

A Multi-Scale Analysis of 27,000 Urban Street Networks*

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Abstract

OpenStreetMap offers an underexplored source of worldwide geospatial data useful to urban researchers. This study uses the OSMnx software to automatically download and analyze over 27,000 street networks from OpenStreetMap at metropolitan, municipal, and neighborhood scales—namely, every US city and town ($N = 19655$), census urbanized area ($N = 497$), and Zillow-defined neighborhood ($N = 6857$). It presents wide-ranging empirical findings on US urban form and street network characteristics, emphasizing measures relevant to urban design and morphology such as structure, connectedness, density, centrality, and resilience. In the past, street network data acquisition has been challenging and ad hoc, but this study illustrates the use of OSMnx and OpenStreetMap to conduct street network analysis with extremely large sample sizes, with clearly defined network definitions and extents for reproducibility, and using nonplanar, directed graphs. These street networks and their measures are now shared in a public repository for other researchers to use.

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1 Introduction

On May 20, 1862, Abraham Lincoln signed the Homestead Act into law, making land across the United States’ Midwest and Great Plains available for free to applicants [41]. Under its auspices over the next 70 years, the federal government distributed 10% of the entire US landmass to private owners in the form of 1.6 million homesteads [32, 44]. New towns with gridiron street networks sprang up rapidly across the Great Plains and Midwest, due to both the prevailing urban design paradigm of the day and the standardized rectilinear town plats used repeatedly to lay out instant new cities [45]. Through path dependence, the spatial signatures of these land use laws, design paradigms, and planning instruments can still be seen today in these cities’ urban forms and street networks.

A cross-sectional analysis of American urban form can reveal these artifacts and histories through street networks at metropolitan, municipal, and neighborhood scales. Network analysis is a natural approach to the study of cities as complex systems [34]. The empirical literature on street networks is growing ever richer, but suffers from some limitations—discussed in detail in [10] and summarized here. First, sample sizes tend to be fairly small due to data availability, gathering, and processing constraints: most studies in this literature that conduct topological or metric analysis tend to have sample sizes ranging around 10 to 50 networks [13, 14, 6, 46], which may limit the generalizability and interpretability of findings. Second, reproducibility has been difficult when the dozens of decisions that go into analysis—such as spatial extents, topological simplification and correction, definitions of nodes and edges, etc.—are ad hoc or only partly reported [e.g., 40, 46]. Third, and related to the first two, studies frequently oversimplify to planar or undirected primal graphs for tractability [e.g., 13, 14, 6, 34], or use dual graphs despite the loss of geographic and metric information [7, 29, 42, 20, 19].

This study addresses these limitations by conducting an urban morphological analysis of street networks at multiple scales, with large sample sizes, with clearly defined network definitions and extents for reproducibility, and using nonplanar, directed graphs. In particular, it examines urban street networks—represented as primal, nonplanar, weighted multidigraphs with possible self-

loops—focusing on structure, connectedness, centrality, and resilience. This study analyzes 27,009 urban street networks at multiple overlapping scales across the US. Namely, it examines the street networks of every incorporated city and town (population size $N = 19655$), census urbanized area ($N = 497$), and Zillow-defined neighborhood ($N = 6857$) in the US. To do so, it uses OSMnx—a new street network research toolkit [10]—to download, construct, and analyze these street networks at metropolitan, municipal, and neighborhood scales. These street networks and their measures data have been shared in a public repository for other researchers to use at [link redacted].

The purpose of this paper is threefold. First, it describes and demonstrates a new methodology for easily and consistently acquiring, constructing, and analyzing large samples of street networks as nonplanar directed graphs. Second, it presents empirical findings of descriptive urban morphology for the street networks of every US city, urbanized area, and Zillow neighborhood. Third, it investigates with large sample sizes some claims previously made in the research literature with small sample sizes. This paper is organized as follows. In the next section, it discusses the data sources, tools, and methods used to collect, construct, and analyze these street networks. Next, it presents findings of the analyses at metropolitan, municipal, and neighborhood scales. Finally, it concludes with a discussion of these findings and their implications for street network analysis, urban morphology, and city planning.

2 Methodology

A network (also called a *graph* in mathematics) comprises a set of nodes connected to one another by a set of edges. Street networks can be conceptualized as primal, directed, nonplanar graphs. A primal street network represents intersections as nodes and street segments as edges. A directed network has directed edges: that is, edge uv points one-way from node u to node v , but there need not exist a reciprocal edge vu . A planar network can be represented in two dimensions with its edges intersecting only at nodes [e.g., 50, 38]. Most street networks are nonplanar—due to grade-separated expressways, overpasses, bridges, tunnels, etc.—but most quantitative studies of urban street networks represent them as planar [e.g., 13, 14, 6, 34, 46] for tractability because bridges and

tunnels are uncommon in some cities. Planar graphs may reasonably model the street networks of old European town centers, but poorly model the street networks of modern autocentric cities like Los Angeles or Tokyo with many grade-separated expressways, bridges, and underpasses.

2.1 Study Sites and Data Acquisition

This study uses OSMnx to download, construct, correct, analyze, and visualize street networks at metropolitan, municipal, and neighborhood scales. OSMnx is a Python-based research tool that easily downloads OpenStreetMap data for any place in the world and constructs it into a spatially-embedded graph-theoretic object for analysis and visualization [10]. OpenStreetMap is a collaborative worldwide mapping project that makes its spatial data available via various APIs [16, 31]. These data are of high quality and compare favorably to CIA World Factbook estimates and US Census TIGER/Line data [26, 39, 54, 33, 52, 24]. In 2007, OpenStreetMap imported the TIGER/Line roads (2005 vintage) and since then, many community-led corrections and improvements have been made [51]. Many of these additions go beyond TIGER/Line’s scope, including passageways between buildings, footpaths through parks, bike routes, and detailed feature attributes such as finer-grained street classifiers, speed limits, etc.

To define the study sites and their spatial boundaries, this study uses three sets of geometries. The first defines the metropolitan-scale study sites using the 2016 TIGER/Line shapefile of US census bureau urban areas. Each census-defined urban areas comprises a set of tracts that meet a minimum density threshold [49]. We retain only the *urbanized areas* subset of these data (i.e., areas with greater than 50,000 population), discarding the small *urban clusters* subset. The second set of geometries defines our municipal-scale study sites using 51 separate TIGER/Line shapefiles (again, 2016) of US census bureau *places* within all 50 states plus DC. We discard the subset of *census-designated places* (i.e., small unincorporated communities) in these data, while retaining every US city and town. The third set of geometries defines the neighborhood-scale study sites using 42 separate shapefiles from Zillow, a real estate database company. These shapefiles contain neighborhood boundaries for major cities in 41 states plus DC. This fairly new data set comprises nearly 7,000 neighborhoods, but as Schernthanner et al. [43] point out, Zillow does not publish the

methodology used to construct these boundaries. However, despite its newness it already has a track record in the academic literature: Besbris et al. [9] use Zillow boundaries to examine neighborhood stigma and Albrecht and Abramovitz [3] use them to study neighborhood-level poverty in New York.

For each of these geometries, we use OSMnx to download the (drivable, public) street network it contains, a process described in detail in [10] and summarized here. First OSMnx buffers each geometry by 0.5 km, then downloads the OpenStreetMap “nodes” and “ways” within this buffer. Next it constructs a street network from these data, corrects the topology, calculates street counts per node, then truncates the network to the original, desired polygon (ensuring that intersections are not considered dead-ends simply because an incident edge connects to a node outside the desired polygon). OSMnx saves each of these networks to disk as GraphML and shapefiles. Finally, it calculates metric and topological measures for each network, described below. Such measures extend the toolkit commonly used in urban form studies [47, 23].

