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Multidimensional geometric complexity in urban transportation system

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Abstract: Transportation networks serve as windows into the complex world of urban systems. By properly characterizing a road network, one can better understand its encompassing urban system. This study offers a geometrical approach toward capturing inherent properties of urban road networks. It offers a robust and efficient methodology toward defining and extracting three relevant indicators of road networks—area, line, and point thresholds—through measures of their grid equivalents. By applying the methodology to 50 U.S. urban systems, one can successfully observe differences between eastern versus western, coastal versus inland, and old versus young cities. Moreover, we show that many socioeconomic characteristics, as well as travel patterns, within urban systems are directly correlated with their corresponding area, line, and point thresholds.

Keywords: complex urban systems, transportation networks, quantitative geography

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1 Introduction

Transportation systems have geometric properties. While their topologic characteristics can be examined as graphs (Garrison & Marble, 1962; Kansky, 1963; Haggett & Chorley, 1969; Taaffe, 1973), complex analysis approaches and more specifically network topological methods (Watts & Strogatz, 1998; Barabasi & Albert, 1999; Newman, 2003; Derrible & Kennedy, 2009; Antunes, Bavaud, & Mager, 2009; Barthélemy, 2011; Derrible & Ahmad, 2015; Ahmad & Derrible, 2015) have recently been used extensively for that purpose (Buhl et al., 2006; Courtat, Gloaguen, & Douady, 2011). With the recent abundance of transport data (Cottrill & Derrible, 2015; Karduni, Kermanshah, & Derrible, 2016), many researchers have focused on presenting a broader picture of transportation networks by showing that they possess general properties such as self-organization (Yerra & Levinson, 2005; Levinson & Yerra, 2006; Samaniego & Moses, 2008; Barthélemy & Flammini, 2009), fractal (Batty & Longley, 1994; Li, 2002; Batty, 2008), scale-free or power-law distribution (Lämmer, Gehlsen, & Helbing, 2006; Porta, Crucitti, & Latora, 2006; Kalapala, Sanwalani, Clauset, & Moore, 2006; Jiang, 2007; Jiang & Liu, 2012), Zipf's rank law (Gabaix, 1999; Chen & Zhou, 2004; Gonzalez-Val, 2011;

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Chen & Wang, 2014), and other properties (Scellato, Cardillo, Latora, & Porta, 2006; Crucitti, Latora, & Porta, 2006; Kurant & Thiran, 2006; Barthélemy & Flammini, 2008; Levinson, 2012; Louf, Jensen, & Barthelemy, 2013), to name a few. There are a number of studies of urban systems that have used simulated grid networks for different purposes (Yerra & Levinson, 2005; Levinson & Yerra, 2006; Xie & Levinson, 2007; Masucci, Smith, Crooks, & Batty, 2009; Amini, Peiravian, Mojarradi, & Derrible, 2016). Other studies also relate transport network properties to a variety of performance metrics (Derrible, Saneinejad, Sugar, & Kennedy, 2010; Kermanshah & Derrible, 2016).

This work focuses on measuring inherent geometric characteristics of urban road networks through studying their grid equivalents. Then, it is further extended by studying the relationships between the results and their corresponding urban systems' socioeconomic characteristics and travel patterns. At first, the methodology to perform those measurements is developed, and then it is applied to 50 urban areas in the United States to extract and analyze the characteristics of their road systems. These cities were selected because they cover a wide and diverse range of parameters such as road network structure, topology, morphology, history, size, population, area, and socioeconomic characteristics.

Cities are complex systems, consisting of a variety of interacting elements. From the time of its inception, an urban settlement goes through an evolutionary process that affects all of its constituents, among them its transportation system. Since a road network grows, expands, and evolves along with and similar to its encompassing urban system, it offers a proper means to study the complexity of its corresponding urban system and to express it using meaningful indicators (Hillier & Hanson, 1984). As Samaniego and Moses described it, "understanding the topology of urban networks that connect people and places leads to insights into how cities are organized" (Samaniego & Moses, 2008). Moreover, similar to other emerging (Yerra & Levinson, 2005) and self-organizing systems (Xie & Levinson, 2009a), the evolution of road networks is not a simple "product of conscious design" (Levinson & Yerra, 2006), but rather a complex and dynamic process (Xie & Levinson, 2009b) that is the result of the interaction of many different factors. Such influencing parameters include not only the system users and its infrastructure (Xie & Levinson, 2009a), but also its topological, morphological, technical, economic, social, and political factors (Xie & Levinson, 2009b), all of which are also determinants of the changes in the road network's encompassing urban system. In fact, even for cities that "look" different, their transportation systems can demonstrate a variety of similarities (Jiang & Claramunt, 2004; Batty, 2005; Lämmer, Gehlsen, & Helbing, 2006; Cardillo, Scellato, Latora, & Porta, 2006; Barthélemy, 2011). Based on the above argument, this study contributes to a better understanding of the complex nature of urban road networks by offering a robust and efficient approach that serves as a compliment to other existing methods.

At the first glance, and from a network perspective, a road system is simply seen as a collection of connected segments or links. Understandably, this perspective shifts the main attention towards studying its links as a way of understanding the whole network. This "link" aspect of urban transportation systems is paramount in terms of geometry and perhaps more closely related to the concept of "lines" (although not related to Space Syntax (Hillier, 1999)). We will therefore look for a *line* indicator that can represent the links in a road system.

An urban road network, however, is more than the sum of its links or lines. Similar to the circulatory system that serves the whole body, a road network serves its encompassing urban system by dividing it into smaller blocks that make it easier to reach every corner of that system. The coverage area of the road network is therefore another important factor to be studied. Thus, we will also represent the coverage area of a given road network by an *area* indicator.

Moreover, the locations where the road segments cross, i.e., their intersections, also play an important role in the daily operation of a road network. For that, their representation should also be a part of any comprehensive study of the complexity of their corresponding urban system. This provides another objective for this study, which is to find a *point* indicator for a given road network.

Based on the above arguments, an analysis of a road network, as a representative of the complexity of its encompassing urban system, requires three different yet related geometric indicators: *area, line,* and *point.* From a mathematical perspective, these three indicators also represent the three main geometric dimensions of an urban system, D^2, D^1, and D^0, respectively. This study offers a unified and systematic approach for the characterization of urban road networks through their *area*, *line*, and *point* indicators, later referred to as *thresholds*.

2 Methodology

In order to explain the methodology towards the development of the three geometric indicators of a given road network, Chicago's urban system is used as an example, for which the process can be summarized in the following three steps. Further details and information are provided in the Appendix.

Step 1: As the first task, the extent of the urban system for the given city is determined. In the U.S., the commonly used representation of such an influence area is the city's Metropolitan Statistical Area (MSA)[1]. The choice of MSA not only provides a consistent means for the selection of the extents of an urban area, but it also makes data collection easier as the MSA boundaries are readily available in shapefile format. Figure 1 exhibits Chicago MSA and its road network.

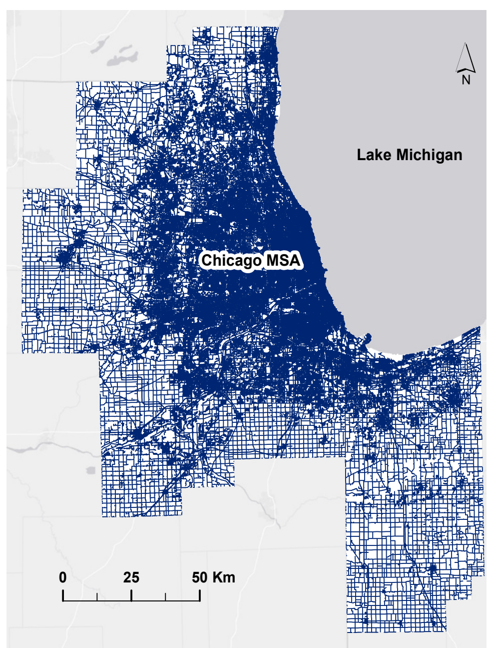


Figure 1: Chicago MSA road network

If we consider an MSA transportation network for a given urban area, it splits the MSA area into many polygons. Since the MSA boundary is a fictitious polyline and, generally speaking, is not a part of the MSA transportation network, the peripheral polygons that are along the MSA boundary are in fact open polygons that extend into the adjacent MSAs. By excluding such polygons, the collection of the

[1] MSA is defined as the "geographical region with a relatively high population density at its core and close economic ties throughout the area" (Wikipedia, 2014). This means that "a typical metropolitan area is centered on a single large city that wields substantial influence over the region" (Wikipedia, 2014), e.g., Chicago. More precisely, "Metropolitan Statistical Areas have at least one urbanized area of 50,000 or more population, plus adjacent territory that has a high degree of social and economic integration with the core as measured by commuting ties." (Nussle, 2008)

remaining polygons constructs the largest area in the MSA that can be enclosed/encircled by its transportation network, and thus be fully served by it. Therefore, instead of the entire MSA area, only those polygons are considered that are completely enclosed by the MSA road network links. This is desirable since full MSA areas artificially inflate the areas of the urban systems instead of focusing on the areas serviced by their road networks.

