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Parking by the bay: The supply and implications of parking infrastructure in the San Francisco Bay Area

Rui Li
Arizona State University
ruili11@asu.edu

Alysha Helmrich
Arizona State University
ahelmric@asu.edu

Mikhail Chester (corresponding author)
School of Sustainable Engineering and the Built Environment
Arizona State University
mchester@asu.edu

Abstract: The San Francisco Bay Area is one of the most progressive transportation regions in the deployment of high-capacity transit and the use of policies to encourage active transportation. Yet, there remains a dearth of knowledge on the abundance and location of parking infrastructure. The extent and location of parking supply, including on-street and off-street spaces, are estimated for the nine-county Bay Area by creating a federated database that joins land use, transportation, parcel, building, and parking code layers to estimate the number and characteristics of parking spaces at the census block scale. This bottom-up parking space inventory results in an estimated 15 million parking spaces in the region: 8.6 million on-street and 6.4 million off-street. Residential parking dominates the share of supply at 70%, followed by commercial at 9.4%. Space density is greatest in downtown San Francisco, Oakland, and San Jose—largely attributed to high-rise structures. On-street parking is dominant in the North Bay, commanding 78% of total parking in Napa, 75% in Solano, 68% in Sonoma, and 67% in Marin County. Parking area constitutes 7.9% of the total incorporated area. Notably, when compared to other southwest cities (Phoenix Metropolitan Area and Los Angeles County), the Bay Area parking supply appears better utilized considering spaces per person, per car, and per job. The density and quantity of parking spaces in the Bay Area are critical insights toward developing targeted policies that encourage active mobility and support affordable housing.

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1 Introduction

Parking appears to persist as one of the largest infrastructure in urban areas yet is largely unaccounted for. Parking seems to be everywhere, and with growing evidence of the consequences of abundant and underpriced parking, regions generally have little to no information about the extent of the infrastructure. This information is critical to focus policymaking, such as pricing strategies and zoning decisions. As such, creating parking infrastructure estimates that are spatially resolute represents an important frontier for urban policymakers and researchers, and makes an important contribution to those who are

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seeking to shift driving behavior to more sustainable modes.

Few studies have attempted to systematically estimate parking inventories across an entire urban area or region. Existing estimates tend to follow one of four primary approaches: 1) analyzing satellite imagery (Akbari et al., 2003), 2) surveying (Davis et al., 2010), 3) applying gross space-to-vehicle ratios (Chester et al., 2010), and 4) applying parking requirements to land use (assessor) databases (Chester et al., 2015; Hoehne et al., 2019). The analysis of satellite imagery is promising but distinguishing parking from other surfaces to develop meaningful parking space counts is challenging. Some cities have produced parking space counts when enacting parking policies. These efforts are usually focused on smaller areas such as central business districts where particular policies or technologies will be deployed (City of Oakland, 2016; Schwartz et al., 2016). The application of gross space-to-vehicle ratios can provide a big-picture perspective of parking but is not spatially explicit, and its accuracy requires validation. Chester et al. (2010) used this approach to develop bounding scenarios of parking space totals for the U.S., estimating between 730 to 840 million spaces, and the corresponding energy and emissions footprints relative to vehicle travel. Applying parking requirements to assessor databases yields region-wide estimates but requires extensive data analytics and may need to address historical changes in parking requirements. The result, however, is spatially explicit estimates of parking associated with parcels or neighborhoods and associated with land uses. For regions focused on developing broad parking policies or concerned about the spatial impacts of parking, the third approach yields rich and targeted information. For example, a parking space inventory for Los Angeles County was used to analyze car-sharing behavior (Brown, 2019; Chester et al., 2015), and an inventory for the Phoenix Metropolitan Area shows where the infrastructure contributes to the urban heat island effect (Hoehne et al., 2019, 2020). Where significant changes to parking policy are being considered, detailed estimates of parking inventories are needed. This is the case of the San Francisco Bay Area (herein, the Bay Area), a region with a history of progressive transportation policies aimed at achieving environmental and equity goals, that has recently been exploring alternative policies for existing parking standards.

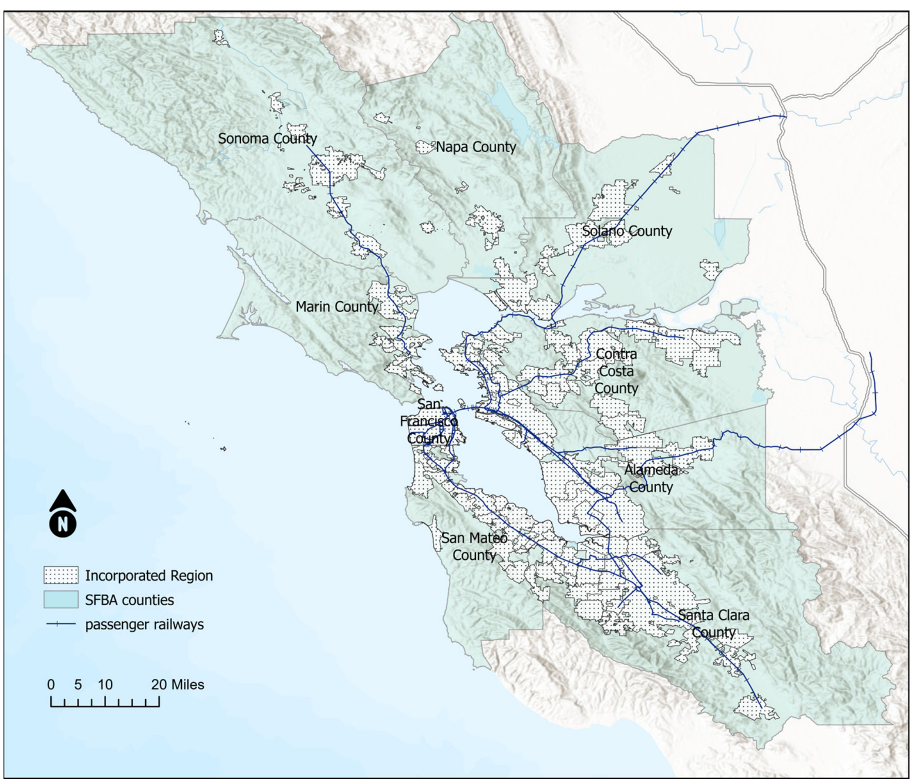

Figure 1. San Francisco Bay Area as counties and incorporated regions: Bay Area's nine counties, incorporated region, and major passenger railways are shown

The Bay Area in Northern California (Figure 1), with a population of approximately 7.2 million, is the second-largest urban area in California and the seat of the fifth largest combined statistical area in the U.S. (Census Bureau, 2010, 2021). With a land area of 3,797 square kilometers (938,229 acres), the incorporated region is constrained by the Pacific Ocean, the San Francisco Bay, and various mountain ranges (Metropolitan Transportation Commission, 2019). Aggressive conservation efforts have protected open space (e.g., micro parks to nature preserves) in the area, accounting for over one-quarter of the region's total land area (Grant & Szambelan, 2019; McGhee et al., 2014). These geographic realities, in part, help explain the history of progressive transportation policies. Further, the region deployed local and long-distance rail systems that have affected growth (Cervero, 1993); tested alternative fuel vehicle and fuel technologies (Chandler, 2008); piloted novel models for carsharing (Beroldo, 1990; Shaheen et al., 2016); and aggressively pursued the promotion of walking, biking, and transit (Nolan & Reiskin, 2016). In 2010, the City of San Francisco piloted a dynamic parking pricing program in the central business district to deploy novel technologies to help manage supply and demand (Fabusuyi & Hampshire, 2018). There has been a growing interest in the region to rethink parking supply more broadly (Angst, 2021; SF Gate, 2018).