2.2 Street Network Measures

Brief descriptions of these OSMnx-calculated measures are discussed here, but extended technical definitions and algorithms can be found in e.g. [48, 2, 22, 11, 17, 35, 36, 5, 18]. *Average street length*, the mean edge length in the undirected representation of the graph, serves as a linear proxy for block size and indicates how fine-grained or coarse-grained the network is. *Node density* is the number of nodes divided by the area covered by the network. *Intersection density* is the density of the set of nodes with more than one street emanating from them (thus excluding dead-ends). *Edge density* is the sum of all edge lengths divided by area, and the physical *street density* is the sum of all edges in the undirected representation of the graph divided by area. These density measures all provide further indication of how fine-grained the network is. Finally, *average circuitry* represents the average ratio between an edge length and the straight-line distance between the two nodes it links.

The *average node degree*, or mean number of edges incident to each node, quantifies how well the nodes are connected on average. Similarly, but more concretely, the *average streets per node*

measures the mean number of physical streets (i.e., edges in the undirected representation of the graph) that emanate from each intersection and dead-end. This adapts the average node degree for physical form rather than directed flow. The statistical and spatial distributions of number of streets per node characterize the type, prevalence, and dispersion of intersection connectedness in the network. *Connectivity* measures the minimum number of nodes or edges that must be removed from a connected graph to disconnect it. The *average node connectivity* (ANC) of a network—the mean number of internally node-disjoint paths between each pair of nodes in the graph—represents the expected number of nodes that must be removed to disconnect a randomly selected pair of non-adjacent nodes [8, 21].

The *clustering coefficient* of a node is the ratio of the number of edges between its neighbors to the maximum possible number of edges that could exist between these neighbors [30, 37]. The weighted clustering coefficient weights this ratio by edge length and the average clustering coefficient is the mean of the clustering coefficients of all the nodes in the network. Centrality indicates the importance of nodes in a network [27, 53]. *Betweenness centrality* evaluates the number of shortest paths that pass through each node [4]. The maximum betweenness centrality (MBC) in a network specifies the proportion of shortest paths that pass through the most important node. This is an indicator of resilience: networks with a high MBC are more prone to failure or inefficiency should this single choke point fail. Finally, *PageRank* ranks nodes based on the structure of incoming links and the rank of the source node [12, 28, 1, 15, 25].

In total, this study cross-sectionally analyzes 27,009 networks: 497 urbanized areas’ street networks, 19,655 cities’ and towns’ street networks, and 6,857 neighborhoods’ street networks. These sample sizes are larger than those of any previous similar study. The following section presents the findings of these analyses at metropolitan, municipal, and neighborhood scales.

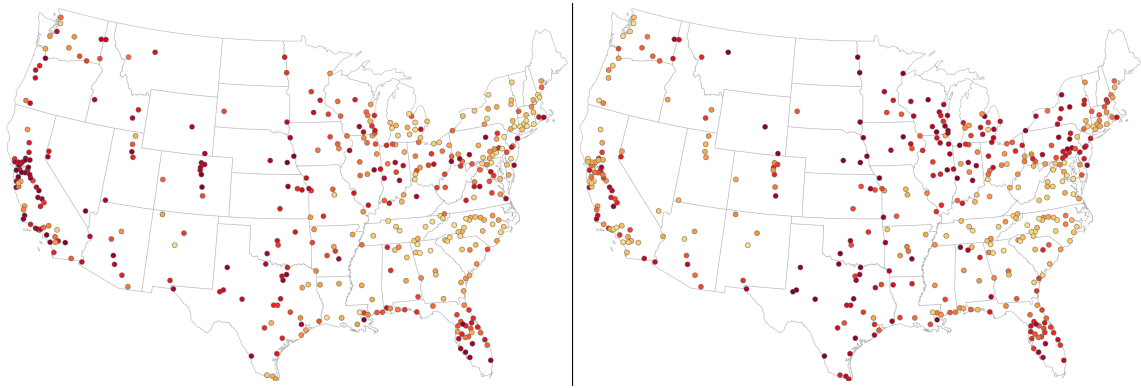


Figure 1: Intersection density per urbanized area (left) and average streets per node per urbanized area (right) from lowest (pale yellow) to highest (dark red), in the contiguous US

3 Results

3.1 Metropolitan-Scale Street Networks

Table 1 presents summary statistics for the entire data set of 497 urbanized areas. These urbanized areas span a wide range of sizes, from the Delano, CA Urbanized Area’s 26 km² to the New York–Newark, NY–NJ–CT Urbanized Area’s 8,937 km²—thus, density and count-based measures demonstrate substantial variance. Further, these urbanized areas span a wide spectrum of terrains, development eras and paradigms, and cultures.

Nevertheless, looking across the data set provides a sense of the breadth of American metropolitan street networks. New York’s urbanized area—America’s largest—has 373,309 intersections and 79 million meters of linear street (or 417,570 and 83.4 million if including service roads). Delano, CA’s urbanized area—America’s smallest—has 874 intersections and 222,328 meters of linear street (or 964 and 231,000 meters if including service roads). The typical American urbanized area is approximately 185 km² in land area, has 5,830 intersections, and 1.3 million linear meters of street. Its street network is about 7.4% more circuitous than straight-line as-the-crow-flies edges between nodes would be. The most circuitous network is 14% more circuitous than straight-line would be, and least is only 2%. Looking density, grain, and connectivity in the typical urbanized area, the average street segment length (a proxy for block size) is 160 meters. The longest average street

Table 1: Central tendency and statistical dispersion for selected measures of all US urbanized areas’ street networks.

measure	mean	std dev	min	median	max
Area (km ²)	460.657	858.125	25.685	184.898	8937.429
Avg of the avg neighborhood degree	2.886	0.109	2.626	2.875	3.228
Avg of the avg weighted neighborhood degree	0.032	0.018	0.021	0.03	0.321
Avg circuitry	1.076	0.019	1.023	1.074	1.14
Avg clustering coefficient	0.042	0.009	0.015	0.042	0.071
Avg weighted clustering coefficient	0.002	0.001	<0.001	0.001	0.006
Intersection count	12582	26054	751	4593	307848
Avg degree centrality	0.001	0.001	<0.001	0.001	0.007
Edge density (km/km ²)	13.455	2.137	7.961	13.352	21.233
Avg edge length (m)	158.588	17.653	117.341	157.332	223.08
Total edge length (km)	6353	12625	427	2393	1.42E+08
Proportion of dead-ends	0.213	0.055	0.077	0.207	0.416
Proportion of 3-way intersections	0.593	0.046	0.444	0.591	0.778
Proportion of 4-way intersections	0.187	0.063	0.054	0.178	0.422
Intersection density (per km ²)	26.469	6.256	12.469	26.029	49.423
Average node degree	5.153	0.302	4.307	5.143	6.056
m	40890	83678	2516	14955	981646
n	16032	32585	874	5830	373309
Node density (per km ²)	33.628	7.641	17.675	33.071	61.655
Max PageRank value	0.001	0.001	<0.001	0.001	0.003
Min PageRank value	<0.001	<0.001	<0.001	<0.001	<0.001
Self-loop proportion	0.008	0.008	<0.001	0.006	0.071
Street density (km/km ²)	7.262	1.221	4.217	7.171	11.797
Average street segment length (m)	161.331	17.765	119.573	160.288	225.92
Total street length (km)	3480	7026	222	1269	79046
Street segment count	22011	45725	1281	7868	533757
Average streets per node	2.764	0.162	2.223	2.77	3.217

segment is the 226-meter average of urbanized Danbury, CT. Puerto Rican cities hold the top four positions for shortest average street segment length, but among the 50 states plus DC, the shortest average street segment is the 125.3-meter average of urbanized Tracy, CA, indicating a much finer street network. The urbanized area of Portland, Oregon, with its famously compact walkable blocks, ranks second at 125.5 meters on average.

