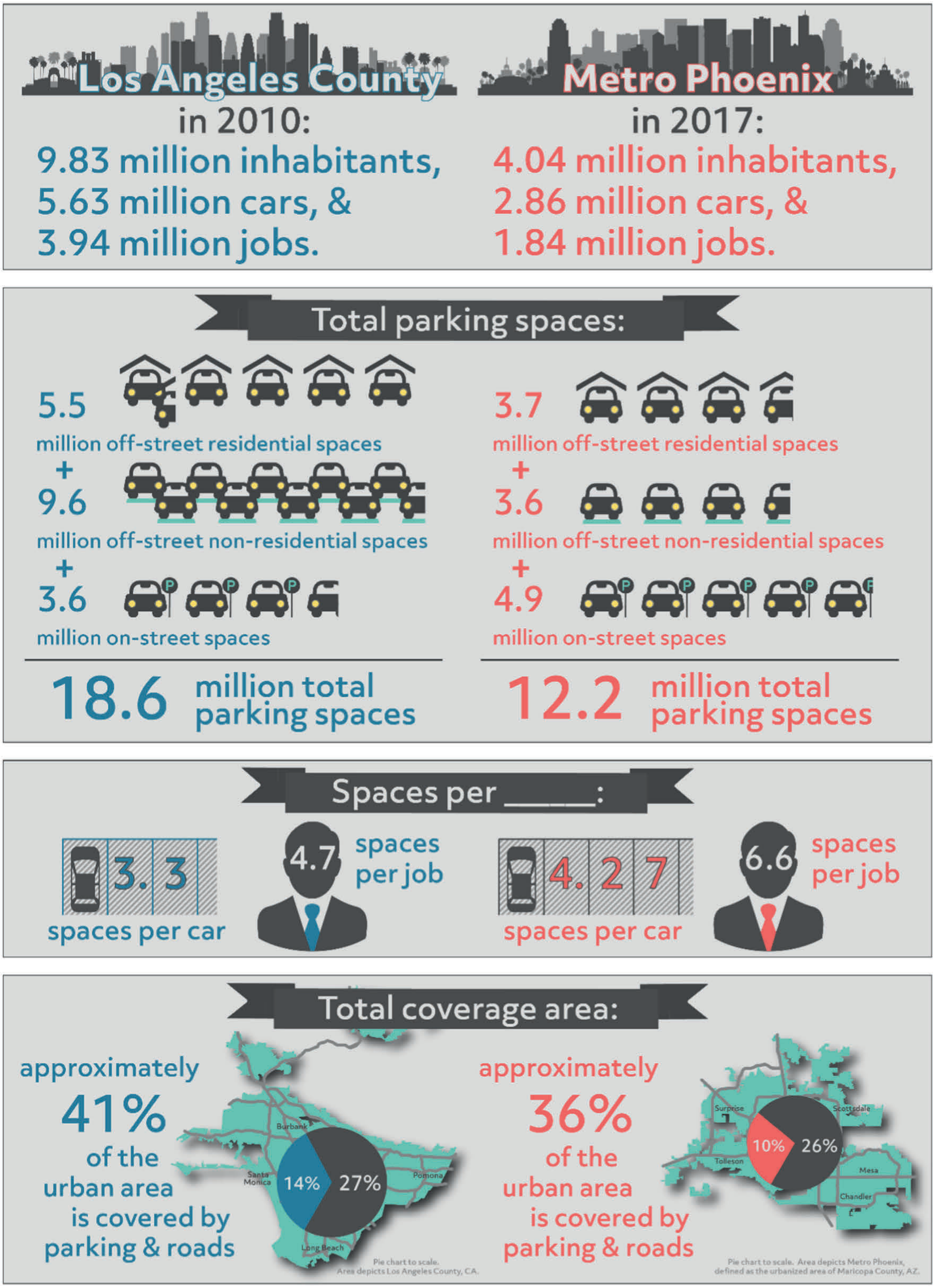

Fig. 7. Summary parking statistics for Los Angeles County in 2010 (via Chester et al., 2015) and urbanized Maricopa County (metro Phoenix) in 2017. "Cars" are defined as all registered non-commercial passenger vehicles in the region; "jobs" are defined as all non-farm employment in the region. Note that coverage area is an estimate that includes excess space needed to maneuver and space within parking garages. UZAs of Los Angeles County (bottom left) and Maricopa County (bottom right) pictured are at the same scale.

valuable, especially as reforming standards will not immediately address issues with already built infrastructure. Excess parking area could be increasingly repurposed for temporary alternative uses such as hosting special events, greenspaces, or increased bike storage. Parking management strategies could also be useful to ensure parking spaces are more efficiently used (Barter, 2010; Cao, Menendez, & Waraich, 2017), optioning further parking repurposing and reform of minimum requirements.