An example can been seen in Figure 2 in the case of Las Vegas, NV, in which the difference between the road polygons area created using the above approach versus the MSA area for Las Vegas is demonstrated. As it can be seen, there is a substantial difference between the MSA and the service area to be analyzed.

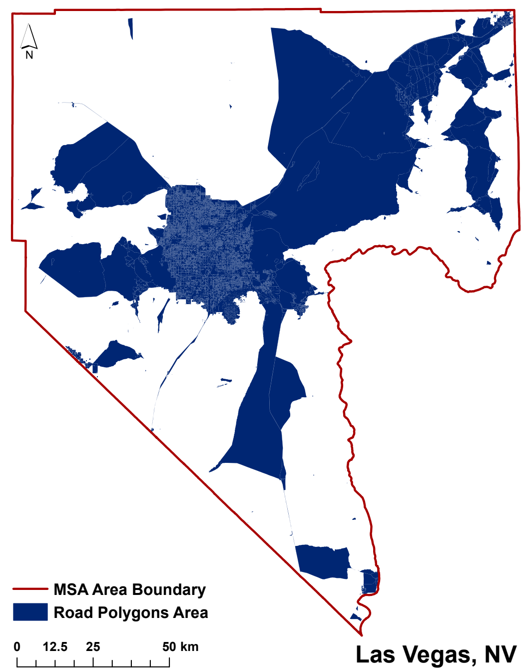


Figure 2: Difference between the service area of the transportation system, created by closed road polygons, and the MSA area for the city of Las Vegas

Having determined the road polygons sub-area of the MSA using the above process, the following three quantities are defined and calculated:

i. Area (*A*): which is the coverage area of the sub-area within the MSA,
ii. Length (*L*): which is the sum of the lengths of all the links in the transportation network within the MSA,
iii. Number of points or intersections (P): which is the total number of all the intersections in the transportation network within the MSA.

Step 2 involves two parts:

Part 1:

i. Creating a grid with a chosen cell size,
ii. Overlaying the grid on the MSA road network,
iii. Extracting the grid cells needed to cover all the road segments (i.e., omitting the grid cells that do not fall on any road segment).

Figure 3 demonstrates Chicago road polygons and a grid with 10 km x 10 km cells that covers Chicago MSA road network.

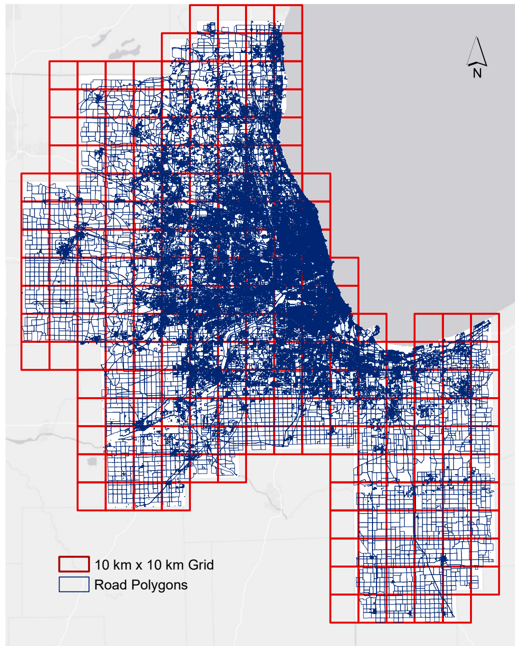


Figure 3: Chicago road polygons and 10 km x 10 km grid network

Part 1 is repeated for several grid cell sizes, namely: 10 km, 9 km, 8 km, 7 km, 6 km, 5 km, 4 km, 3 km, 2 km, 1km, 900 m, 800 m, 700 m, 600 m, 500 m, 400 m, 300 m, 200 m, and 100 m. The complete process for Chicago MSA road network is presented in Part B in the Appendix.

Part 2: For the remaining cells of each individual grid, resulted from the above process, define and calculate the following three quantities:

i. Area (*a*): which is the coverage area of the grid,

ii. Length (*l*): which is the total length of all the links in the grid,

iii. Number of points or intersections (*p*): which is the total number of all the nodes in the grid.

Step 3: The final task involves a comparison of the values obtained from Steps 1 and 2, i.e., *a* versus *A*, *l* versus *L*, and *p* versus *P*. The goal is to find the specific grids that are equivalent to the given road network with respect to total coverage area, total road length, and total number of intersections. As mentioned before, those criteria represent the given road network's area, line, and point characteristics, successively. The idea is that while a given urban road system might have an irregular configuration, something which is a part of its complex identity, one should be able to find equivalent grid networks that possess the same area, line, or point geometric characteristics as it has. The block sizes of such equivalent grid networks will then be considered as the indicators, or as called hereafter, the "*thresholds,*" for its corresponding geometric characteristic (area or line or point).

It should be emphasized that keeping only the cells that fall on the road network links during the above process ensures the uniqueness of the equivalent grid networks that satisfy the condition for the above geometric (area or line or point) indicators.

The procedure explained above is applied to the Chicago MSA road network. Due to its dense configuration, however, only a north-western portion of the road network along with its equivalent grid networks are demonstrated in Figure 4.

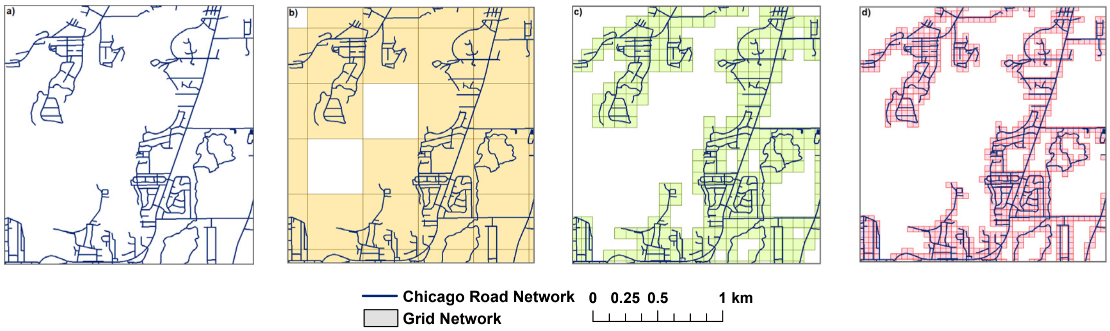


Figure 4: Comparison of (a) Chicago road network, and different grids with b) equal coverage area, c) equal road length, and d) equal number of nodes.

To explain their differences, the process involves overlaying grids with gradually decreasing block sizes over the original road system. At the beginning, the area covered by the grid is larger than the corresponding coverage area of the road network under study. As the cell size of the grid is gradually reduced, at some point the two areas become equal (Figure 4b). At that very moment, the grid network crosses a threshold. Since it marks the point where the two networks are equivalent in an "*area*" dimensional perspective, the grid network's block size is then designated as the "*area threshold*." After that point, the focus shifts to the comparison of the total road lengths of the two networks. As the grid network's block size becomes smaller and smaller, its total road length gradually increases, up to a point at which it becomes equal to the total road length of the original network (Figure 4c). That moment marks another threshold, at which the block size of the grid network is designated as the "*line threshold,*" i.e., when the two networks are equivalent in a "*line*" dimensional sense. The same process continues further, until a point when the total numbers of intersections (points) in both networks become equal (Figure 4d). That marks the third threshold, at which the block size of the grid network is designated as the "*point threshold*." At that very moment, the two networks are equivalent in a "*point*" dimensional sense.

As discussed before, a given urban road network can be examined from different perspectives. One is the area it encompasses or serves. Another one is the links (lines) that facilitate the services it provides. And the third one is the intersections (points) that in turn facilitate the transfer of services between links (lines). Measuring these three components, and their corresponding thresholds (as explained above), can help better understand the characteristics of the urban system itself.

In order to find the three area, line, and point thresholds accurately, the following approach is taken. For a given urban road network, its coverage area (A), total road length (L), and total number of intersections (P) is calculated and extracted from its shapefile, easily obtainable from Census TIGER/Lines dataset (U.S. Census Bureau, 2013). In comparison, for any chosen grid network with a block size of ε, the area it serves (a), the total road length it consists of (l), and the total number of intersections that it has (p), can also be extracted from its shapefile. One should note that A, L, and P are constants for a given MSA road network, while a, l, and p vary based on the chosen grid cell size.

Instead of comparing the two sets of numbers, the grid network values are normalized by dividing them by the road network's corresponding values, and are then compared with unity (one), i.e., plots of a/A, l/L, and p/P, are drawn and intersected with a horizontal line with the value of 1. At the point of intersection, the block size (ε) of the grid network is extracted and reported as the corresponding threshold. In other words, grid cell sizes where the a/A or l/L or p/P values equal one, are called "Area Threshold," "Line Threshold," and "Point Threshold," respectively. In essence, they represent the grid cell sizes at which the grids become equivalent to the real transportation network of that urban system from the Area, Length, and Points perspectives. Examples of the diagrams for the area, line, and point thresholds for the Chicago MSA road network are presented in Figure 5.