The typical urbanized area has 26 intersections per km². Both the densest and the sparsest are in the Deep South: the sparsest is 12.5 (Gainesville, GA urbanized area) and the densest is 49.4 (New Orleans urbanized area). However, New Orleans is an anomaly in the Deep South.

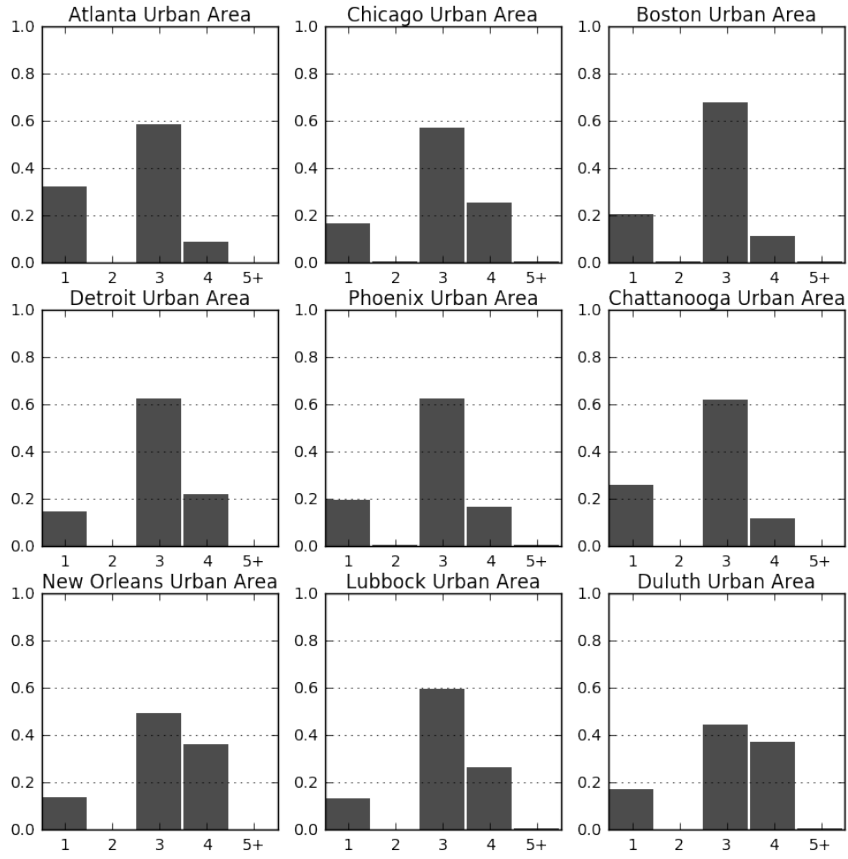


Figure 2: Distribution of node types in 9 urbanized areas, with number of streets emanating from the node on the x -axis and proportion of nodes of this type on the y -axis

Figure 1 depicts the intersection density of each American urbanized area: the highest intersection densities concentrate west of the Mississippi River, while the lowest concentrate in a belt running from Louisiana, through the Carolinas and Appalachians, and into New England. In general, only the largest cities on the east coast (e.g., Boston, New York, Philadelphia, Washington) and Florida escape this trend.

The distribution of node types (i.e., intersections and dead ends) provides an indicator of network connectedness. The typical urbanized area averages 2.8 streets per intersection: many 3-way intersections, fewer dead-ends, and even fewer 4-way intersections. The gridlike San Angelo, TX urbanized area has the most streets per node (3.2) on average, and (outside of Puerto Rico, which contains the seven lowest urbanized areas) the sprawling, disconnected Lexington Park, MD urbanized area has the fewest (2.2). These two urbanized areas fit the trend seen in the spatial distribution across the US in Figure 1: urbanized areas in the great plains and Midwest have particularly high numbers of streets per node on average, indicating more gridlike, connected networks. Cities in the southern and western US tend to have fewer streets per node, reflecting more dead-ends and a disconnected network. This finding is discussed in more detail in the upcoming section.

In the typical urbanized area, 18% of nodes are 4-way intersections, 59% are 3-way intersections, and 21% are dead-ends. However, this distribution varies somewhat: examining a small sample of nine urbanized areas, chosen to maximize variance, reveals this in clearer detail. In Figure 2, urban Atlanta and Chattanooga have very high proportions of dead-ends—each over 30% of all nodes—and very few 4-way intersections, indicating a disconnected street pattern. The urbanized areas of Phoenix, Boston, Detroit, and Chattanooga have particularly high proportions of 3-way intersections, each over 60%, indicating a prevalence of T-intersections. Conversely, Chicago, New Orleans, Duluth, and Lubbock have high proportions of 4-way intersections, indicating more gridlike connected networks. But what is perhaps most notable about Figure 2 is that these nine urbanized areas, despite being chosen to maximize variance, are overwhelmingly similar to each other. Every large American urban agglomeration is characterized by a preponderance of 3-way intersections.

The relationship between fine-grained networks and connectedness/gridness is not, however, clear-cut: intersection density has only a weak, positive linear relationship with the proportion

of 4-way intersections in the urbanized area ($r^2 = 0.17$). But the relationship between network circuitry and gridness is somewhat clearer: average circuitry has a negative linear relationship with the proportion of 4-way intersections ($r^2 = 0.43$).

Table 2: Selected measures of the 30 largest (by land area) urbanized areas' street networks.

urban area core city	land area km ²	avg circuity	avg clustering coefficient	dead-end ratio	3-way ratio	4-way ratio	intersect density/km ²	street density km/km ²	avg street length (m)	avg streets/streets/node
New York	8937	1.06	0.04	0.18	0.62	0.2	34.44	8.84	148	2.86
Atlanta	6850	1.1	0.04	0.32	0.58	0.09	18.39	6.16	186	2.45
Chicago	6325	1.07	0.04	0.17	0.57	0.25	27.05	7.77	163	2.92
Philadelphia	5132	1.08	0.05	0.17	0.63	0.2	26.65	7.3	159	2.87
Boston	4852	1.09	0.05	0.2	0.68	0.11	24.23	6.44	154	2.71
Dallas	4612	1.07	0.05	0.15	0.61	0.23	34.16	9.16	156	2.95
Los Angeles	4497	1.06	0.03	0.21	0.56	0.22	39.45	10.59	151	2.82
Houston	4303	1.08	0.04	0.2	0.57	0.22	33.49	8.62	145	2.83
Detroit	3461	1.07	0.04	0.15	0.63	0.22	31.1	8.56	159	2.93
Washington	3424	1.09	0.04	0.26	0.56	0.17	31.22	8.26	146	2.66
Miami	3204	1.1	0.05	0.17	0.59	0.23	40.54	10.61	149	2.89
Phoenix	2968	1.09	0.05	0.2	0.62	0.17	35.31	9.1	150	2.77
Minneapolis	2647	1.08	0.05	0.19	0.57	0.23	29.54	8.68	167	2.84
Seattle	2617	1.07	0.03	0.3	0.54	0.16	31.57	8.2	143	2.57
Tampa	2479	1.1	0.05	0.2	0.58	0.21	31.35	8.46	153	2.83
St. Louis	2392	1.1	0.04	0.22	0.62	0.15	29.68	8.16	154	2.73
Pittsburgh	2345	1.09	0.04	0.23	0.6	0.16	23.57	6.71	165	2.72
San Juan	2245	1.11	0.02	0.36	0.56	0.08	26.57	6.43	131	2.36
Cincinnati	2040	1.07	0.03	0.31	0.54	0.14	17.96	6.1	186	2.51
Cleveland	2004	1.07	0.04	0.19	0.66	0.14	19.13	6.51	198	2.76
Charlotte	1920	1.08	0.04	0.3	0.57	0.11	21	6.43	170	2.51
San Diego	1897	1.08	0.03	0.28	0.54	0.17	28.89	8.32	159	2.62
Baltimore	1857	1.09	0.04	0.23	0.59	0.17	27.72	7.56	152	2.72
Indianapolis	1828	1.08	0.05	0.23	0.59	0.17	27.62	7.63	157	2.7
Kansas City	1756	1.06	0.04	0.21	0.58	0.2	32.09	8.57	152	2.79
Denver	1729	1.07	0.05	0.2	0.57	0.22	40.6	9.84	138	2.84
Orlando	1548	1.11	0.06	0.2	0.61	0.18	26.3	7.44	163	2.79
San Antonio	1547	1.07	0.05	0.17	0.6	0.21	28.33	7.91	162	2.87
Nashville	1460	1.08	0.03	0.27	0.59	0.14	19.08	6.1	181	2.6
Milwaukee	1413	1.06	0.06	0.14	0.55	0.3	28.27	7.81	157	3.03