Towards advancing insights into the extent and characteristics of parking in metropolitan regions, we developed a parking space inventory for the entirety of the Bay Area by combining emerging spatial and analytical techniques as well as multiple autonomous transportation and land use data layers into a federated database. This space inventory includes on-street and off-street parking and its associated land uses. In the following section, we start by describing our approach: the use of OpenStreetMap (OSM) data, assessor databases, and city-specific parking requirements to estimate parking spaces at parcels which are then aggregated to the census block scale. Next, we discuss our results, detailing on-street and off-street space characteristics. We conclude by discussing a few implications for the parking inventory. This parking space inventory is the most detailed assessment of parking infrastructure produced for the Bay Area and represents an important starting point for addressing the impacts of surplus parking and crafting policy for future transportation goals.

2 Methodology

In estimating the Bay Area's parking inventory, we advance existing bottom-up parking inventorying techniques by creating a metro region (9 counties) federated database that joins land use, transportation, parcel, building, and parking code layers to estimate the number and characteristics of parking spaces at the census block scale. While existing bottom-up studies exist for metro regions, no identified study has combined multiple heterogeneous county and city datasets to generate a federated database for a large metro region. No single data layer could capture all types of parking in the metro region. Our approach consists of two phases. In the first phase, on-street parking spaces are estimated by evaluating curb length and removing "unparkable" segments. In the second phase, off-street spaces are estimated by joining a Bay Area assessor database with city-specific parking requirements.

The approach is generalizable to any metropolitan region and involves public data layers parsed through the Python programming environment (Figure 2). Common data and generally publicly available data inputs (light gray boxes) include county assessor databases (describing land use, parcel, and building characteristics), city parking codes, roadway areas where parking is prohibited (including bus stops, fire hydrants, and driveways), roadway geometry and characteristics (available through OSM), and census geography. Python modules are used to code on-street and off-street parking inventory estimate logic, including the handling of edge cases (e.g., manual inputs of large-scale public service facilities) and calibration (e.g., validating with existing space counts). The specifics of the model are described in the following subsections and the Discussion includes thoughts regarding the generalizability of the framework).

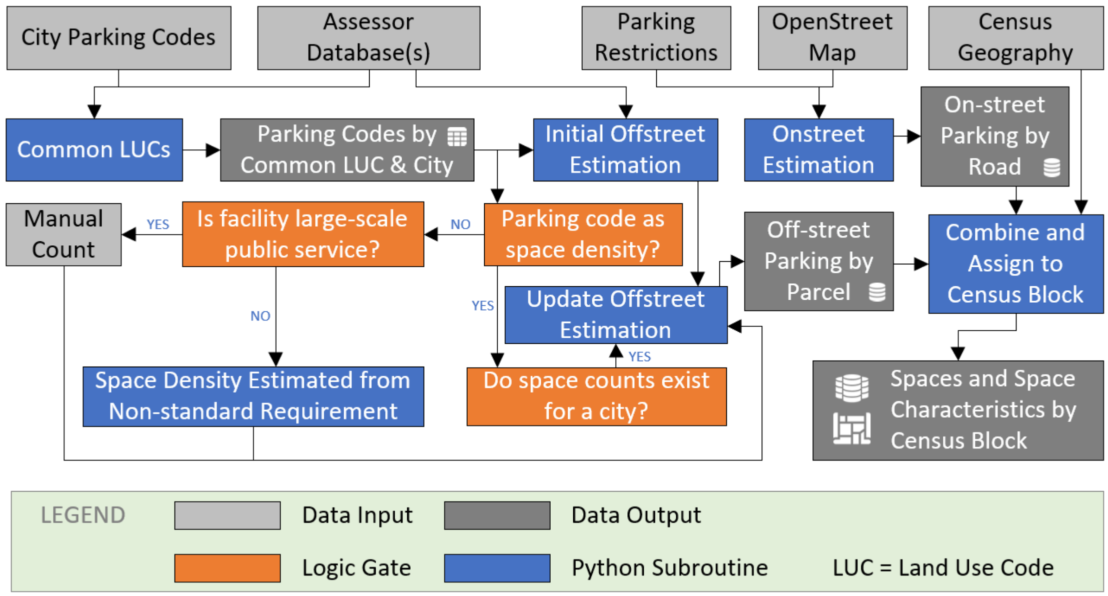

Figure 2. Metro parking inventory model framework

2.1 Estimating on-street parking

On-street parking was estimated from curb lengths of residential and secondary roadways. OSM provides 36 roadway classifications in the Bay Area, including highway, busway, bike and pedestrian path, and trunk road (OpenStreetMap contributors, 2015). Residential, secondary, and tertiary roadways with a travel speed of less than 72 kph or 45 mph (amounting to 35,452 road-kilometers or 22,029 road-miles) were selected for analysis. These roadways correspond largely to local and collector roadways, where on-street parking is most likely to exist and be utilized. The roadways were additionally classified as either residential or non-residential based on the roadway type tag in OSM. On-street parking in unincorporated areas (associated with 15,162 road-kilometers or 9,421 road-miles) is unlikely to be present, as these roads are largely rural. Therefore, on-street, non-residential parking in unincorporated regions was removed. The curb length was reduced to account for bus stations (10 m or 33 ft); intersections (10 m or 33 ft); bridges, tunnels, driveways (4.6 m or 15 ft); and fire hydrants (1 space per 153 m or 500 ft of curb). A curb space length is needed to assess the number of on-street parking spaces and areas. For all counties excluding San Francisco, an average curb space length of 6.1 m (20 ft) and width of 2.3 m (7.5 ft) was used (area of 14 sq. m. or 150 sq. ft.). In San Francisco County/City, there are 81 road-kilometers (50 road-miles) of perpendicular on-street parking (Moran, 2020). This amounts to 3.7% of the 2,179 road-kilometers (1,364 total road-miles). The distribution of parallel and perpendicular spaces was accounted for by developing a weighted average curb space length of 5.6 m (18.4 ft). Metered spaces were not tagged as no region-wide dataset was identified to specify these space types. However, it is expected that metered spaces are captured in the on-street inventory.

2.2 Estimating off-street parking

An inventory of residential and non-residential off-street parking was developed by cross-referencing regional land parcel data with municipal off-street parking requirements. Parcels are flagged based on land use codes that include major categories such as residential, commercial retail, commercial office, recreational, industrial, agricultural, institutional, and miscellaneous. The commercial retail category included uses such as retail stores, shopping centers, restaurants, and gas stations; the commercial office category accounts for land uses such as office buildings, medical buildings, financial buildings, and skyscrapers. 211 land use codes were used to describe off-street parking requirements across the nine counties in the Bay Area. Each county used a unique subset of land use codes to identify their parcels: Alameda (81 of the 211 codes are used), Contra Costa (63), Marin (22), Napa (39), San Francisco (54), San Mateo (88), Santa Clara (104), Solano (51), and Sonoma (145). Marin County, for instance, primarily used general land use codes for major land uses (e.g., "Commercial (General)" was used for all commercial retail uses). Meanwhile, other counties used further delineations of land use types within the major categories presented (e.g., delineating between retail stores, shopping centers, restaurants, etc. within the commercial retail category).