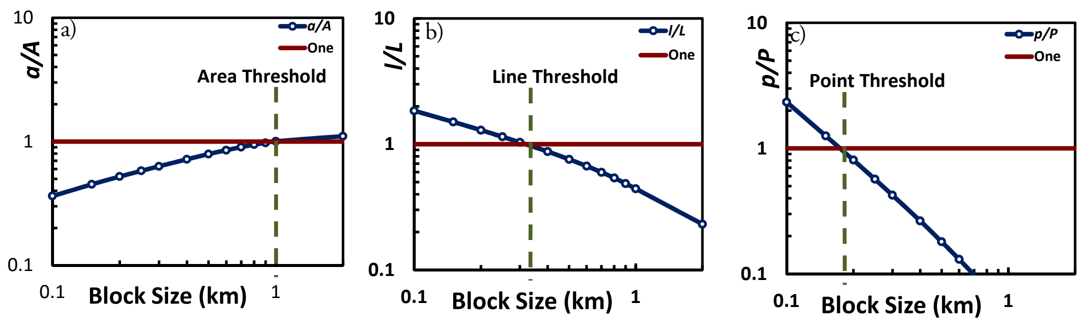


Figure 5: Determining the three thresholds for Chicago MSA road network: a) Area, b) Line, and c) Point Thresholds.

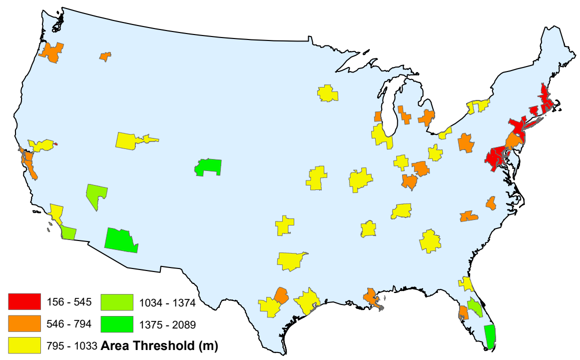
3 Results and discussion

Similar steps were executed for a total of 50 urban areas across the U.S. (see the Appendix for a complete list of cities as well as individual results). The results of the analyses performed are presented in Figures 6a, 6b, and 6c in the form of three maps, showing the geospatial variations of the three thresholds (area, line, and point) calculated for those urban areas.

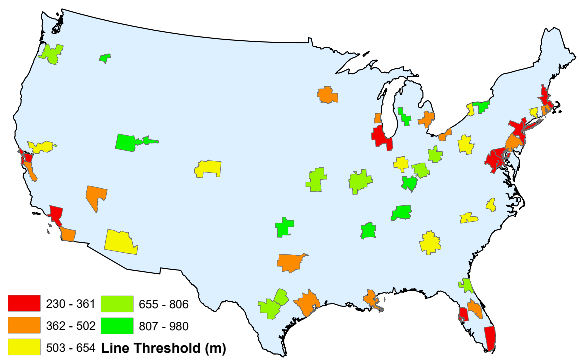
Figure 6a, i.e., area threshold map, shows lower values for older cities (mostly in the north-eastern states) as compared to those for younger cities. This difference is related to the advent of the motorized transportation in the 20^{th} century. "Older" cities tend to be more walkable and have smaller blocks, while "younger" cities tend to have larger block sizes. A comparison between Phoenix, AZ, with Chicago, IL, that have the largest and medium area thresholds, respectively, sheds light on this fact, as shown in Figure 7.

At the same time, Figure 6b, i.e., line threshold map, is different from the previous figure, as one can see that the line thresholds for the cities along the costal line are smaller than the values for the cities inside the country. The reason is partly due to the fact that coastal cities often perform as logistical hubs (e.g., ports) and thus are centers of import and export activities. As a result, their road networks are more compact and have more uniform road segments as compared to inland cities that have larger variations in their road segment lengths. A comparison of the length variations within the road networks of Salt Lake City, UT, with Chicago, IL, that have the largest and medium line thresholds, respectively, presents a visual explanation of this characteristic, as shown in Figure 8.

a)



b)



c)

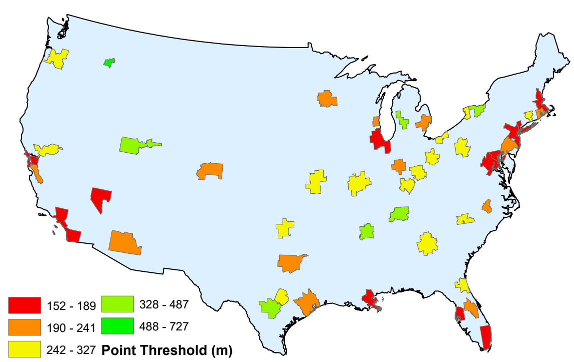


Figure 6: a) Area, b) Line, and c) Point thresholds.

Referring to Figure 6c, i.e., point threshold map, one might expect to see the same trend for the point threshold as the line threshold because intersections are merely where the roads intersect. This, however, is not always the case. One of the factors affecting the point threshold is the way the intersections are created, i.e., 6- or 4-way intersections as compared to T-intersections or cul-de-sacs, each affecting the point-threshold differently. This means that cities with similar line thresholds could have different point thresholds, and vice versa. A good example is Denver, Colorado, that has a mid-range line threshold, but a small point threshold, as can be seen in Figures 6b and 6c.

As mentioned before in the discussion of area threshold, "older" cities with lower area thresholds tend to have smaller blocks, while in comparison "younger" cities in general tend to have larger block sizes and thus higher area thresholds. Figure 7 presents a comparative same-scale illustration of the road polygons in Phoenix, AZ, versus Chicago, IL, that have the largest and medium area thresholds, respectively. It can be seen that overall Chicago offers a denser environment than Phoenix.

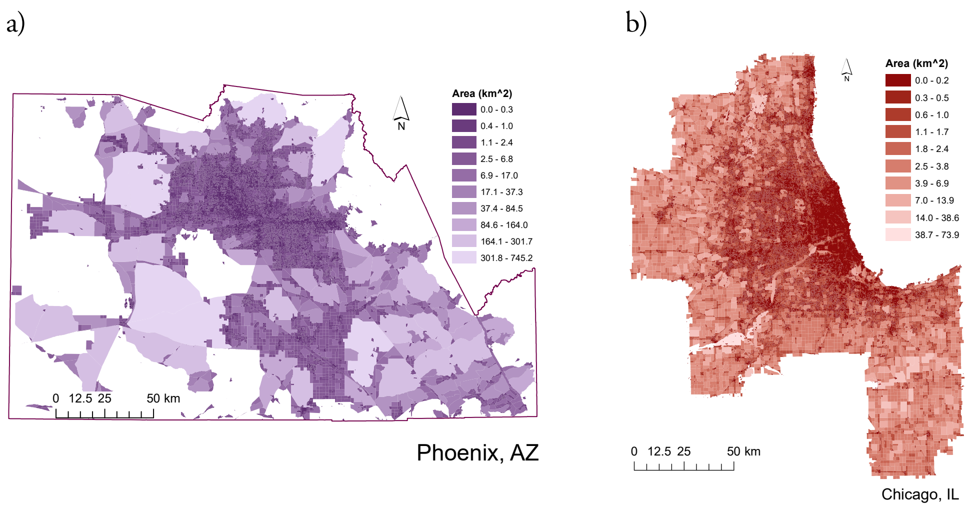


Figure 7: Road polygon size variations for a) Phoenix, and b) Chicago

In comparison, Figure 8 compares the length variations within the road networks of Salt Lake City, UT, and Chicago, IL, that have the largest and medium line thresholds, respectively. This is an example of the inland Salt Lake City versus a logistic hub coastal city like Chicago that is a center of freight activity. It can be seen that as a result, Chicago's road network is more compact and generally has a more uniform distribution of road segments as compared to the non-coastal Salt Lake City that has larger variation in its road segment lengths.

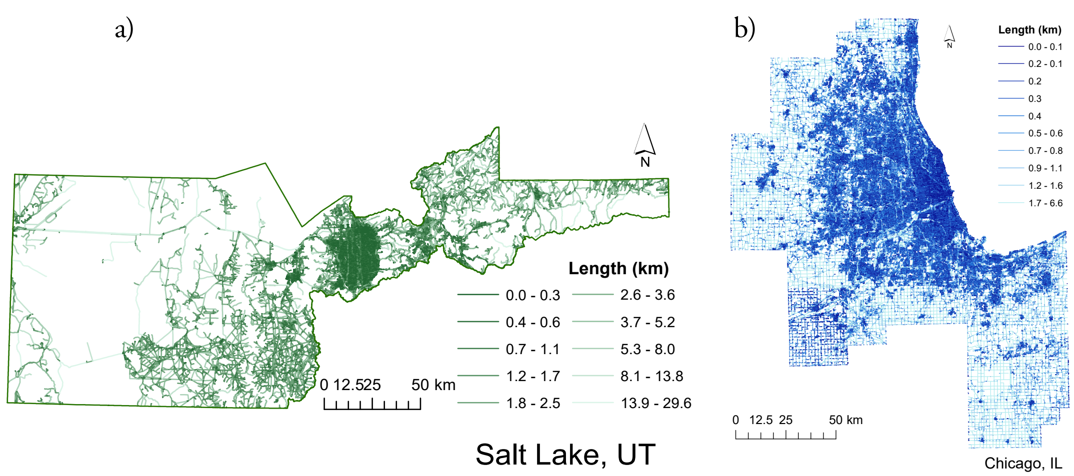


Figure 8: Road segment length variations for a) Salt Lake City, and b) Chicago

Figures 6a, 6b, and 6c demonstrate interesting and insightful aspects of the diversity of the inner complexity of the urban systems studied here. Of relevance, overall no single indicator can completely capture and describe the complexities at play. This emphasizes the fact that any given urban system has its own unique multidimensional complex characteristics, all of which are needed to gain a complete picture of its urban characteristics.