Due to the substantial variation in urbanized area size, from 25 to 9,000 km², the preceding analysis covers a wide swath of metropolitan types. To better compare apples-to-apples, Table 2 focuses on the 30 largest urbanized areas cross-sectionally to examine their metric and topological measures. This provides more consistent spatial scales and extents, while offering a window into the similarities and differences in the built forms of America’s largest agglomerations.

Among these urbanized areas, Milwaukee has the least circuitous network (6% more circuitous than straight-line edges would be), and Orlando has the most (12%). San Juan and Atlanta have the fewest streets per node on average (2.36 and 2.45, respectively), while Milwaukee has the most (3.03). Cincinnati has both the lowest intersection density (18/km²) and street density (6.1 km/km²) while Denver has the highest intersection density (40.6/km²) and Miami and Los Angeles have the highest street density (10.6 km/km², apiece). In other words, Cincinnati has a particularly coarse-grained network with few connections and paths. The average street segment length, a proxy for block size, also reflects this: Cincinnati has the second highest (186 m), bested only by Cleveland (198 m). In contrast, the two lowest are Denver’s 138-meter average and San Juan’s 131-meter average.

These metropolitan analyses consider trends in the built form at the scale of broad self-organized human systems and urbanized regions. However, they aggregate multiple heterogeneous municipalities and neighborhoods—the scales of human life, urban design projects, and planning jurisdiction—into single units of analysis. To disaggregate and analyze finer characteristics, the following subsections examine municipal- and neighborhood-scale street networks.

3.2 Municipal-Scale Street Networks

Table 3 presents summary statistics of street network characteristics across the entire data set of 19,655 cities and towns—every incorporated city and town in the US. Following recent work by Barthlemy and Flammini [6] and Strano et al. [46], we examine the relationship between the total street length L and the number of nodes n . The former proposed a model of cities in which L and n scale nonlinearly as $n^{1/2}$, and the latter recently confirmed this empirically with a small sample of ten European cities. However, their small sample size may limit the generalizability of this finding.

Table 3: Selected summary stats for every incorporated city and town in the US.

measure	mean	std dev	min	median	max
Area (km ²)	16.703	107.499	0.039	3.918	7434.258
Avg of the avg neighborhood degree	2.94	0.297	0.4	2.953	3.735
Avg of the avg weighted neighborhood degree	0.033	0.141	<0.001	0.029	9.357
Avg circuitry	1.067	0.159	1	1.055	20.452
Avg clustering coefficient	0.048	0.041	<0.001	0.04	1
Avg weighted clustering coefficient	0.01	0.018	<0.001	0.005	0.524
Intersection count	324	1266	0	83	62996
Avg degree centrality	0.093	0.136	<0.001	0.052	2.667
Edge density (km/km ²)	12.654	6.705	0.006	11.814	58.603
Avg edge length (m)	161.184	80.769	25.822	144.447	3036.957
Total edge length (km)	159.067	578.521	0.052	40.986	24728.326
Proportion of dead-ends	0.192	0.093	<0.001	0.184	1
Proportion of 3-way intersections	0.572	0.11	<0.001	0.579	1
Proportion of 4-way intersections	0.237	0.129	<0.001	0.217	1
Intersection density (per km ²)	29.363	21.607	<0.001	24.719	259.647
Average node degree	5.251	0.668	0.8	5.268	7.166
m	1046	3924	2	275	176161
n	401	1516	2	103	71993
Node density (per km ²)	35.449	24.409	0.047	30.718	296.74
Max PageRank value	0.034	0.046	<0.001	0.021	0.87
Min PageRank value	0.005	0.018	<0.001	0.002	0.5
Self-loop proportion	0.005	0.015	<0.001	<0.001	1
Street density (km/km ²)	6.528	3.435	0.003	6.109	29.302
Average street segment length (m)	162.408	81.035	25.822	145.479	3036.957
Total street length (km)	86.096	331.048	0.026	21.005	15348.008
Street segment count	558	2208	1	140	107393
Average streets per node	2.851	0.282	1	2.852	4

To investigate this empirically, we examine the relationship between L and n for 19,655 US cities and towns and instead find a strong *linear* relationship ($r^2 = 0.98$), as depicted in Figure 3. We also find a similar linear relationship at the metropolitan and neighborhood scales.

Previous findings [e.g., 34] also suggest street segment lengths in an urban network follow a power-law distribution. However, we find that these networks instead generally follow a lognormal distribution. This makes theoretical sense as most street networks are not truly scale-free: for example, a typical street network might comprise very few very long street segments (e.g., 1 km), more medium-length segments (e.g., 250 m), many short segments (e.g., 80 m), but very few very

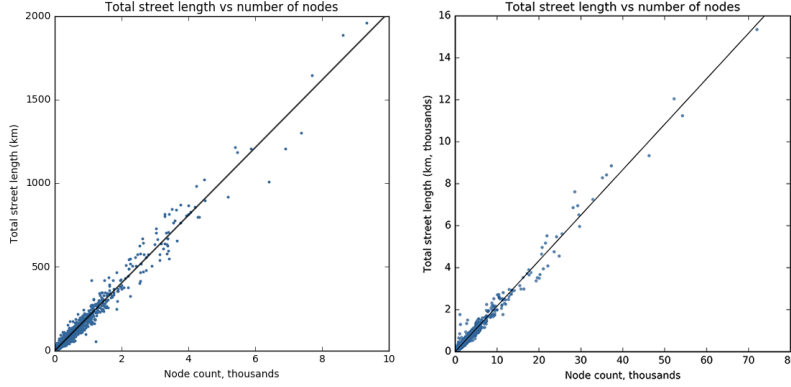


Figure 3: The linear relationship between total street length and number of nodes in the street networks of 6,857 US neighborhoods (left) and 19,655 US cities and towns (right).

short segments (e.g., 10 m). This theoretical illustration suggests the lognormal distribution that this study generally finds across municipal US street networks. An exception, of course, lies in consistently-sized orthogonal grids filling a city’s incorporated spatial extents. Such distributions are extremely peaked around a single value: the linear length of a grid block.