Each county in the Bay Area maintains a separate assessor database that describes each parcel, the land use code, and other characteristics (e.g., building area, parcel area, number of bedrooms, etc.). A parcel is defined as "a contiguous area of land for which location and boundaries are known, described, and maintained, and for which there is a history of defined, legally recognized interests" (National Research Council, 2007). A key challenge was working across the nine assessor databases that each used a separate set of land use codes. The Bay Area's Metropolitan Transportation Commission (MTC) provided a consolidated assessor database, including a consistent set of land use codes applicable for all nine counties. All counties had complete parcel data reported and were published between March 2019 and January 2020. An overview of the distribution of parcels by land use category and county is shown in Table 1.

Table 1. Distribution of parcels and roads by land use categories: on-street percentages describe the fraction of roadways classified as residential versus non-residential; off-street percentages calculated as the proportion of total parcels

County	Off-street Land Use Category								On-street Road Category	
	Residential	Commercial Retail	Commercial Office	Public Service	Recreational	Industrial	Agricultural	Miscellaneous	Residential	Non-residetnial
Alameda	92.60%	2.18%	0.63%	1.73%	0.06%	1.29%	1.52%	0.00%	67.16%	32.84%
Contra Costa	95.54%	1.24%	0.46%	0.91%	0.04%	0.39%	1.41%	0.02%	72.19%	27.81%
Marin	92.34%	1.22%	1.84%	1.58%	0.17%	0.53%	1.92%	0.39%	71.70%	28.30%
Napa	88.57%	3.35%	0.43%	0.36%	0.12%	1.27%	5.89%	0.01%	63.85%	36.15%
San Francisco	92.64%	2.20%	0.88%	0.60%	0.02%	1.29%	1.80%	0.57%	70.84%	29.16%
San Mateo	94.00%	2.06%	0.77%	0.43%	0.11%	1.22%	1.33%	0.09%	70.30%	29.70%
Santa Clara	93.38%	1.55%	0.92%	0.62%	0.08%	1.37%	2.09%	0.00%	69.74%	30.26%
Solano	86.83%	1.66%	0.44%	0.26%	0.04%	0.78%	7.31%	2.68%	68.71%	31.29%
Sonoma	81.47%	1.57%	1.03%	0.70%	0.10%	1.05%	13.54%	0.54%	70.18%	29.82%

Municipal off-street parking requirements describe the minimum number of vehicular parking spaces required for land uses. The municipal requirements were associated with one or more land use codes. These requirements vary from city to city. Of the 101 municipalities in Bay Area, residential and non-residential parking requirements were identified for 99 municipalities. Eighty-nine of the municipal codes reviewed were current as of 2020 or 2021, with the remainder varying (Belvedere: 1989; Hercules: 1998; Belmont and San Leandro: 2008; Livermore: 2010; Dixion: 2012; Windsor: 2013; Cloverdale and San Ramon: 2015). Atherton and Ross were the only municipalities where residential and non-residential parking requirements were not identified. For the cities where codes were not identified, an average of the corresponding county's various municipal codes was used. This same method was used for municipalities that did not report a particular land use type. Through these efforts, a database of the Bay

Area municipal codes was developed (available on GitHub at https://ruilee16.github.io/sfba_parking).

Next, the consolidated county assessor database and municipal parking requirements database were joined. Most off-street parking requirements are based on building area; lot size; or, in the case of residential parcels, the number of bedrooms — all of which are available in the consolidated assessor database. If a land use code did not have an associated parking requirement, equivalent parking was assigned to a similar use. Some parking requirements are based on variables not found in the consolidated assessor database, and these edge cases were assessed using alternative approaches (Table 2). For instance, the number of off-street spaces required at hospitals is generally based on the number of patient beds and/or the number of employees. These edge cases were handled on a case-by-case basis. Additionally, municipalities would occasionally have different parking regulations for various zones (e.g., downtown areas), and these were accommodated when zoning maps were available.

Table 2. Estimation techniques for edge case land uses: edge cases represent instances where land use codes were not identified in the parcel data or parking requirements did not accurately reflect reported spaces

Land Use *Code*	**Examples of Parking Units** (other than building area)	**Estimation Technique**
Airports *6501*	Specific to project	Either manual count (via Google Maps) or reported by the entity.
Assembly Places (e.g., Funeral Homes, Skating Rinks, Clubs) *2037, 2048, 4001, 4002, 4004, 4005, 4006, 4007, 4008, 4009, 4012, 4014, 4015, 4016, 9215*	Area of assembly area; Number of seats	Parking requirements are generally based on assembly and not building area. If parking is > 5 spaces per 93 sq. m. (1,000 sq. ft.), reduce building area by 40% and recalculate.
Auto Repair *2024*	Number of bays	Assumed 10 per facility in San Francisco and 10 spaces per 93 sqm (1,000 sq. ft.) elsewhere.
Car Wash *2025*	Number of bays	Assumed 10 per facility.
Cemetery *9108*	Specific to project	Assumed 10 per facility.
Places of Worship *9101*	Area of assembly/chapel area; Number of seats	Parking requirements are generally based on assembly and not building area. If parking is >5 spaces per 93 sq. m. (1,000 sq. ft.), reduce building area by 50% and recalculate.
Convention Centers *4011*	Area of assembly area; Number of seats; Specific to project	Either manual count (via Google Maps) or reported by the entity.
Day Care *2032*	Number of students; Number of employees	Assumed 10 per facility.
Gas Stations *2020, 2041*	Number of service bays; Number of employees	Assumed 5 per facility.
Golf Courses *4028*	Number of tees; Number of holes	Assumed 4 spaces per hole and 18 holes.
Hospitals *9104, 9219*	Number of beds; Number of employees	Either manual count (via Google Maps) or reported by the entity.
Marina *4003*	Number of berths	Assumed 275 berths per marina and 1 space per berth.
Nursing Homes *9106*	Number of beds; Number of employees	Assumed 100 beds per nursing home.

Land Use *Code*	**Examples of Parking Units** (other than building area)	**Estimation Technique**
Restaurants *2012, 2013, 2014, 2016*	Seating area; Number of seats; Number of employees	Parking requirements are generally based on assembly and not building area. If parking is > 14 spaces per 93 sq. m. (1,000 sq. ft.), reduce building area by 40% and recalculate.
Schools *9102, 9203*	Number of students; Number of classrooms; Number of employees; Specific to project	Assumed 4 seats per 3 sqm (32 sq. ft.); 1 parking space per 4 seats; Assume 5% of building area is for the seated area.
Universities *9103, 9204*	Number of students; Number of classrooms; Number of employees; Specific to project	Where the university population is 10,000 students or greater, either manual count (via Google Maps) or reported by the entity.
Stadiums *4010*	Number of seats; Specific to the project	Either manual count (via Google Maps) or reported by the entity.
Theaters *4020, 4021*	Number of seats; Number of Employees	Assumed 4 seats per 3 sqm (32 sq. ft.); 1 parking space per 4 seats; Assumed 10% of building area is the for seating area.
Parks and Recreation *4027, 9202*	Specific to project	Assumed on-street parking if less than 0.02 sq. km. (5 acres) (community/micro parks); Assumed 30 per facility if greater.
Public Utilities *9216*	Number of employees; Specific to project	Assumed equivalent to office use if a building is present. If no building is present, 0 parking is assumed.