In order to better present and visually compare the thresholds calculated for the cities studied in this work, all the values obtained are plotted in one diagram. Figure 9 clearly shows that each threshold has its own variation and no two thresholds are behaving similarly, again a manifestation of the complex nature of urban systems and their road networks.

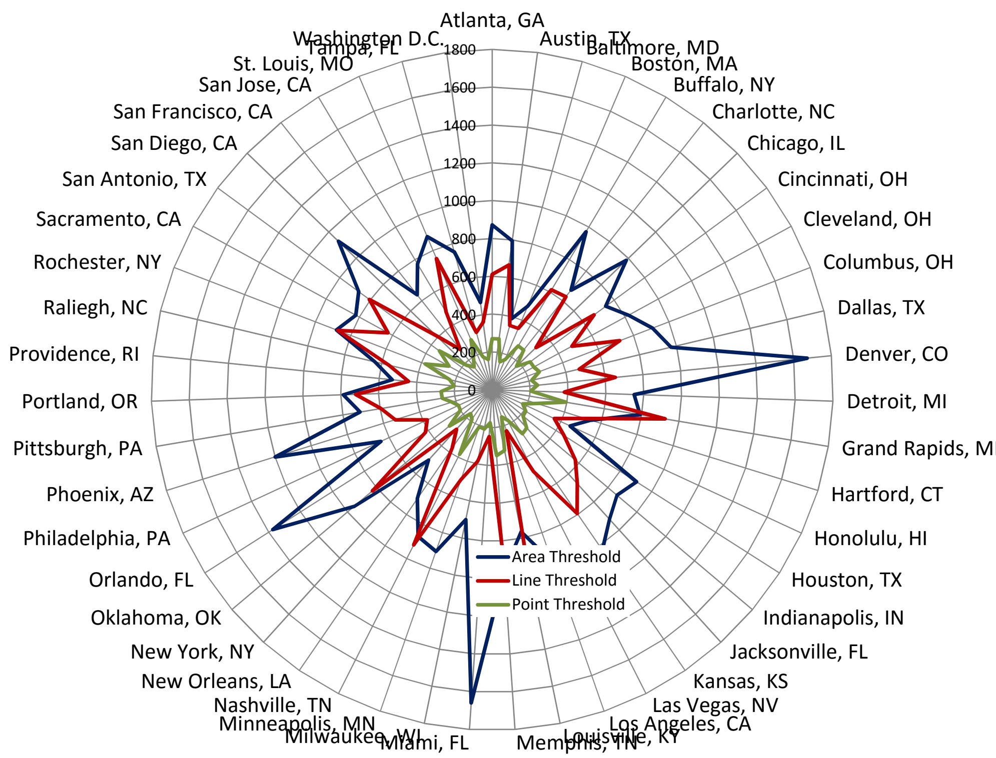


Figure 9: Area, line, and point thresholds for 50 U.S. urban areas.

The significance of the three thresholds found in this work was further investigated through analyzing their relationships with several socioeconomic parameters as well as travel patterns related to their corresponding urban areas studied here. A plot of the area threshold versus age of the urban systems (Wikipedia, 2013) studied here is presented in Figure 10.

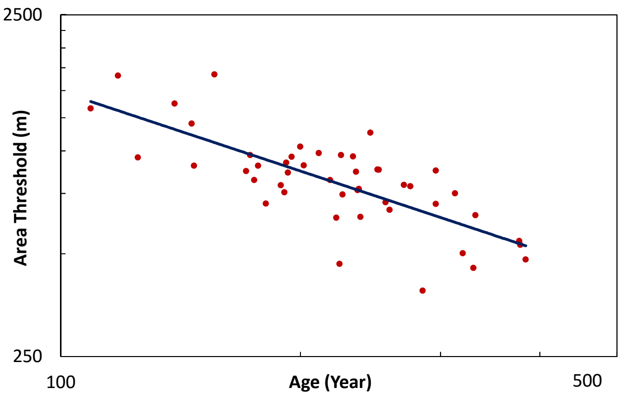


Figure 10: Relationship between the area threshold and the age of the urban system

Figure 10 shows a power law trend (*Area Threshold* = 52057 $Age^{-0.772}$, $R^2 = 0.51$, and |t-score| = 6.8), which means that the older a city is, the shorter its area threshold will be. This supports the fact that in older cities the polygons created by road networks are generally smaller due to their more-developed state, while in younger cities one would generally see larger polygon sizes. This figure is able to capture nearly two hundred years of urban and regional planning theory and the advent of motorized.

From another perspective, one witnesses a relationship between population density and line and point thresholds, as shown in Figure 11. This phenomenon is common and expected (Jacobs, 1961; Hanson & Giuliano, 2004; Peiravian, Derrible, & Ijaz, 2014), since, if other conditions remain the same, neighborhoods with smaller blocks (i.e., with higher road and intersection densities, as compared to larger blocks) tend to create safer environments and thus attract more people, hence higher population density.

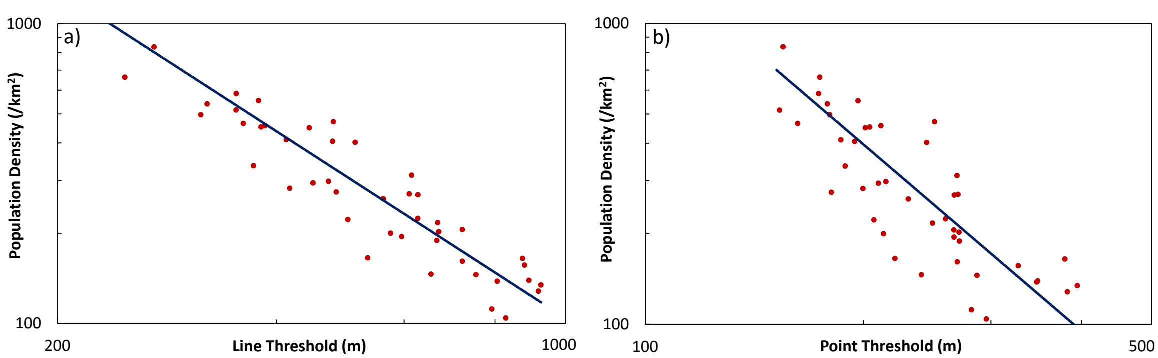


Figure 11: Relationship between Population density and a) Line and b) Point thresholds

Figure 11a shows that an increase in line threshold, which means larger block size, has a negative power law impact on population density (*Population density* = $5\text{x}10^6$ *Line threshold*$^{-1.566}$, $R^2 = 0.56$, and |t-score| = 7.6). The reason is that longer road segments, i.e., larger block sizes, essentially translate into larger residential units, thus lower population density.

Similarly, population density is affected by point threshold (*Population Density* = $2\text{x}10^7$ *Point threshold*$^{-2.061}$, $R^2 = 0.43$, and |t-score| = 5.8), as shown in Figure 11b. This shows the fact that closer and denser intersections translate into city blocks that are smaller and thus more suitable for housing with higher concentration of people per area.

Using the 2010 American Community Survey (ACS) data (U.S. Census Bureau 2010), we find that many travel patterns within the U.S. have power law relationships with the line threshold. Figures 12 exhibit the variations of the average travel time for all modes and also total transit travel time per capita with respect to the line threshold. Other travel patterns found to possess similar trends, including all-modes total travel time per capita, total number of trips, and total number of transit trips.

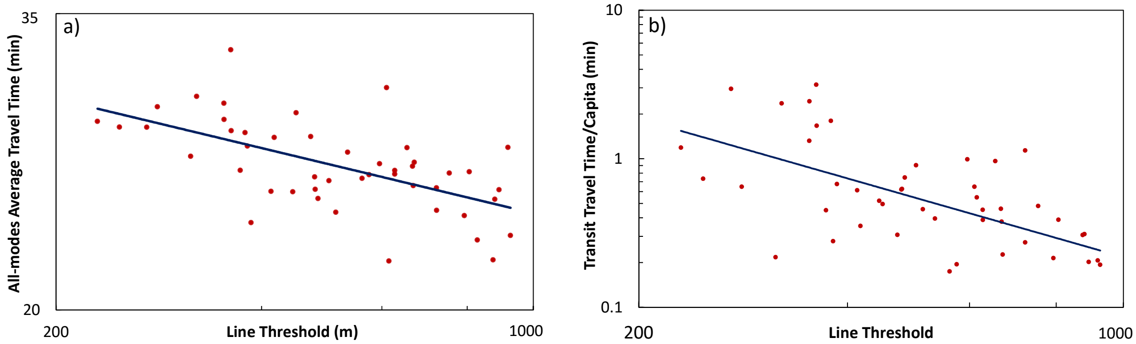


Figure 12: Relationship between the a) Average travel time for all modes, and b) Total transit travel time per capita, and the Line threshold.