We find that such cities are not uncommon in the US, particularly between the Mississippi River and the Rocky Mountains: the Great Plains states are characterized by a unique street network form that is both orthogonal and reasonably dense. The *former* is partly the result of topography (flat terrain that allows idealized grids) and design history (rapid platting and development during the late nineteenth century) that favor orthogonal grids, as discussed earlier. The *latter* results from the fact that most towns across the Great Plains exhibit minimal suburban sprawl. Thus, municipal boundaries snugly embrace the gridlike street network, without extending to accommodate a vast peripheral belt of twentieth century sprawl, circuitry, and “loops and lollipops” [45] that characterizes cities in California that were settled in the same era but later subjected to substantial suburbanization.

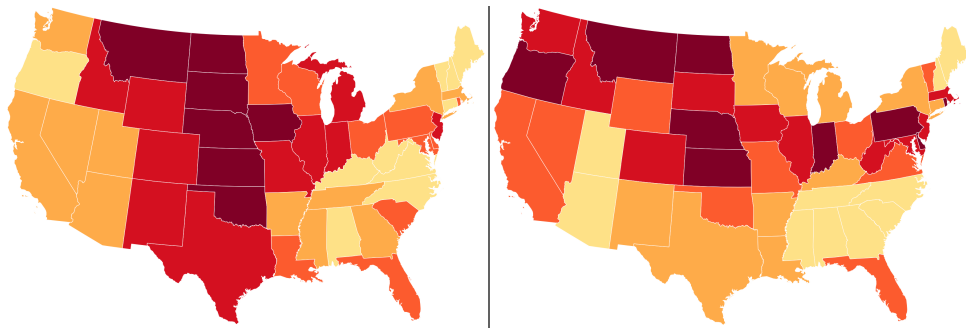


Figure 4: Left: contiguous US states by median of mean streets per node in municipal street networks, from lowest (pale yellow) to highest (dark red). Right: contiguous US states by median of mean street segment length in municipal street networks, from longest (pale yellow) to shortest (dark red).

Table 4: Median values, aggregated by state plus DC, of selected measures of the municipal-scale street networks for every city and town in the US.

State	Intersect density (per km ²)	Avg streets per node	Avg circuitry	Avg street seg- ment length
AK	1.28	2.43	1.1	223.5
AL	9.7	2.64	1.07	190.81
AR	15.75	2.78	1.06	166.32
AZ	12.45	2.77	1.08	171.8
CA	32.58	2.74	1.07	143.79
CO	29.26	2.88	1.06	136.68
CT	28.05	2.7	1.07	165.87
DC	58.91	3.26	1.04	122.23
DE	25.3	2.8	1.06	127.8
FL	26.26	2.87	1.07	150.75
GA	15.25	2.78	1.07	177.5
HI	8	2.42	1.07	177.93
IA	24.08	3.02	1.04	129.36
ID	33.85	2.91	1.06	132.08
IL	29.02	2.93	1.05	137.77
IN	35.25	2.93	1.05	125.72
KS	43.94	3.14	1.04	124.39
KY	25.12	2.68	1.07	151.28
LA	17.14	2.79	1.06	162.62
MA	32.33	2.76	1.07	135.98
MD	28.67	2.79	1.07	133.69
ME	7.69	2.67	1.07	198.93
MI	20.93	2.9	1.05	153.5
MN	18.96	2.87	1.06	152.92
MO	29.87	2.89	1.06	138.29
MS	14.76	2.75	1.06	174.86
MT	38.94	3.11	1.04	126.89
NC	19.28	2.65	1.06	166.69
ND	34.28	3.07	1.04	123.93
NE	45.89	3.16	1.04	119.79
NH	12.22	2.69	1.1	175.88
NJ	44.98	2.88	1.04	130.79
NM	18.5	2.93	1.05	152.02
NV	13.86	2.77	1.07	147.35
NY	21.89	2.75	1.06	156.88
OH	25.23	2.8	1.05	142.08
OK	28.22	3.03	1.05	139.5
OR	35.08	2.69	1.06	121.18
PA	35.69	2.87	1.05	128.34
RI	56.23	2.86	1.05	110.35
SC	18.76	2.81	1.06	169.21
SD	32.01	3.12	1.04	130.75
TN	13.62	2.71	1.07	192.83
TX	23.85	2.92	1.05	160.44
UT	12.58	2.71	1.06	191.04
VA	25.18	2.63	1.08	145.65
VT	18.91	2.55	1.08	145.18
WA	28.71	2.75	1.06	134.02
WI	17.87	2.81	1.06	156.19
WV	28.45	2.67	1.08	136.57
WY	23.48	2.92	1.06	143.63

For example, if we measure connectedness in terms of average number of streets per node at the city-scale and then aggregate these cities by state (Table 4), we find Nebraska, Kansas, South Dakota, Montana, North Dakota, Oklahoma, and Iowa have, in order, the highest medians (Figure 4). This indicates the most gridlike networks. If we measure intersection density at the city-scale and then aggregate these cities by state, we find Rhode Island, Nebraska, New Jersey, Kansas, and Montana have, in order, the highest medians. We again see three Great Plains states near the top, alongside small densely populated East Coast states. Nebraska also has the smallest block sizes (measured via the proxy of average street segment length) while the largest concentrate in the Deep South, upper New England, and Utah (Figure 4).

However, municipal boundaries vary greatly in their extents around the built-up area. While Rhode Island averages 56 intersections/km² in its cities and towns, Alaska averages only 1.3, because the latter’s municipal boundaries often extend thousands of km² beyond the actual built-up area. In fact, Alaska has four cities (Anchorage, Juneau, Sitka, and Wrangell) with such large municipal extents that their land areas exceed that of the state of Rhode Island. These state-level aggregations of municipal street network characteristics show clear variation across the country that reflect topography, economies, culture, planning paradigms, and settlement eras. But they also aggregate and thus obfuscate the variation within each state and within each city. To explore these smaller-scale differences, the following section examines street networks at the neighborhood scale.

3.3 Neighborhood-Scale Street Networks

We have thus far examined every urban street network in the US at the metropolitan and municipal scales. While the metropolitan scale captures the emergent character of the wider region’s complex system, and the municipal scale captures planning decisions made by a single city government, the neighborhood best represents the scale of individual urban design interventions into the urban form. Further, this scale more commonly reflects individual designs, eras, and paradigms in street network development than the “many hands, many eras” evolution of form at larger scales.