While the edge cases represent a small percentage of the total parcels, they can contribute a significant number of parking spaces within a census block. For example, universities and stadiums may have a large number of spaces in a relatively small area, such as San Jose State University which operates 7,500 parking spaces (SJSU, 2021). A variety of estimation techniques were used to estimate parcels of various land use types appropriately (Table 2, third column). The first technique entailed referencing parking requirements across the Bay Area to generate a static standard for a land use type, which was then cross-validated with a manual count of select facilities across the region. The estimation was deployed because the parking requirements used a unit that was not available in the consolidated assessor database (e.g., number of holes at a golf course), but the variation within a land use type was relatively minimal. The manual count for validation was conducted using satellite imagery on Google Maps. This technique was applied to car washes, gas stations, daycares, golf courses, marinas, and nursing homes. For marinas and nursing homes, assumptions had to be made before generating a static standard. For nursing homes, an average of 100 beds per facility was assumed (Gabrel, 2000), as the number of beds regulates nursing home parking. Marina parking is based on the number of berths which was not reported in the assessor database. An average of 275 berths was assumed per marina based on the approximately 11,000 berths across 40 marinas in the Bay Area (Boating San Francisco, 2020).

The second technique confirmed parking at large-scale public service facilities through either a manual count or validation through facility websites and/or parking databases (e.g., Parkopedia, Park-Me). This technique was applied to land uses that required significant amounts of parking — which included airports, hospitals, stadiums, convention centers, and universities — and were isolated enough to count manually. Initial assessments of these facilities produced extensive parking space, so particular attention was given to developing accurate estimates. Again, the units provided in the parking requirements were not available in the consolidated assessor database. The variation within each land use type restricted the ability to create a standard like the previous estimation technique. For instance, the San Francisco International Airport operates near 15,000 parking spaces. Meanwhile, the Oakland International Airport manages around 7,000 parking spaces. An inventory of spaces for Bay Area Rapid Transit parking structures was also incorporated in this manner (BART, 2021).

The third estimation technique involved developing a non–standard parking density estimation per land use type; these standards were produced through manual counts of satellite images on Google Maps and cross-validated with parking requirements. This technique was used in instances where there was a variation of parking requirements within a land use code, and it was not feasible to count every facility (e.g., restaurants). Parking requirements for assembly places, places of worship, and restaurants are largely determined by assembly space, congregation areas, or seating areas, respectively. Therefore, if the parking code made this specification, the building area was reduced by the listed percentage in Table 2. A similar approach was followed for schools and theaters, utilizing an estimation of assembly space and seating area. Historic places of worship in high-density areas often did not have off-street parking; therefore, if the parcel structure was built prior to 1930 — roughly the time when off-street parking requirements emerged — no off-street parking was assumed. This rule was also applied to historical (pre-1930) parcels in San Francisco.

Spaces associated with multi-story structures were adjusted to match reported counts in downtown San Francisco, Oakland, and San Jose. Parking space counts for select areas within the cities were available, which created an opportunity for calibration. San Francisco reported 87,400 off-street non-residential spaces in a study area marking the Northeast quadrant of the city (Schwartz et al., 2016). Oakland reported 21,235 spaces for the downtown area (Nelson\Nygaard Consulting Associates Inc., 2016). San Jose reported 33,537 off-street spaces in its downtown area (San Jose Downtown Association, 2021). When requirements based on city-specific parking codes were applied to multi-story buildings (over six stories), the estimated number of parking spaces was much larger than the actual spaces reported by the San Francisco and Oakland studies. As such, for off-street parking of multi-story buildings, reductions of 65% and 79% were applied for the respective cities in their downtown areas. Meanwhile, in San Jose, the estimates underpredicted relative to the spaces reported by 1.1%. San Francisco and Oakland have a larger share of older multi-story buildings so reductions in parking are expected, whereas San Jose — with newer buildings downtown — appears to be building parking consistent with recent code. As such downtown off-street spaces in San Jose were increased by this percentage to match. The overestimates (for San Francisco and Oakland) may correspond to facility parking variances, either because sufficient underutilized parking is nearby, alternative travel modes exist, or upon construction, it was argued that not all of the building space would be used simultaneously. Variances differ by city, as found in their respective municipal codes (e.g., transit-accessible areas reductions vary from 25% in San Francisco, 30% in Oakland, and 50% in San Jose).

Finally, auto repair shops, cemeteries, parks and recreation spaces, and public utilities were estimated by land use type based on a manual count of select locations (at least 20 parcels) across counties utilizing the land use code. Cemeteries, parks and recreation spaces, and public utilities oftentimes did not have any parking requirements to reference as they were determined by the project within the respective city for which it was developed. Parks under 0.02 sq. km. (5 acres) (micro and community parks, (City of Los Angeles, 2010)), were assumed to have no off-street parking, utilizing on-street parking instead.

Low-resolution assessor data for specific counties and land uses required additional alternative estimation techniques. The Marin County assessor data did not disaggregate land uses beyond a general commercial category. It was assumed that any building over one story or with square footage greater than 3,000 was a commercial office or otherwise commercial retail space. In Marin and Napa counties, recreational land use codes were not used. It was assumed that tax-exempt tagged parcels (often public recreation space) have 30 spaces if over 0.02 sq. km. (5 acres) in size, consistent with the estimation technique used for parks in other counties. Lastly, Santa Clara and San Mateo counties have classified agriculture parcels, typically without reported building structures. For these parcels, it was assumed that there are 2 spaces present. There were no agricultural parcels listed for San Francisco.

To estimate the density of off-street parking, a space size must be used. Two space sizes are considered: one for single-family residential and another for multi-family residential and non-residential. For single-family residential, based on observations of off-street space sizes, a length of 9 meters (20 ft) and width of 2.7 meters (9 ft) is used, resulting in an area of 16.7 sq. m. (180 sq. ft.). For multi-family residential and non-residential off-street spaces both the space itself plus the accessway is considered. An area of 30.7 sq. m. (330 sq. ft.) is applied from (Shoup, 2014), which corresponds to a parking space plus accessways, which are typically needed for lots and structures.

2.3 Modeling environment

A Python program is used to join, analyze, and calibrate the heterogeneous inputs into a federated database. On-street spaces were estimated using a Python module that combines OSM layers, restricted parking layers (bus stops, hydrants, etc.), and census geography. A separate Python module is used to estimate off-street spaces by joining the consolidated assessor database, municipal off-street parking requirements, and manual counts for large-scale public service facilities and perform calibration. The on-street and off-street datasets are combined into a single consolidated federated database using a third Python module. The Python program is available on GitHub.

3 Results

The parking inventory catalogs approximately 15 million parking spaces for the 7.7 million residents in the Bay Area (Census Bureau, 2019), equating to 1.9 spaces per person. There are 2.7 spaces per every employed individual (Census Bureau, 2019). For every registered auto and light-duty truck, there are 2.4 spaces per vehicle (California DMV, 2019). There are 8.6 million on-street parking spaces (6.7 million residential and 1.9 million non-residential) and 6.4 million off-street parking spaces (3.8 million residential and 2.6 million non-residential). Assessing the distribution at a census block level, the median parking density is 4,868 total spaces per sq. km. (19.7 spaces per acre), 2,595 on-street spaces per sq. km. (10.5 spaces per acre), 2,076 off-street spaces per sq. km. (8.4 spaces per acre), 3,558 residential spaces per sq. km. (14.4 spaces per acre), and 865 non-residential spaces per sq. km. (3.5 spaces per acre).

While parking varies spatially across the Bay Area, it is concentrated in the incorporated areas. The total number of parking spaces corresponds to 276 sq. km. (68,272 acres), which is approximately 1.5% of the total 17.8 thousand sq. km. (4.4 million acres) of land area. However, in the 3.48 thousand sq. km. (0.86 million acres) of incorporated area, parking spaces are approximately 7.9% of the land area in the region. This is an average of 840 spaces per sq. km. (3.4 spaces per acre) in the entire Bay Area and 3,262 spaces per sq. km. (13.2 spaces per acre) in the incorporated region. An overview of parking by land use category and county is mapped in Figure 3 and summarized in Table 3. On-street parking averages 58% of total parking per county. Residential parking, the largest parking contributor, accounts for an average of 70% of total parking per county. The second-largest off-street parking land use is commercial (retail and office) parking, averaging 9.4% of off-street parking per county. In total, the edge cases (hospitals, universities, stadiums, etc.) represent an estimated 466,829 spaces or 7.2% of total parking spaces.