The power law trend seen in Figure 12a (*All-modes avg. travel time* = 60.725 *Line threshold*$^{-0.134}$, R^2 = 0.38, and |t-score| = 5.2) shows that as the line threshold increases, the average travel time for all modes decreases. The reason is that an increase in the lengths of the road segments, which partially represents the existence of freeways and thus lower road density, results in a higher car use as the dominant choice of transportation mode in the U.S. A similar trend exists for the reduction in the use of public transit, shown in Figure 12b (*Total transit travel time per capita* = 2147 *Line threshold*$^{-1.331}$, R^2 = 0.37, and |t-score| = 4.7). As a result, the total transit travel time per capita also drops as line threshold increases.

As for the point threshold, studies (Brown et al., 2013; Peiravian, Derrible, & Ijaz, 2014) have shown that denser road networks, which translate into closer and more compact intersections, support active modes of transportation, including walking. Walking data from 2010 American Community Survey supports this idea, as shown in Figure 13.

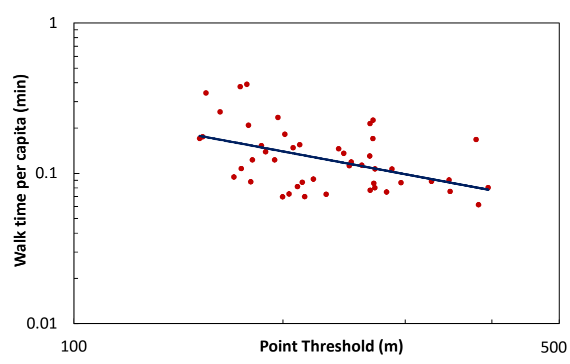


Figure 13: Relationship between Walk time per capita and Point threshold.

Based on this figure, urban areas with shorter point thresholds tend to have higher walk time per capita (*Walk time per capita*=13.405 *Point threshold*$^{-0.861}$, R^2 = 0.38, and |t-score| = 3.1), which is due to the fact that shorter point thresholds mean more and closer intersections. This result simply reflects the fact that, among other parameters, the closer the intersections, the more encouraging and supportive the environment is for pedestrians. In other words, pedestrians are willing to walk longer distances in areas with shorter point thresholds.

4 Conclusions

This study offered a complementary perspective into the complex nature of urban systems via geometric properties of their road networks. By creating grid networks of varying block sizes and overlaying them on the road networks under study, three indicators were extracted, each representing a distinct geometric property of the network. In this study, we first developed a methodology to measure these three thresholds, which was then applied to 50 U.S. urban systems with a wide variety of characteristics. Together, the area, line, and point thresholds obtained through the method developed in this study succeeded in capturing important and complex characteristics of an urban system. We also showed that there are correlations between the thresholds defined and extracted in this study and the socioeconomic characteristics as well as travel patterns for a given urban area. While two cities may share similarities for one of the thresholds, they may not be similar with respect to the other two, thus allowing us to capture their unique properties from different perspectives.

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Authors' contributions

Authors jointly designed the study, performed the research, analyzed the data, drafted the manuscript, and gave final approval for publication.

Conflict of interest

The authors declare no conflict of interest.

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Software and data accessibility

The software used for the analysis and production the figures included ArcGIS and Microsoft Excel.

The data used in this research were 2013 road network TIGER/Lines shapefiles and 2010 American Community Survey data, both obtained from U.S. Census Bureau at www.census.gov.

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Appendix

A. List of 50 U.S. urban systems studied and their characteristics
B. Explanation for Step 2, Part 1 of the Methodology (Case study: Chicago, IL)
C. Road networks for 50 U.S. urban systems
D. Area, point, and line thresholds for 50 U.S. road systems

A. List of 50 U.S. urban systems studied and their characteristics

Urban Area, State	Founded in[1]	Population[2]	Area (km^2)[3]	Pop Density	Road Length (km)[3]	# of Intersections[3]
Atlanta, GA	1843	5486738	20306.8	270.2	67215.1	243462
Austin, TX	1835	1784094	9440.8	189.0	30382.0	111234
Baltimore, MD	1729	2895944	5624.9	514.8	35556.3	220784
Boston, MA	1630	4892136	8368.7	584.6	49139.9	261949
Buffalo, NY	1789	1191744	3821.4	311.9	12293.0	41429
Carson, NV	1858	87743	109.0	804.9	900.6	3045
Charlotte, NC	1755	1927130	7177.5	268.5	24978.8	93988
Chicago, IL	1803	9594379	17783.6	539.5	86788.9	396704
Cincinnati, OH	1788	2252951	10398.8	216.7	33834.5	141744
Cleveland, OH	1796	2272776	4827.5	470.8	19472.2	64630
Columbus, OH	1812	1949603	9483.2	205.6	27764.3	106156
Dallas, TX	1841	6501589	21833.1	297.8	83815.2	350762
Denver, CO	1858	2666592	18262.0	146.0	46547.0	182157
Detroit, MI	1701	4369224	9664.6	452.1	46880.4	187960
Grand Rapids, MI	1825	895227	6665.8	134.3	16684.6	42990
Hartford, CT	1637	1400709	3487.6	401.6	14992.7	56695
Honolulu, HI	1809	953207	775.4	1229.3	4678.9	22904
Houston, TX	1837	6052475	20585.7	294.0	83365.0	353831
Indianapolis, IN	1821	1856996	9289.1	199.9	32389.9	150469
Jacksonville, FL	1822	1451740	7182.3	202.1	22067.4	76396
Kansas City, KS	1868	2138010	19148.1	111.7	50639.6	184748
Las Vegas, NV	1905	2010951	7330.1	274.3	20926.8	104925
Lewiston, ID	1861	85096	2104.6	40.4	4206.1	6334
Los Angeles, CA	1781	13059105	10913.2	1196.6	70096.7	335638
Louisville, KY	1778	1443801	9227.8	156.5	24453.7	82680
Memphis, TN	1819	1398172	10049.2	139.1	25028.4	74462
Miami, FL	1896	5571523	8410.3	662.5	42827.1	178680
Milwaukee, WI	1833	1602022	3507.8	456.7	17207.1	66802
Minneapolis, MN	1867	3412291	15365.8	222.1	57532.0	259788
Nashville, TN	1779	1740134	13588.3	128.1	32653.8	90700
New Orleans, LA	1718	1247062	3715.5	335.6	18340.7	83361
New York, NY	1624	19217139	15551.5	1235.7	105344.0	499969
Oklahoma, OK	1889	1359027	13051.0	104.1	34167.6	120303
Orlando, FL	1875	2257901	7996.6	282.4	28876.5	123076
Philadelphia, PA	1682	6234336	11271.7	553.1	58104.3	256023
Phoenix, AZ	1868	4262838	25763.0	165.5	60738.6	241836

A. List of 50 U.S. urban systems studied and their characteristics continued

Urban Area, State	**Founded in**[1]	**Population**[2]	**Area (km^2)**[3]	**Pop Density**	**Road Length (km)**[3]	**# of Intersections**[3]
Pittsburgh, PA	1758	2503836	12859.9	194.7	45196.4	167027
Portland, OR	1845	2363554	14669.4	161.1	44544.0	174765
Providence, RI	1636	1695760	3773.5	449.4	18431.5	83871
Raliegh, NC	1792	1258825	4830.5	260.6	18678.0	81802
Rochester, NY	1803	1159166	7037.2	164.7	17863.9	47275
Sacramento, CA	1839	2277843	10167.0	224.0	34020.6	124839
Salt Lake, UT	1847	1246208	10895.1	114.4	22387.0	59736
San Antonio, TX	1718	2239307	16213.5	138.1	44137.5	127773
San Diego, CA	1769	3144425	7668.0	410.1	29499.1	144194
San Francisco, CA	1776	4472992	5352.1	835.7	33483.0	172400
San Jose, CA	1777	1992872	4921.2	405.0	19824.6	93610
St. Louis, MO	1763	2934412	20184.1	145.4	57670.8	205269
Tampa, FL	1823	2858974	5756.8	496.6	31421.2	143714
Washington D.C.	1790	5916033	12735.0	464.5	74190.6	437470

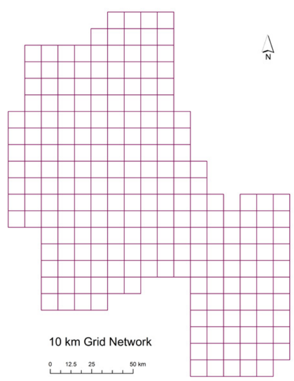
1. Wikipedia, Accessed 2014-06: http://www.wikipedia.org/

2. U.S. Census Bureau American FactFinder, 2010: http://factfinder2.census.gov/

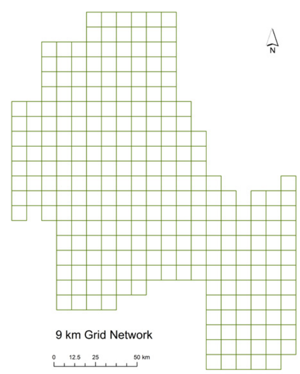
3. Calculated from U.S. Census Bureau TIGER/Line Shapefiles, 2010: https://www.census.gov/geo/maps-data/data/tiger-line.html

B. Explanation for Step 2, Part 1 of the Methodology (Case study: Chicago, IL)

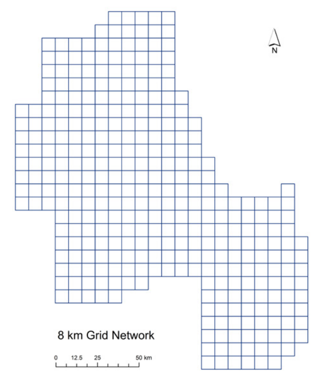
In Step 1 of the methodology, as explained before, at first the MSA of the given urban area was chosen as its extent. In Step 2, Part 1, successive grids with varying block sizes were created and then overlaid on the road network, from which the cells needed to cover all the road segments within the MSA were extracted. Figures below demonstrate the creation of grids with cells ranging from 10 km to 100 m for Chicago MSA road network. They show how the grid network evolves towards the real road network. During this process, there are thresholds at which the grid network becomes equivalent to the road network from area, line, and point dimensional perspectives. The last figure demonstrates the real road network for visual comparison.