Table 5 presents summary statistics for these 6,857 neighborhoods. Compared to the metropolitan and municipal scales, we see much greater variance here, as expected, given the smaller network

Table 5: Selected summary stats for all the neighborhood-scale street networks.

	mean	std dev	min	median	max
Area (km ²)	5.322	15.463	0.008	1.738	323.306
Avg of the avg neighborhood degree	2.598	0.436	<0.001	2.67	3.632
Avg of the avg weighted neighborhood degree	0.031	0.041	<0.001	0.029	2.991
Avg circuitry	1.08	0.411	1	1.044	24.29
Avg clustering coefficient	0.044	0.055	<0.001	0.034	1
Avg weighted clustering coefficient	0.01	0.027	<0.001	0.005	0.799
Intersection count	173	379	0	76	8371
Avg degree centrality	0.13	0.27	0.001	0.054	4
Edge density (km/km ²)	17.569	7.095	0.025	18.152	59.939
Avg edge length (m)	142.279	59.182	8.447	133.848	2231.331
Total edge length (km)	71.369	166.566	0.017	29.88	3563.409
Proportion of dead-ends	0.17	0.131	<0.001	0.145	1
Proportion of 3-way intersections	0.559	0.146	<0.001	0.574	1
Proportion of 4-way intersections	0.275	0.176	<0.001	0.234	1
Intersection density (per km ²)	49.497	28.33	<0.001	46.43	444.355
Average node degree	4.675	0.836	0.545	4.736	7.283
m	5201	1185	1	217	27289
n	208	459	2	90	9327
Node density (per km ²)	58.677	31.802	0.063	55.626	499.9
Max PageRank value	0.055	0.086	<0.001	0.026	0.889
Min PageRank value	0.01	0.041	<0.001	0.002	0.5
Self-loop proportion	0.007	0.034	<0.001	<0.001	1
Street density (km/km ²)	9.744	4.085	0.013	9.882	33.737
Average street segment length (m)	143.664	60.023	7.376	134.877	2231.331
Total street length (km)	40.049	93.987	0.009	16.248	1960.643
Street segment count	288	656	1	119	14754
Average streets per node	2.925	0.408	1	2.944	4.026

sizes at the neighborhood scale. A few neighborhoods have no intersections within their Zillow-defined boundaries, resulting in a minimum intersection density of 0 across the data set. Meanwhile, the small neighborhood of Cottages North in Davis, California has the highest intersection density in the country, 444/km², largely an artifact of its small area as the denominator. Nationwide, the typical neighborhood averages 2.9 streets per intersection, reflecting the prevalence of 3-way intersections in the US, discussed earlier. The median proportions of each node type are 14.5% for dead-ends, 57.4% for 3-way intersections, and 23.4% for 4-way intersections. The typical neighborhood averages 135-meter street segment lengths and 46.4 intersections per km².

Due to the extreme values seen—resulting from the large variance in neighborhood size—we can filter the data set to examine only large neighborhoods (i.e., with area greater than the median value across the data set). In this filtered set, the five neighborhoods with the highest intersection density are all in central Philadelphia. Central neighborhoods are common at the top of this list, including Point Breeze, Philadelphia; Central Boston; Central City, New Orleans; Downtown Tampa; and Downtown Portland. The three neighborhoods with the lowest intersection density are on the outskirts of Anchorage, Alaska. In this filtered set, the greatest average numbers of streets per node tend to be in older neighborhoods with orthogonal grids, such as Virginia Park, Tampa; Outer Sunset, San Francisco; and New Orleans’ French Quarter. The neighborhoods with the lowest tend to be sprawling and often hilly suburbs far from the urban core, such as Scholl Canyon in Glendale, California or Sonoma Ranch in San Antonio, Texas.

To illustrate these morphologies, Figure 5 compares one square mile of the centers of Philadelphia, Portland, and San Francisco with one square mile of each of their suburbs. The connectedness and density of the central cities is clear, as is the disconnectivity of their suburbs. In fact, the suburbs have more in common with one another—despite being hundreds or thousands of miles apart—than they do with their central city neighbors, suggesting that land use and an era’s prevailing design paradigm is paramount to geographical localism and regional context. The top row of Figure 5 represents an era of planning and development that preceded the automobile, while the bottom row reflects the exclusionary zoning and mid-late twentieth century era of automobility in residential suburb design—namely the “loops and lollipops” and the “lollipops on a stick” design

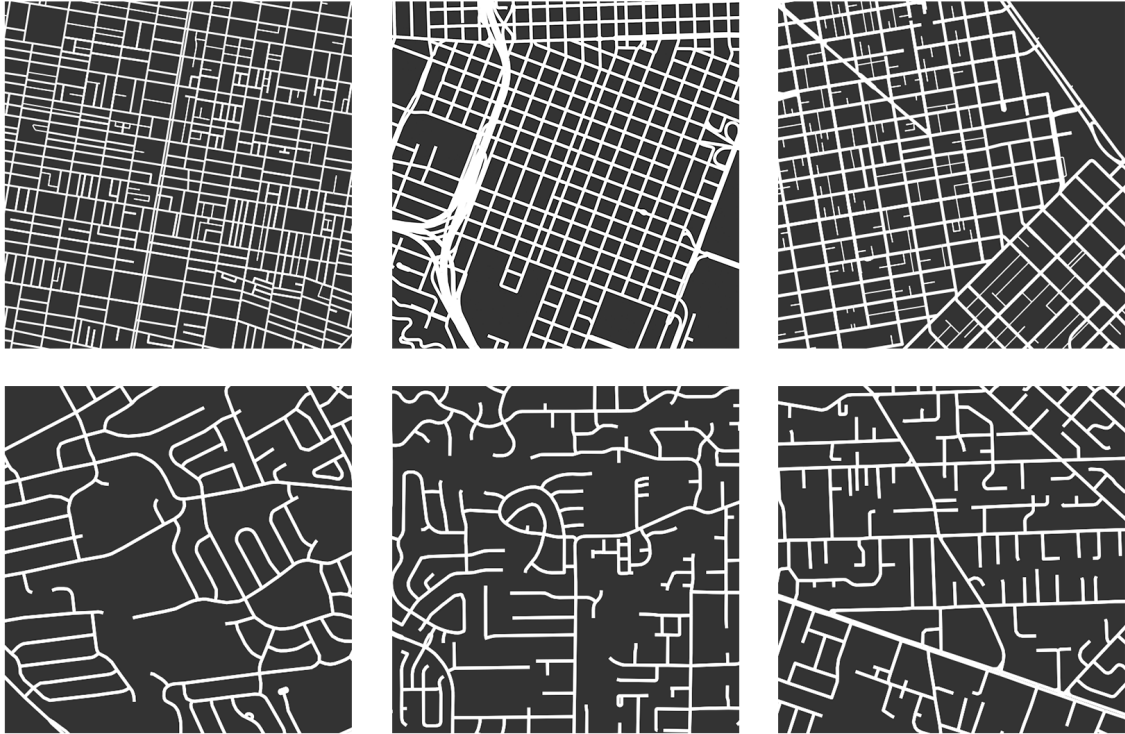


Figure 5: Square-mile comparisons of central cities and their suburbs. Left: top, downtown Philadelphia, PA; bottom, its suburb, King of Prussia. Middle: top, downtown Portland, OR; bottom, its suburb, Beaverton. Right: top, downtown San Francisco, CA; bottom, its suburb, Concord.

patterns identified by Southworth and Ben-Joseph [45].

Finally we briefly take a closer look at San Francisco, California’s neighborhoods alone for a clear cross-sectional analysis with consistent geography to examine resilience through the MBC and ANC measures. Due to its highly connected orthogonal grid, the Outer Sunset neighborhood has the lowest MBC—only 9.6% of all shortest paths pass through its most important node. By contrast, 36% of Chinatown’s shortest paths pass through its most important node, and in Twin Peaks it is 37%. In Chinatown, this is the result of the small neighborhood comprising only a few streets and that these streets are one-way, forcing paths through very few routing options. In Twin Peaks, this is the result of hilly terrain and a disconnected network forcing paths through a small set of chokepoints that link separate subsections of the network. If a large number of shortest paths rely on a single node, the network is more prone to failure or inefficiency given a single point of failure.