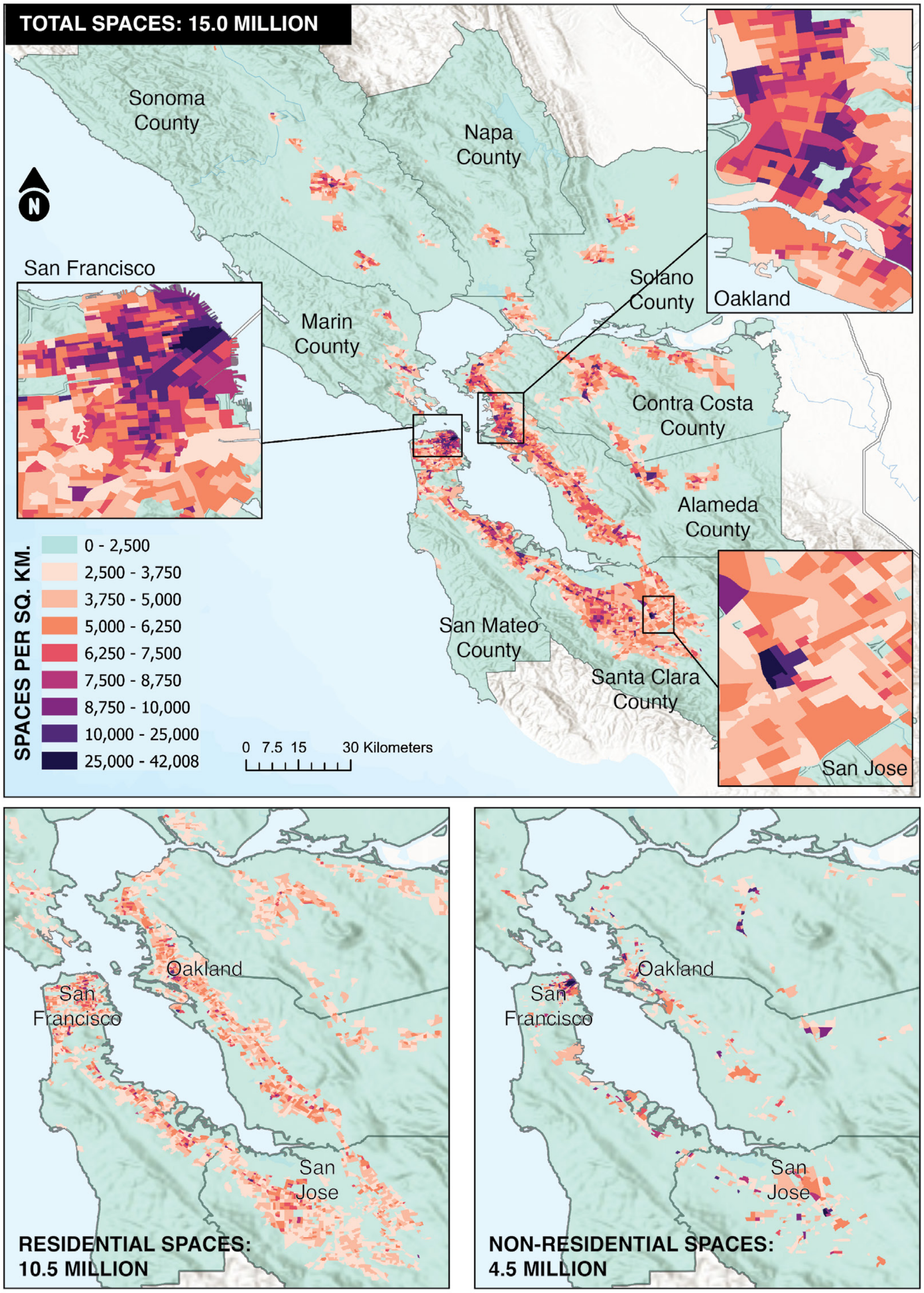

Figure 3. Total parking (on-street and off-street) density by census block

Table 3. On-street and off-street parking by county and land-use category: top of table shows parking spaces and bottom of table shows distributions across land-use types

Land Use	Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma	SFBA Total
Off-street Land Use Category										
Residential	782,019	684,242	164,506	80,814	172,845	395,665	975,860	248,760	320,712	**3,825,423**
Commercial retail	167,487	135,143	3,662	13,962	34,873	53,859	182,451	31,438	58,037	**680,912**
Commercial office	113,619	87,505	67,756	3,006	71,586	108,839	237,353	11,103	35,819	**736,586**
Public service	78,945	74,216	7,020	408	25,236	5,049	39,168	5,614	15,567	**251,223**
Recreational	27,244	11,283	4,425	1,529	4,248	5,891	22,430	2,121	13,149	**92,319**
Industrial	295,966	52,152	7,554	14,471	11,223	64,238	281,543	14,971	42,318	**784,435**
Agricultural	2,477	251	76	51	0	421	7,700	125	756	**11,856**
Miscellaneous	0	0	0	0	63	0	0	0	0	**63**
On-street Road Category										
Incorporated Residential	931,860	815,624	216,467	105,629	202,773	430,308	890,493	318,373	289,578	**4,201,105**
Incorporated Non-residential	424,135	349,768	66,153	37,299	111,215	194,115	473,033	155,319	99,448	**1,910,486**
Unincorporated Residential	272,437	297,366	225,394	252,378	0	144,324	237,353	459,970	635,833	**2,525,055**
Total Residential Spaces	**1,986,316**	**1,797,232**	**606,367**	**438,820**	**375,619**	**970,297**	**2,103,706**	**1,027,103**	**1,246,123**	10,551,583
Total Non-residential Spaces	**1,109,873**	**710,318**	**156,647**	**70,725**	**258,444**	**432,412**	**1,243,677**	**220,691**	**265,094**	4,467,880
Total of Off-street Spaces	**1,467,756**	**1,044,791**	**254,999**	**114,240**	**320,075**	**633,961**	**1,746,505**	**314,132**	**486,358**	6,382,817
Total of On-street Spaces	**1,628,432**	**1,462,758**	**508,014**	**395,305**	**313,988**	**768,748**	**1,600,879**	**933,662**	**1,024,859**	8,636,645
Sum Total of Spaces	**3,096,189**	**2,507,550**	**763,014**	**509,545**	**634,063**	**1,402,709**	**3,347,383**	**1,247,794**	**1,511,217**	15,019,462
Off-street Land Use Category										
Residential	25.3%	27.3%	21.6%	15.9%	27.3%	28.2%	29.2%	19.9%	21.2%	**25.5%**
Commercial retail	5.4%	5.4%	0.5%	2.7%	5.5%	3.8%	5.5%	2.5%	3.8%	**4.5%**
Commercial office	3.7%	3.5%	8.9%	0.6%	11.3%	7.8%	7.1%	0.9%	2.4%	**4.9%**
Public service	2.6%	3.0%	0.9%	0.1%	4.0%	0.4%	1.2%	0.5%	1.0%	**1.7%**
Recreational	0.9%	0.5%	0.6%	0.3%	0.7%	0.4%	0.7%	0.2%	0.9%	**0.6%**
Industrial	9.6%	2.1%	1.0%	2.8%	1.8%	4.6%	8.4%	1.2%	2.8%	**5.2%**
Agricultural	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.0%	0.1%	**0.1%**
Miscellaneous	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	**0.0%**
On-street Road Category										
Incorporated Residential	30.1%	32.5%	28.4%	20.7%	32.0%	30.7%	26.6%	25.5%	19.2%	**28.0%**
Incorporated Non-residential	13.7%	14.0%	8.7%	7.3%	17.5%	13.8%	14.1%	12.5%	6.6%	**12.7%**
Unincorporated Residential	8.8%	11.9%	29.5%	49.5%	0.0%	10.3%	7.1%	36.9%	42.1%	**16.8%**