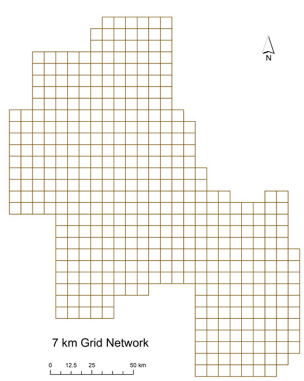
a) 10 km Grid Network



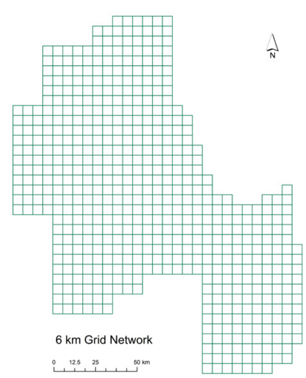
b) 9 km Grid Network



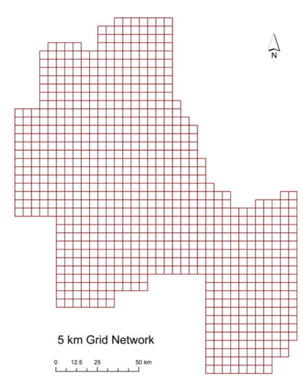
c) 8 km Grid Network



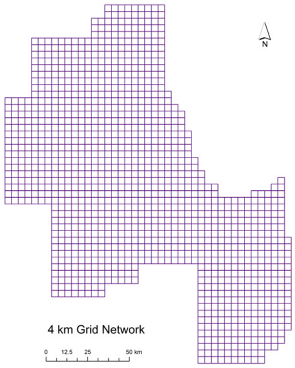
d) 7 km Grid Network



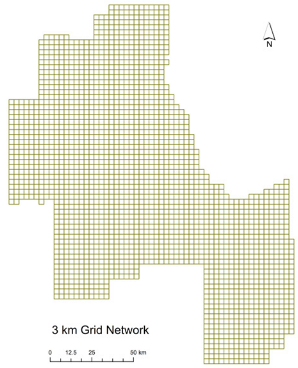
e) 6 km Grid Network



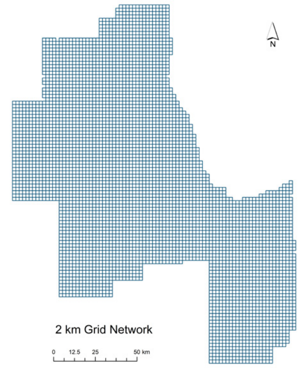
f) 5 km Grid Network



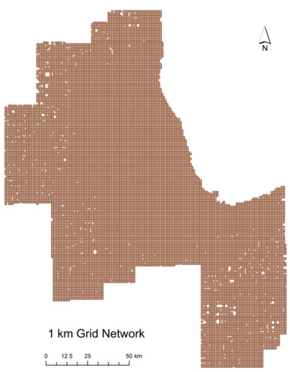
g) 4 km Grid Network



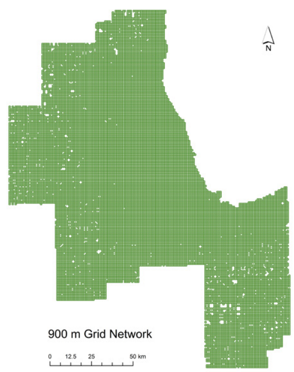
h) 3 km Grid Network



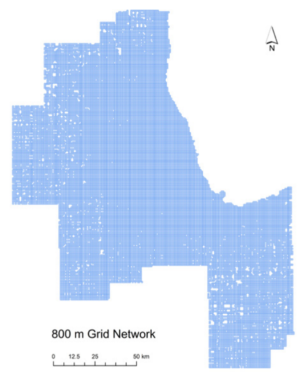
i) 2 km Grid Network



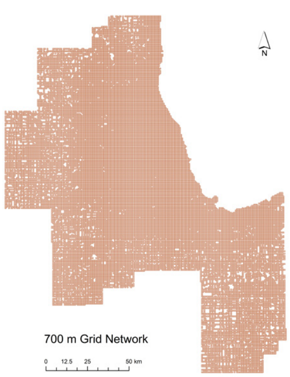
j) 1 km Grid Network



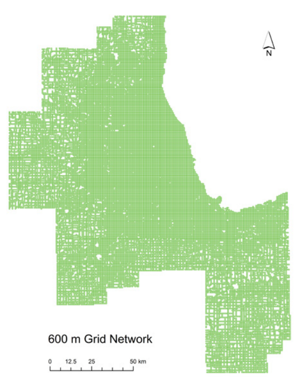
k) 900 m Grid Network



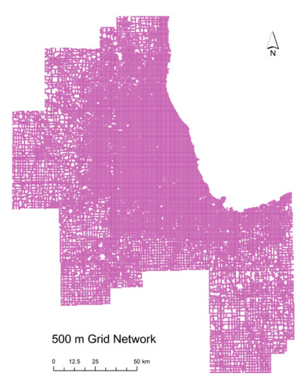
l) 800 m Grid Network