ANC is another indicator of resilience. In San Francisco, Twin Peaks’ network has the lowest ANC: on average only 1.05 nodes must be removed to disconnect a randomly selected pair of nodes. Outer Sunset has the highest ANC: 3.2. These concur with the above descriptions of these networks. However, some central San Francisco orthogonal grid networks with many 4-way intersections—such as Downtown, Chinatown, and the Financial District—have surprisingly low ANCs: 1.5, 1.3, and 1.6 respectively. These neighborhoods comprise primarily one-way streets. Although they have dense, highly connected networks, they can be easily disconnected given that traffic cannot flow bidirectionally. These three neighborhoods also exhibit the greatest increase in ANC if all their edges are made undirected: Chinatown’s increases 87%, Downtown’s 80%, and the Financial District’s 75%. By contrast, Outer Sunset’s street network sees only a 6% increase due to it already comprising primarily bidirectional streets. Targeted conversion of one-way streets in networks like Downtown, the Financial District, and Chinatown may yield substantial resilience gains.

4 Discussion

These findings suggest the influence of planning eras, design paradigms, transportation technologies, topography, and economics on US street network density, resilience, and connectedness. Overall, every large US metropolis is characterized by its preponderance of 3-way intersections. Sprawling suburban neighborhoods rank low on density and connectedness. The orthogonal grids we see in the downtowns of Portland and San Francisco have high density (i.e., intersection and street densities), connectedness (i.e., average number of streets per node), and order (based on circuitry and statistical dispersion of node types), but low resilience in the presence of one-way streets, measured by MBC and ANC increases when switching from one-way to bidirectional edges.

A critical takeaway is that *scale* matters. The median average circuitry is lower across the neighborhoods data set than across the municipal set, which in turn is lower than across the urbanized areas set. Conversely, the median average number of streets per node is higher across the neighborhoods data set than across the municipal set, which in turn is higher than across the urbanized areas set. The median intersection density per km² is about 83% higher in the neighborhoods data set than in the municipal or urbanized areas sets. These findings make sense: the Zillow neighborhood boundaries focus on large, core cities with older and denser street networks. The municipal boundaries only include incorporated cities and towns—discarding small census-designated places and unincorporated communities. The urbanized area boundaries include far-flung sprawling suburbs.

The characteristics of city street networks fundamentally depend on what *city* means: municipal boundaries, urbanized areas, or certain central neighborhoods? The first is a legal/political definition, but captures the scope of city planning authority and decision-making for top-down interventions into human circulation. The second captures a wider self-organized human system and its emergent built form, but tends to aggregate multiple heterogeneous built forms together into a single unit of analysis. The third captures the nature of the local built form and lived experience, but at the expense of a broader view of the urban system and metropolitan-scale trip-taking. In short, multiple scales in concert provide planners and scholars a clearer view of the urban form and

the topological and metric complexity of the street network than any single scale can.

This analysis finds a strong linear relationship, invariant across scales, between total street length and the number of nodes in a network. This differs from previous findings in the literature that relied on smaller sample sizes and examined European instead of US cities. We also find that most networks typically follow a lognormal distribution of street segment lengths. As discussed, this finding seems to make sense theoretically and is supported by these large-sample data at multiple scales, but obvious exceptions to lognormal distribution lie in those networks that exhibit substantial uniformity. At the neighborhood scale, examples include downtowns with consistent orthogonal grids, such as that of Portland, Oregon. At the municipal scale, examples include towns in the Great Plains that have orthogonal grids with consistent block sizes, platted at one time, and never subjected to expansion or sprawl.

These findings reveal urban form legacies of the practice and history of US planning. The spatial signatures of the Homestead Act, successive land use regulations, urban design paradigms, and planning instruments remain clearly etched in these cities' urban forms and street networks today. Accordingly when comparing median municipal street networks in each state, Nebraska has the lowest circuitry, the highest average number of streets per node, the second shortest average street segment length, and the second highest intersection density. These findings illustrate how street networks across the Great Plains developed all at once, but grew very little afterwards—unlike, for instance, most cities in California that were settled in the same era but later subjected to sprawl.

Future research should incorporate temporal analyses that goes beyond the present study's cross-sectional data. This empirical analysis emphasized network structure, but further linking structural complexity to the temporal complexity of city dynamics and processes lies ahead as critical work. As OSMnx can automatically calculate several dozen street network measures, future work can use dimensionality reduction to identify significant baskets of factors and cluster places into types. These variables can also be used as advanced urban form measures in hedonic regressions and accessibility studies.

5 Conclusion

This paper had three primary purposes. First, it examined urban morphology through metric and topological measures of these networks—particularly focusing on density, connectedness, and resilience. Second, these methods and findings demonstrate the use of OSMnx as a new street network research toolkit. They suggest to urban planners and scholars new methods for acquiring and analyzing street network data. Third, it investigated claims about the distribution of street segment lengths and the relationship between the total street length and the number of nodes in a network. This study has made all of these network datasets—for 497 urbanized areas, 19,655 cities and towns, and 6,857 neighborhoods—along with all of their attribute data and morphological measures available in an online public repository for other researchers to study and repurpose at [redacted for peer review].

References

- [1] Agryzkov, T., J. L. Oliver, L. Tortosa, and J. F. Vicent (2012). An algorithm for ranking the nodes of an urban network based on the concept of PageRank vector. *Applied Mathematics and Computation* 219(4), 2186–2193.
- [2] Albert, R. and A.-L. Barabási (2002). Statistical mechanics of complex networks. *Reviews of Modern Physics* 74(1), 47.
- [3] Albrecht, J. and M. Abramovitz (2014). Indicator Analysis for Unpacking Poverty in New York City. Technical report, CUNY, New York, NY.
- [4] Barthlémy, M. (2004). Betweenness centrality in large complex networks. *The European Physical Journal B: Condensed Matter and Complex Systems* 38(2), 163–168.
- [5] Barthlémy, M. (2011). Spatial networks. *Physics Reports* 499(1-3), 1–101.
- [6] Barthlémy, M. and A. Flammini (2008). Modeling Urban Street Patterns. *Physical Review Letters* 100(13).

- [7] Batty, M. (2005). Network geography: Relations, interactions, scaling and spatial processes in GIS. In D. J. Unwin and P. Fisher (Eds.), *Re-presenting Geographical Information Systems*, pp. 149–170. Chichester, England: John Wiley & Sons.
- [8] Beineke, L. W., O. R. Oellermann, and R. E. Pippert (2002). The Average Connectivity of a Graph. *Discrete Mathematics* 252(1), 31–45.
- [9] Besbris, M., J. W. Faber, P. Rich, and P. Sharkey (2015). Effect of neighborhood stigma on economic transactions. *Proceedings of the National Academy of Sciences* 112(16), 4994–4998.
- [10] Boeing, G. (2017). OSMnx: New Methods for Acquiring, Constructing, Analyzing, and Visualizing Complex Street Networks. (Manuscript submitted for publication).
- [11] Brandes, U. and T. Erlebach (Eds.) (2005). *Network analysis: methodological foundations*. Number 3418 in Lecture Notes in Computer Science. Berlin, Germany: Springer.
- [12] Brin, S. and L. Page (1998). The anatomy of a large-scale hypertextual web search engine. *Computer Networks and ISDN Systems: Proceedings of the Seventh International World Wide Web Conference* 30(1-7), 107–117.
- [13] Buhl, J., J. Gautrais, N. Reeves, R. V. Sol, S. Valverde, P. Kuntz, and G. Theraulaz (2006). Topological patterns in street networks of self-organized urban settlements. *The European Physical Journal B: Condensed Matter and Complex Systems* 49(4), 513–522.
- [14] Cardillo, A., S. Scellato, V. Latora, and S. Porta (2006). Structural properties of planar graphs of urban street patterns. *Physical Review E* 73(6).
- [15] Chin, W.-C.-B. and T.-H. Wen (2015). Geographically Modified PageRank Algorithms: Identifying the Spatial Concentration of Human Movement in a Geospatial Network. *PLoS ONE* 10(10), e0139509.
- [16] Corcoran, P., P. Mooney, and M. Bertolotto (2013). Analysing the growth of OpenStreetMap networks. *Spatial Statistics* 3, 21–32.