3.1 On-street parking

The 8.6 million on-street parking spaces in the Bay Area are concentrated in incorporated areas (Figure 4). The majority of on-street parking is classified as residential, averaging 78% of total on-street parking across the counties. There are 1.1 spaces per inhabitant, 1.5 spaces per employed individual, and 1.4 spaces per registered auto and light-duty truck (California DMV, 2019). San Francisco, Napa, and Marin counties have less on-street parking in comparison to other Bay Area counties. Likely, on-street parking cannot accommodate the higher density of people and jobs in San Francisco, Oakland, and San Jose. On-street parking is dominant in the North Bay counties: Napa (78% of parking is on-street), Solano (75%), Sonoma (68%), and Marin (67%). The North Bay is less populated and incorporated than the remaining Bay Area counties. Napa and Sonoma counties, in particular, have more parking identified in on-street unincorporated areas than incorporated areas.

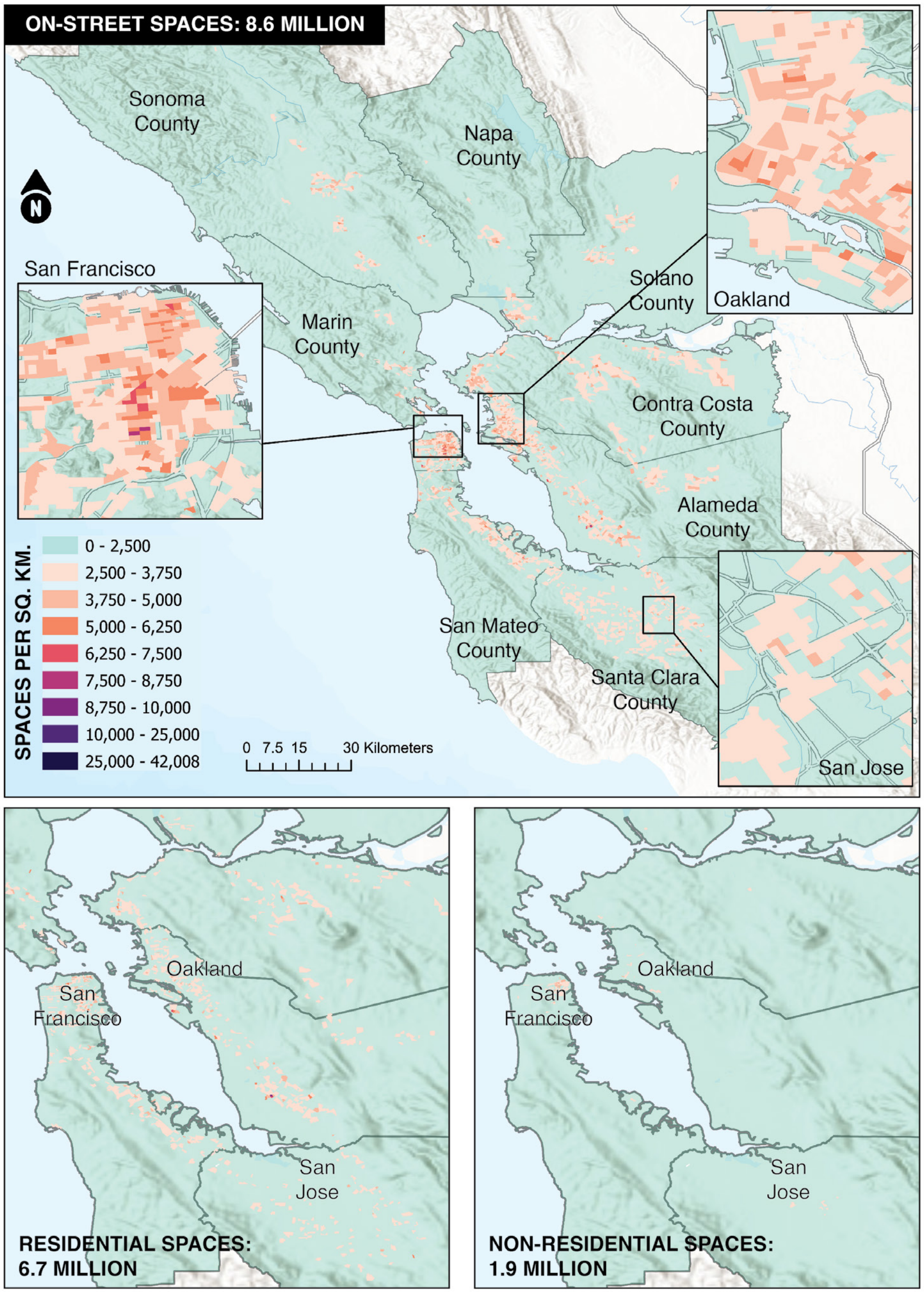

Figure 4. On-street parking density by census block

3.2 Off-street parking

The 6.4 million off-street spaces are concentrated in the core municipalities around the San Francisco Bay, but also are extensive in the East Bay and North Bay edge cities. The greatest densities of spaces are found in the San Francisco, Oakland, and San Jose downtown areas (Figure 5). Downtown San Francisco represents the greatest concentration of parking density owing to the numerous high-rise structures present.