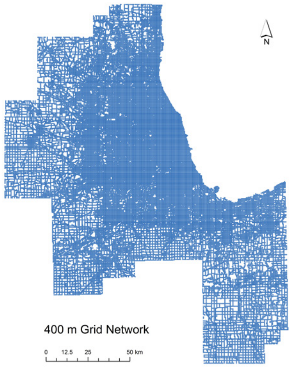
m) 700 m Grid Network



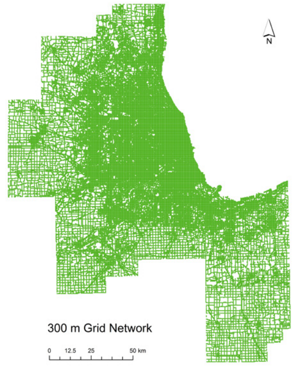
n) 600 m Grid Network



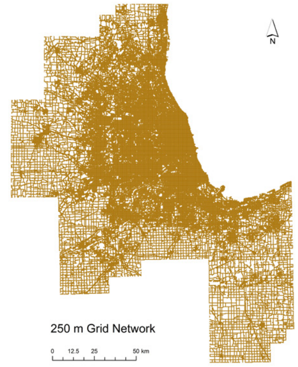
0) 500 m Grid Network



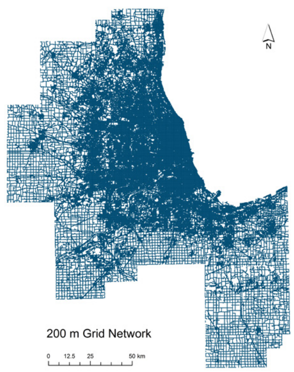
p) 400 m Grid Network



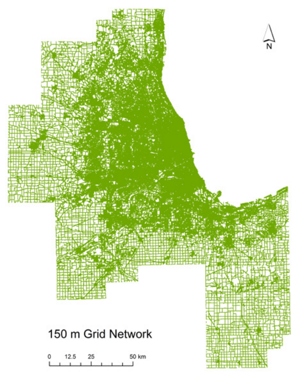
q) 300 m Grid Network



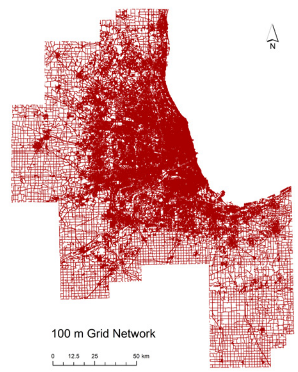
r) 250 m Grid Network



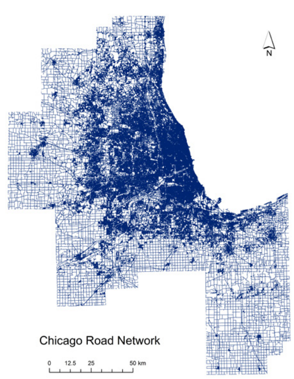
s) 200 m Grid Network



t) 150 m Grid Network



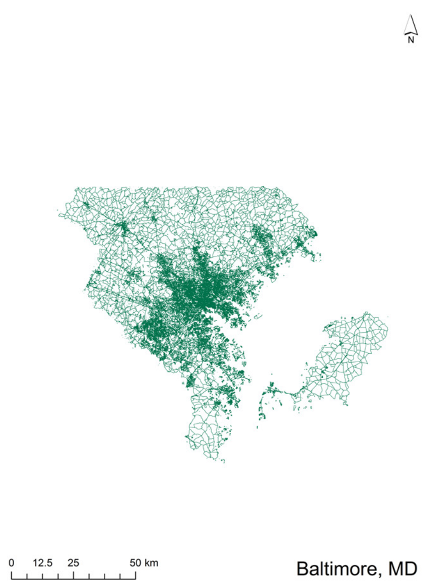
u) 100 m Grid Network

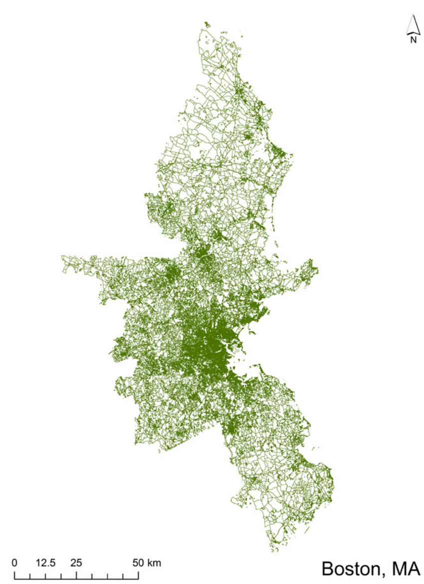


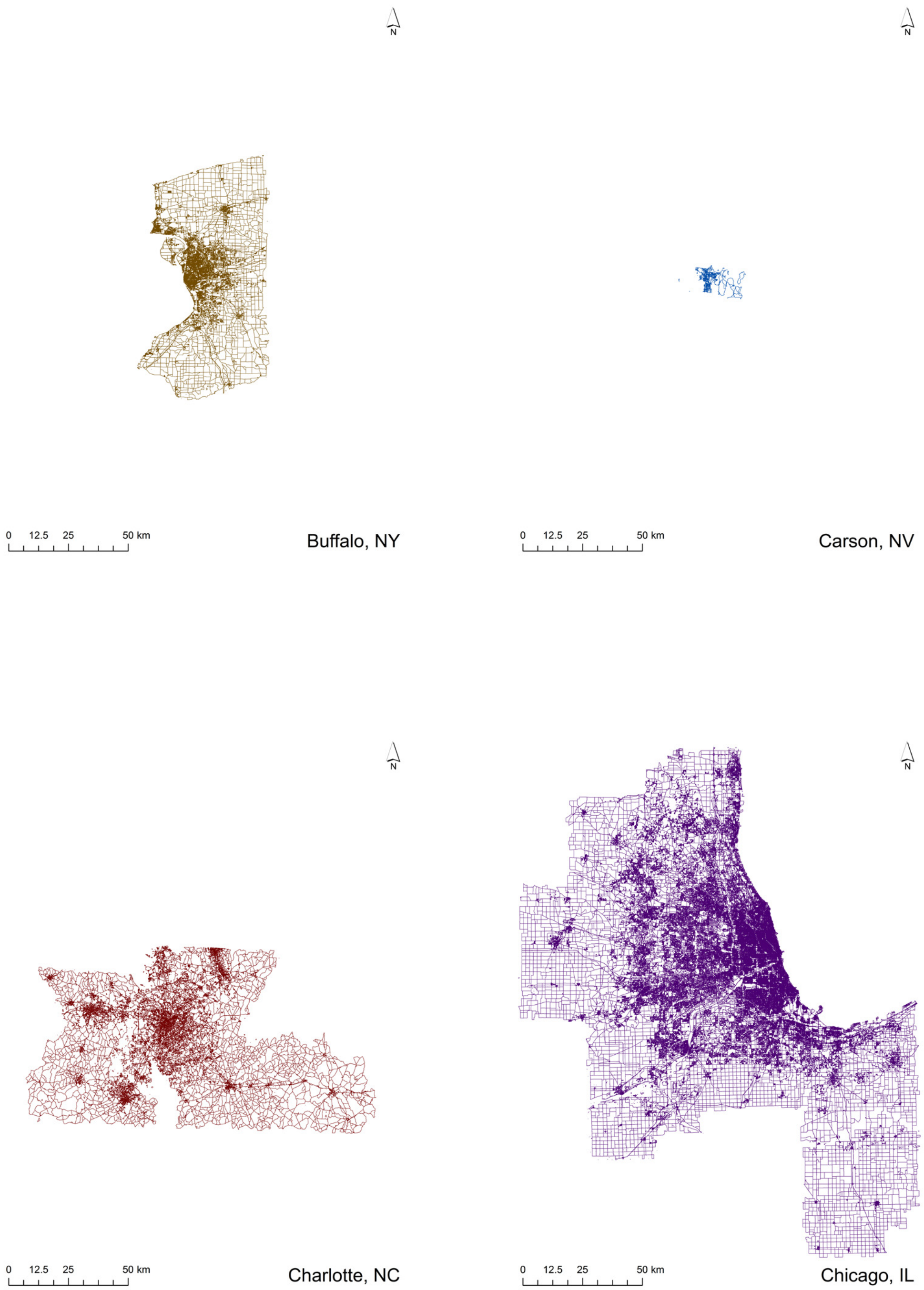
v) Chicago Road Network

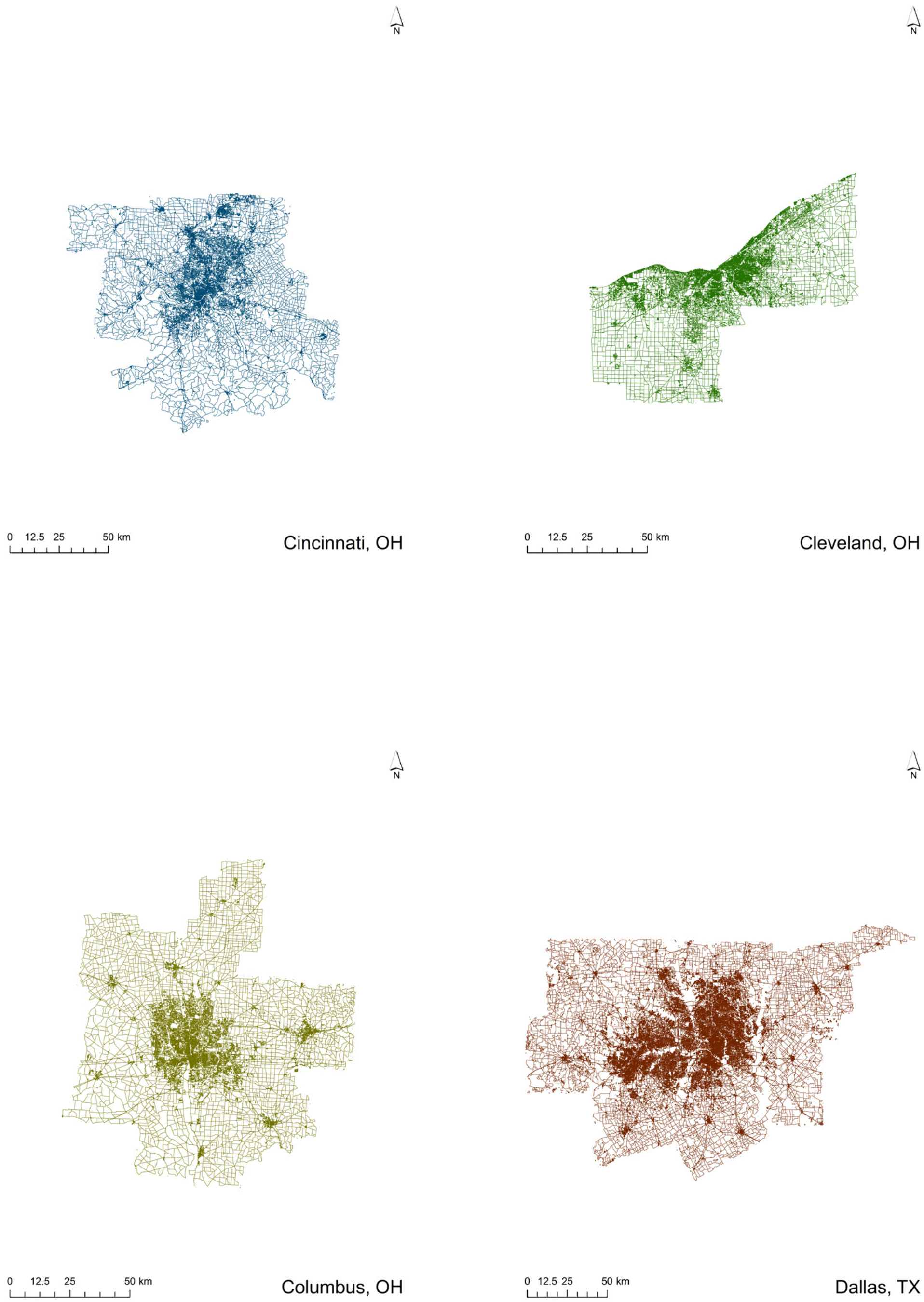
Figure B. Evolution of grid networks for Chicago MSA road network