- [17] Costa, L. d. F., F. A. Rodrigues, G. Travieso, and P. R. Villas Boas (2007). Characterization of complex networks: A survey of measurements. *Advances in Physics* 56(1), 167–242.
- [18] Cranmer, S. J., P. Leifeld, S. D. McClurg, and M. Rolfe (2017). Navigating the range of statistical tools for inferential network analysis. *American Journal of Political Science* 61(1), 237–251.
- [19] Crucitti, P., V. Latora, and S. Porta (2006a). Centrality in networks of urban streets. *Chaos: An Interdisciplinary Journal of Nonlinear Science* 16(1), 015113.
- [20] Crucitti, P., V. Latora, and S. Porta (2006b). Centrality measures in spatial networks of urban streets. *Physical Review E* 73(3), 036125.
- [21] Dankelmann, P. and O. R. Oellermann (2003). Bounds on the average connectivity of a graph. *Discrete Applied Mathematics* 129(2), 305–318.
- [22] Dorogovtsev, S. and J. Mendes (2002). Evolution of networks. *Advances in Physics* 51(4), 1079–1187.
- [23] Ewing, R. and R. Cervero (2010). Travel and the Built Environment: A Meta-Analysis. *Journal of the American Planning Association* 76(3), 265–294.
- [24] Frizzelle, B., K. Evenson, D. Rodriguez, and B. Laraia (2009). The importance of accurate road data for spatial applications in public health: customizing a road network. *International Journal of Health Geographics* 8(24).
- [25] Gleich, D. F. (2015). PageRank Beyond the Web. *SIAM Review* 57(3), 321–363.
- [26] Haklay, M. (2010). How Good is Volunteered Geographical Information? A Comparative Study of OpenStreetMap and Ordnance Survey Datasets. *Environment and Planning B: Planning and Design* 37(4), 682–703.
- [27] Huang, X., Y. Zhao, C. Ma, J. Yang, X. Ye, and C. Zhang (2016). TrajGraph: A Graph-Based Visual Analytics Approach to Studying Urban Network Centralities Using Taxi Trajectory Data. *IEEE Transactions on Visualization and Computer Graphics* 22(1), 160–169.

- [28] Jiang, B. (2008). Predicting human movement using PageRank in an urban environment.
- [29] Jiang, B. and C. Claramunt (2002). Integration of space syntax into GIS: new perspectives for urban morphology. *Transactions in GIS* 6(3), 295–309.
- [30] Jiang, B. and C. Claramunt (2004). Topological Analysis of Urban Street Networks. *Environment and Planning B: Planning and Design* 31(1), 151–162.
- [31] Jokar Arsanjani, J., A. Zipf, P. Mooney, and M. Helbich (Eds.) (2015). *OpenStreetMap in GIScience*. Lecture Notes in Geoinformation and Cartography. Cham, Switzerland: Springer International.
- [32] Lee, L. B. (1979). *Kansas and the Homestead act, 1862-1905*. The management of public lands in the United States. North Stratford, NH: Ayer Company Publishers.
- [33] Maron, M. (2015, November). How complete is OpenStreetMap? *Mapbox*.
- [34] Masucci, A. P., D. Smith, A. Crooks, and M. Batty (2009). Random planar graphs and the London street network. *The European Physical Journal B: Condensed Matter and Complex Systems* 71(2), 259–271.
- [35] Newman, M. E. J. (2003). The Structure and Function of Complex Networks. *SIAM Review* 45(2), 167–256.
- [36] Newman, M. E. J. (2010). *Networks: An Introduction*. Oxford, England: Oxford University Press.
- [37] Opsahl, T. and P. Panzarasa (2009). Clustering in weighted networks. *Social Networks* 31(2), 155–163.
- [38] O’Sullivan, D. (2014). Spatial Network Analysis. In M. M. Fischer and P. Nijkamp (Eds.), *Handbook of Regional Science*, pp. 1253–1273. Berlin, Germany: Springer-Verlag.
- [39] Over, M., A. Schilling, S. Neubauer, and A. Zipf (2010). Generating web-based 3d City Models from OpenStreetMap: The current situation in Germany. *Computers, Environment and Urban Systems* 34(6), 496–507.

- [40] Porta, S., P. Crucitti, and V. Latora (2006). The network analysis of urban streets: A dual approach. *Physica A: Statistical Mechanics and its Applications* 369(2), 853–866.
- [41] Porterfield, J. (2005). *The Homestead Act of 1862: A Primary Source History of the Settlement of the American Heartland in the Late 19th Century* (1st ed.). New York, NY: Rosen Publishing Group.
- [42] Ratti, C. (2004). Space syntax: some inconsistencies. *Environment and Planning B: Planning and Design* 31(4), 487–499.
- [43] Schernthanner, H., H. Asche, J. Gonschorek, and L. Scheele (2016). Spatial Modeling and Geovisualization of Rental Prices for Real Estate Portals. In O. Gervasi, B. Murgante, S. Misra, A. M. A. C. Rocha, C. M. Torre, D. Taniar, B. O. Apduhan, E. Stankova, and S. Wang (Eds.), *Computational Science and Its Applications - ICCSA 2016*, Number 9788 in Lecture Notes in Computer Science, pp. 120–133. Cham, Switzerland: Springer International. DOI: 10.1007/978-3-319-42111-7_11.
- [44] Sherraden, M. (2005). *Inclusion in the American Dream: Assets, Poverty, and Public Policy*. Oxford, England: Oxford University Press.
- [45] Southworth, M. and E. Ben-Joseph (1997). *Streets and the Shaping of Towns and Cities*. New York, NY: McGraw-Hill.
- [46] Strano, E., M. Viana, L. da Fontoura Costa, A. Cardillo, S. Porta, and V. Latora (2013). Urban Street Networks, a Comparative Analysis of Ten European Cities. *Environment and Planning B: Planning and Design* 40(6), 1071–1086.
- [47] Talen, E. (2003). Measuring Urbanism: Issues in Smart Growth Research. *Journal of Urban Design* 8(3), 195–215.
- [48] Trudeau, R. J. (1994). *Introduction to Graph Theory* (2nd ed.). New York, NY: Dover Publications.

- [49] U.S. Census Bureau (2010). 2010 Census Urban and Rural Classification and Urban Area Criteria.
- [50] Viana, M. P., E. Strano, P. Bordin, and M. Barthélemy (2013). The simplicity of planar networks. *Scientific Reports* 3(3495), 1–6.
- [51] Willis, N. (2008, January). OpenStreetMap project completes import of United States TIGER data. *Linux.com*.
- [52] Wu, J., T. H. Funk, F. W. Lurmann, and A. M. Winer (2005). Improving spatial accuracy of roadway networks and geocoded addresses. *Transactions in GIS* 9(4), 585–601.
- [53] Zhong, C., M. Schlpfer, S. M. Arisona, M. Batty, C. Ratti, and G. Schmitt (2017). Revealing centrality in the spatial structure of cities from human activity patterns. *Urban Studies* 54(2), 437–455.
- [54] Zielstra, D. and H. Hochmair (2011). Comparative Study of Pedestrian Accessibility to Transit Stations Using Free and Proprietary Network Data. *Transportation Research Record: Journal of the Transportation Research Board* 2217, 145–152.