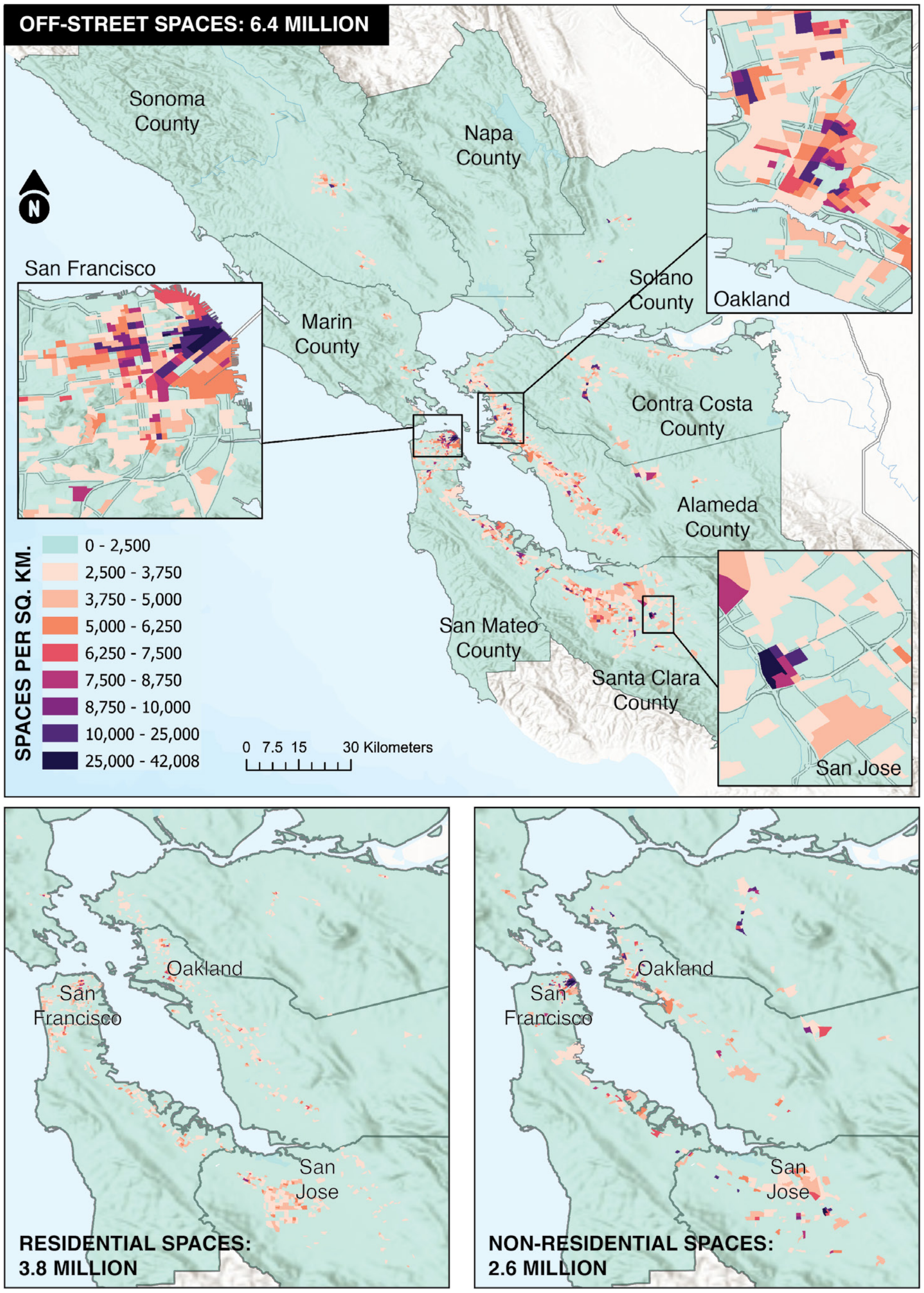

Figure 5. Off-street parking density by census block

Off-street parking is largely associated with residential and commercial land uses, with residential accounting for 54% (Alameda County) to 79% (Solano County) of total off-street parking. This is explained by the dominating share of residential land use codes in each county (Table 1).

Pockets of dense off-street parking are seen throughout the Bay Area but tend to be concentrated in the more heavily populated areas along the East Bay and Peninsula subregions from San Francisco and Oakland south to San Jose. San Francisco has the highest density of off-street parking, reaching 43,595 spaces per sq. km. (140 spaces per acre) in the Financial District. The median census block parking density for downtown San Francisco is 16,309 spaces per sq. km. (66 spaces per acre), dominated by non-residential land uses. Similarly, Oakland's greatest density of spaces occurs downtown at a median density of 11,120 spaces per sq. km. (45 spaces per acre), also driven by non-residential land uses. San Jose appears unique in that it produces pockets of high-density off-street spaces (15,815 spaces per sq. km. or 64 spaces per acre occurring downtown) in a large area of moderate density driven by mixes of residential and non-residential land uses. Pleasant Hill, CA has a major BART-operated parking structure which drives the high density of off-street parking (30,641 spaces per sq. km. or 124 spaces per acre occurring at the BART Pleasant Hill / Contra Costa station). Other notable pockets of high-density parking appear in the downtowns of Concord (11,614 spaces per sq. km. or 47 spaces per acre), Walnut Creek (9,390 spaces per sq. km. or 38 spaces per acre), and Dublin (6,425 spaces per sq. km. or 26 spaces per acre).

A threshold where parking exceeds land area represents an important benchmark for understanding the spatial commitments to parking infrastructure. This threshold occurs at a density of 54,610 spaces per sq. km. (221 spaces per acre). Downtown San Francisco and downtown San Jose have census blocks where the parking density reaches 41,761 spaces per sq. km. (169 spaces per acre), but no census block has a parking area that exceeds land area. However, at the parcel scale, there are over 3,200 non-residential and 780 residential parcels where the parking area exceeds the land area (out of a total of 2.1 million parcels). This dynamic is attributed to heavy concentrations of high-rise structures where multi-story parking is prevalent, often at the base of the building or underground.

3.3 Validation

Validating a region-wide parking inventory at scale is challenging as no commensurate studies of the same region exist; however, internal validation was performed on various pieces of the analysis that, in aggregate, increase confidence in the result's accuracy. First, over 205,000 spaces across at least 3,000 parcels were either counted manually, estimated from dedicated parking lot or structure area reporting, or confirmed via the facility's website or online parking databases (e.g., Parkopedia, ParkMe). Significant validation efforts were made for edge cases, which were either incorrectly or vaguely labeled, not calculable with the available data, or both. Since the parking spaces could not be predicted effectively at these locations, there is no total error to present. The manual counting is subject to errors, such as out-of-date satellite images on Google Maps, concealed parking spaces (e.g., canopy cover, solar panels), and human error. The parking inventory was developed at the parcel scale but aggregated to the census block. In general, parking error at the parcel scale was reduced when total neighborhood parking was aggregated. This is attributed to several factors, including variations actual building level parking construction (possibly constructing more parking than the minimum at times, and less through variances at other times) and the sharing of parking across parcels (e.g., a garage may be utilized by multiple parcels).

Validating against existing reported inventories also provides confidence in the techniques. As previously discussed for multi-story and resulting downtown areas calibration, existing parking counts were available for select regions. In addition to a downtown study area, San Francisco also reports an "extrapolated" city/county-wide estimate of 172,000 spaces (Schwartz et al., 2016). We estimate 153,000 spaces for the same region, which is grounded in a bottom-up count by facility accounting for significantly less density outside of the San Francisco study area. In San Jose, our initial estimates (prior to multi-story adjustments) were within 1.5% of those reported for a downtown study area (San Jose Downtown Association, 2021).

Additionally, efforts were made to manually measure parking space sizes across on-street and off-street land uses and categories. These measurements resulted in the various parking space areas used.

Furthermore, external validation is performed (see Discussion) by comparing the Bay Area results against the Phoenix Metropolitan Area and Los Angeles County regions, where commensurate analyses have been developed.

4 Discussion

The parking inventory results establish a context for assessing the efficacy of dedicating land to storing automobiles and opportunities for guiding urban form and transportation system change. Evaluating the U.S. National Household Travel Survey, vehicles in the San Francisco Bay Area spend on average 97% of the day parked (Federal Highway Administration, 2017). This means that of the 6.2 million automobiles and light-duty trucks registered in the Bay Area, at any given time, there are on average 6 million vehicles that need to be parked. With 15 million spaces, the average utilization rate is 40%. This implies that there are 2.5 times as much parking available across the region than needed.

If all parking spaces were to be spread out on the ground, then a coverage factor can be calculated that describes the percentage of land area dedicated to parking. For example, a 50% coverage factor means that if all parking in the census block were spread out, it would cover one-half of the area. A coverage factor greater than 100% describes a situation where a region has more parking area than land area. The incorporated area of the Bay Area has a coverage factor of 8%, but there are several areas where parking can have larger impact on the use of land. This occurs in locations where multi-story buildings are less prevalent and auto-centered commercial or industrial land uses with an emphasis on surface lots are found. Commercial districts in downtown Livermore result in a coverage factor of 21%, downtown Walnut Creek 40%, and downtown Burlingame 44%. The Southland Mall in Hayward commands a coverage factor of 29%. Industrial areas can also be significant (e.g., industrial zones of Concord result in a coverage factor of 40%). Sporting stadiums can be particularly egregious; the Oakland Coliseum commands an 81% coverage factor. This significant land area coverage and commitment is not just inimical to active transport, but represents a potential slew of environmental concerns, from heat island (Hoehne et al., 2019) to water pollution (Arnold Jr. & Gibbons, 2007) to air quality effects (Chester et al., 2010).