The most common parcel types in metro Phoenix to contribute to the off-street parking supply are SFR properties. An estimated 2.1 million off-street spaces in the region exist due to SFR minimum requirements. Additionally, some jurisdictions in the region require two spaces of sheltered garage parking for SFR properties (e.g. City of Avondale, City of Gilbert). As there are also large amounts of on-street parking in residential neighborhoods, minimum requirements for off-street residential parking could be removed or reduced. For example, minimum requirements could instead be replaced with maximum requirements to encourage use of on-street parking (Manville & Shoup, 2005).

We estimate parking growth has significantly slowed since the 2008 recession. The primary explanation for this is the significant decrease in reported property developments or redevelopments in the Maricopa County Assessors Database. From 2000 to 2008, an average of 4310 parcels were developed or redeveloped per year compared to only an average of 1290 parcels per year since 2009. Population and employment growth also suffered following the 2008 recession, but have since recovered, outpacing parking growth significantly since the recession. Since 2011, 0.66 spaces have been added per new resident, and 1.1 spaces have been added per new job. For comparison, from 2000 to 2008, an average of 2.5 spaces were added per new resident and 6.9 spaces per new job. The overall decrease in property development is the primary reason for decreased parking additions, but there may be two supplementary explanations for slowed growth of parking: 1) a larger amount of property redevelopment in place of new development causes a small increase in space additions relative to existing parking from prior developments; 2) population and employment growth lag behind parking development as land development can precede a property being fully utilized by months or years. Regardless of the specific causes, the slowing raises interesting questions about future parking trends, whether space additions will continue to slow or return to historical trends.

There are many negative externalities of urban sprawl and haphazard parking development independent of sustained automobile dependence, such as further exacerbating urban heat, dis-incentivizing walkability, hindering nearby vegetation growth, and decreasing neighborhood aesthetic appeal. In hot climates, urban heat island and pedestrian thermal comfort are common problems expected to become worse. Local heat islands occur due to high amounts of diurnal solar energy stored in impervious materials (such as parking lot and roadway pavements) slowing radiating back into local air (Asaeda, Ca, & Wake, 1996; Golden & Kaloush, 2006). Being predominantly surrounded by pavements also increases the total amount of reflected solar energy hitting the human body. Wider street canyon widths ratios will decrease shade and increase the total solar radiation reaching the urban floor, decreasing pedestrian thermal comfort (Norton et al., 2015). Parking lot location is also important when promoting walkability and urban greenery. It is common in metro Phoenix to have commercial parking lots wedged between travel ways (roads, bike paths, sidewalks) and buildings. This marginally increases the travel distance and time of pedestrians because they must cross a parking lot to reach a building, potentially also extending their time in local heat islands in summer months. Vegetation near parking lots in hot desert climates may grow poorly compared to vegetation not near asphalt surfaces (Celestian & Martin, 2004). Locating parking lots in-front of instead of behind their associated facility may harm the aesthetic appeal of a neighborhood. Cities in hot climates should be cognizant of these negative externalities from parking lot design and automobile dependence and consider parking lot location, pavement type, and surrounding vegetation in parking standards.

This analysis provides further evidence of several negative outcomes with minimum parking requirements and the consequential state of parking infrastructure development. Furthermore, inconsistencies in current parking standard specifications impede planners and academics from easily understanding the current supply of parking in cities. To most effectively quantify the growth and extent of parking infrastructure in cities, significant improvements in reporting of built and required parking is necessary.

5. Conclusion

Driven by high automobile dependence and the rapid expansion of property development in the latter half of the 20th century, a significant amount of parking infrastructure exists in metro Phoenix. Considering the many unnecessary negative externalities related to parking such as high land and resource use, increased pollution, and continued promotion of automobile dependence, there is a need to rethink parking development. In addition to all of the negative externalities of parking that any city may face, the impact on urban heat island and pedestrian thermal comfort in hot climates such as in Phoenix are likely significant and potentially hazardous. This research provides further evidence that the current lack of parking inventories paired with inconsistent and misguided parking requirements significantly obstructs efficient use of space and may constrain sustainable urban growth. As a result, there is clear value in identifying opportunities for parking reform, quantifying existing parking supply, repurposing excess parking supply, and further exploring the consequences of abundant parking and urban automobile dependence.

Competing interests statement

The authors declare no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cities.2019.02.007.

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