An abundance of parking supply may work against the ability to increase housing supply, but it is also a critical opportunity for redevelopment. California's housing crisis is driven by insufficient housing supply and is contributing to financial instability and homelessness in the state (Alamo & Uhler, 2015). Requiring off-street residential parking reduces the available land for development and opportunities for adapting home garages to accessory dwelling units. As such, identifying locations of dense off-street parking relative to housing supply may help guide strategic change towards improving housing supply. The Bay Area on average commits 80 sq. km. of parking for every 100 sq. km. of residential building floor area. Napa, Solano, and Sonoma counties commit more land to parking than residential buildings, at 110 - 130 parking sq. km. per 100 sq. km. of residential building floor area. San Mateo, Santa Clara, Alameda, Contra Costa, and Marin counties commit 70 - 90 parking sq. km. per 100 sq. km. of residential building floor area. San Francisco has the lowest ratio in the Bay Area, at 40 parking sq. km. per 100 sq. km. of residential building floor area. These land commitments are valuable benchmarks when considering not simply how much more land might be available for development, but perhaps more so in establishing maximum off-street parking requirements such as seen in San Francisco. Establishing upper bounds of how much space cities are willing to commit to parking instead of residential units is an important first step in rethinking land use policy.

Abundant parking near bus and rail stations is likely to work against transit adoption and active transport modes. The Bay Area has a long history of progressive transit policy and investment. As the region confronts heavy automobile congestion and associated inaccessibility, reassessing its commitment to parking near transit will be necessary. The Bay Area defines Transit Priority Areas as an 805 meter (i.e., one-half mile) radius around existing or planned transit (California Legislature, 2020; Metropolitan Transportation Commission, 2017). These areas are shown in Figure 6. There are two parking metrics to consider: density and number of spaces. The Figure 6 chart shows the density of parking spaces for the ten largest Bay Area cities (by population), in ascending order. A greater density of spaces indicates more parking around transit. Following each city's name in the Figure 6 chart is the number of dedicated spaces. San Francisco, Oakland, and San Jose have several hundred thousand spaces around transit, and even if the density is not as large compared to other cities the vast supply represents an opportunity for redevelopment towards encouraging transit ridership.

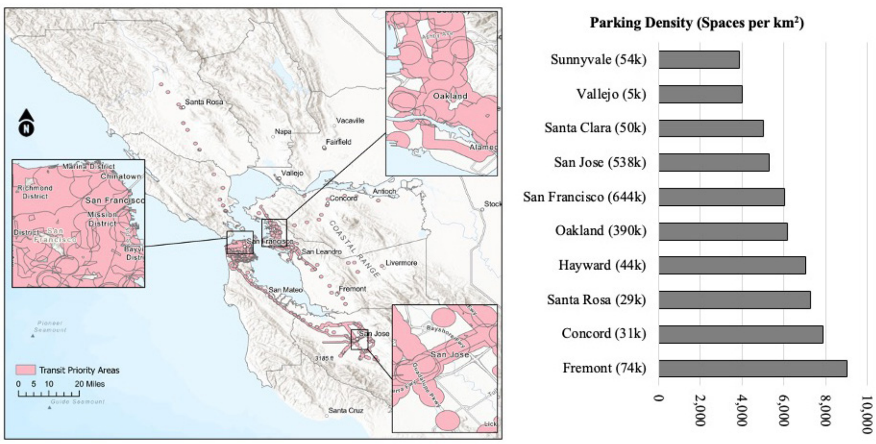

Figure 6. Transit priority areas, parking spaces, and parking density: transit priority areas shown on map on left as pink areas; chart on right shows parking space density and number of spaces (in parenthesis after the city name) in transit priority areas for the ten largest Bay Area cities

4.1 Comparison with commensurate studies

Comparing the Bay Area parking inventory against those developed for Los Angeles and Phoenix provides helpful insights into the commitment, extent, and utilization of parking. In general, the Bay Area outperforms its Southwest counterparts in gross parking utilization metrics. Chester (2015) and Hoehne (2019) provide commensurate findings for Los Angeles County and the Phoenix Metropolitan Area respectively, developed with the same methodological approach to the work here. Comparing key metrics allows for city-to-city comparisons. First, before comparison, it's important to note that while the Bay Area and Phoenix Metropolitan Area results encompass the entire urban area, the Los Angeles County results do not. Los Angeles County is the urban center of the much larger Los Angeles Metropolitan Area, but no region-wide estimate has been developed. Further, the Bay Area includes unincorporated areas, including natural and agricultural lands. The Bay Area with a population of 7.7 million people (Census Bureau, 2019) has less parking (1.9 spaces) per person than the Phoenix Metropolitan Area (4.0 million people and 2.7 spaces per person) but about the same as Los Angeles County (9.8 million people and 1.9 spaces per person). Los Angeles County's comparable share can be attributed to its bounded geography and parking supply usage distributed to a massive population of travelers, as it encompasses several major commuting centers. The Bay Area has 2.4 spaces per car, well below the Phoenix Metropolitan Area (4.3) and Los Angeles County (3.3). It also outperforms on spaces per job at 2.7 (with Phoenix Metropolitan Area at 6.6 and Los Angeles County at 4.7) (Chester et al., 2015; Hoehne et al., 2019). The portion of paved surfaces in the Bay Area is significantly smaller than Phoenix Metropolitan Area and Los Angeles County. Approximately 20% of the incorporated area of the Bay Area is paved with parking (7.9%) and roadways (12.4%). This is roughly one-half that of the 36% paved in the Phoenix Metropolitan Area (10% parking, 26% roadways) and the 41% paved in Los Angeles County (14% parking, 27% roadways) (Chester et al., 2015; Hoehne et al., 2019). In general, the Bay Area appears to have a parking supply that is better utilized than Phoenix Metropolitan Area and Los Angeles County, which is unsurprising given that the region experienced significant growth pre-automobile.

5 Conclusion

The framework advanced in this study provides a methodological foundation for estimating parking land use across a large metro region from heterogeneous but generally publicly available data layers. In combining transportation and land use datasets, the heterogenous layers were combined into a federated database with important characteristics – including on-street and off-street tags, and associated land use characteristics – maintained. The framework can be reproduced for other metro regions following the Figure 2 framework.

The Bay Area parking supply inventory represents a valuable product from which to assess the impacts of policy and urban form changes. The inventory is well-positioned to support assessments of changes to parking supply, including pricing and redevelopment. The results are perhaps most useful when analyzed at the neighborhood level. The spatially explicit results can be used to guide policy and decision-makers toward particular neighborhoods where parking challenges are more prevalent and can provide a benchmark for analyzing policy and redevelopment. Future work could focus on the linkages between parking supply and demand. This could include how parking supply has changed over time and how auto ownership and registrations have followed (Chester et al., 2015; Hoehne et al., 2019), influences vehicle travel, impacts the environment, and contributes to urban heat island (Hoehne et al., 2020), and/or where particular policies (such as allowances for converting home garages to secondary dwelling units to increasing housing supply) are more likely to be impactful. Related, the results provide critical information for rethinking housing policies writ large, for example, where off-street parking requirements constrain the number of units that can be built. Furthermore, transit-oriented development projects should consider the results as an overabundance of parking may work against transit adoption but may be an opportunity for higher-density construction. By establishing spatially-explicit parking supply baselines for the Bay Area, new insights will hopefully be created towards rethinking urban space for future challenges.

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