C. Road networks for 50 U.S. urban systems






N
0 12.5 25 50 km
Buffalo, NY
N
0 12.5 25 50 km
Carson, NV
N
0 12.5 25 50 km
Charlotte, NC
N
0 12.5 25 50 km
Chicago, IL


N
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Cleveland, OH
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Columbus, OH
N
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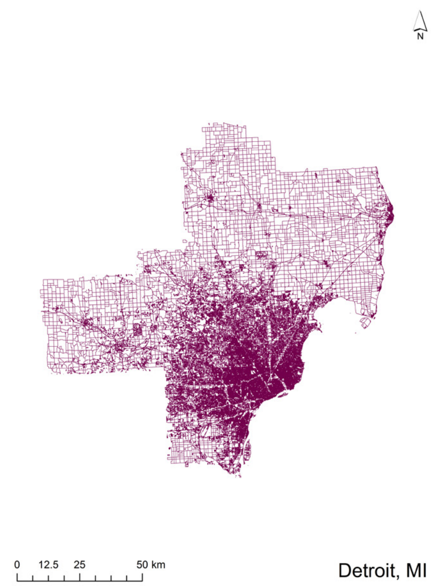
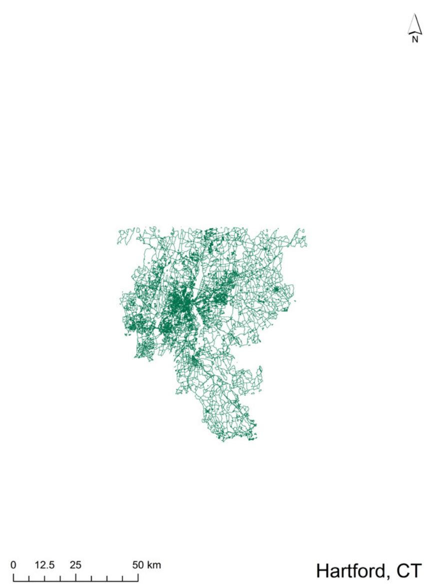
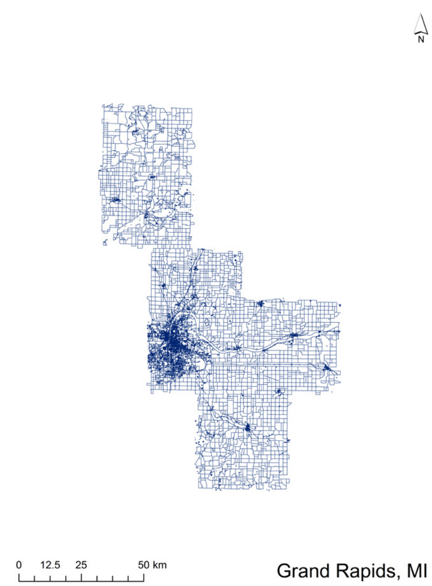
Dallas, TX

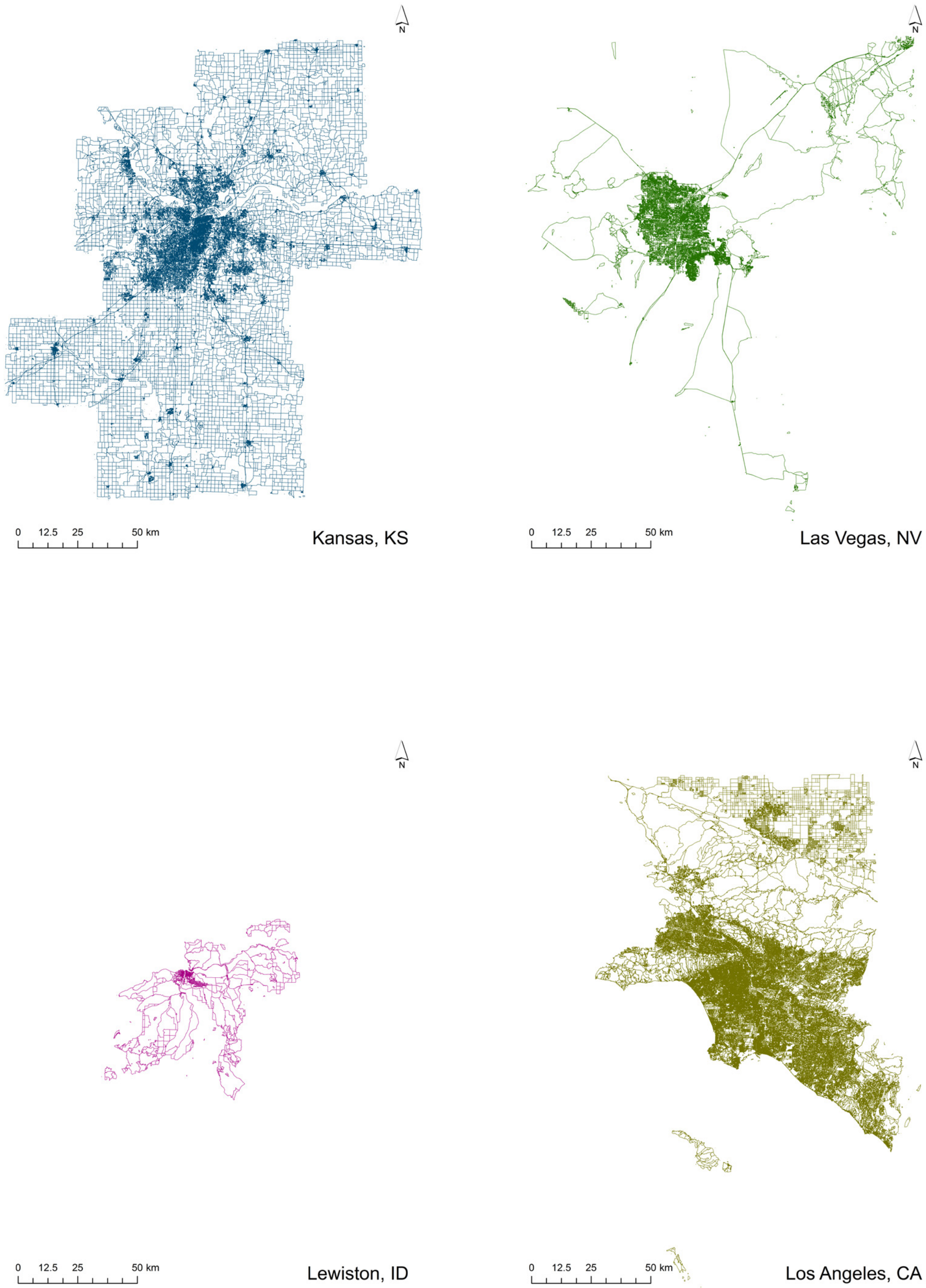

N
0 12.5 25 50 km
Denver, CO


N
0 12.5 25 50 km
Detroit, MI


N
0 12.5 25 50 km
Hartford, CT

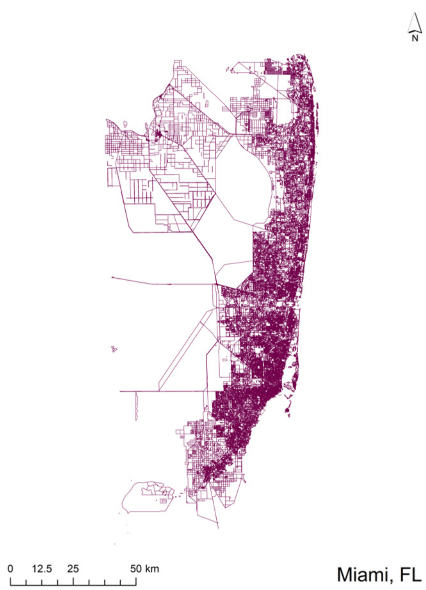

N
0 12.5 25 50 km
Grand Rapids, MI

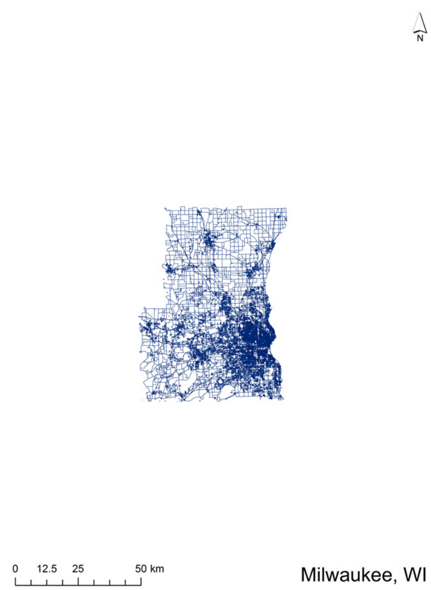

N
0 12.5 25 50 km
Honolulu, HI
N
0 12.5 25 50 km
Houston, TX
N
0 12.5 25 50 km
Indianapolis, IN
N
0 12.5 25 50 km
Jacksonville, FL


N
0 12.5 25 50 km
Kansas, KS
N
0 12.5 25 50 km
Las Vegas, NV
N
0 12.5 25 50 km
Lewiston, ID
N
0 12.5 25 50 km
Los Angeles, CA

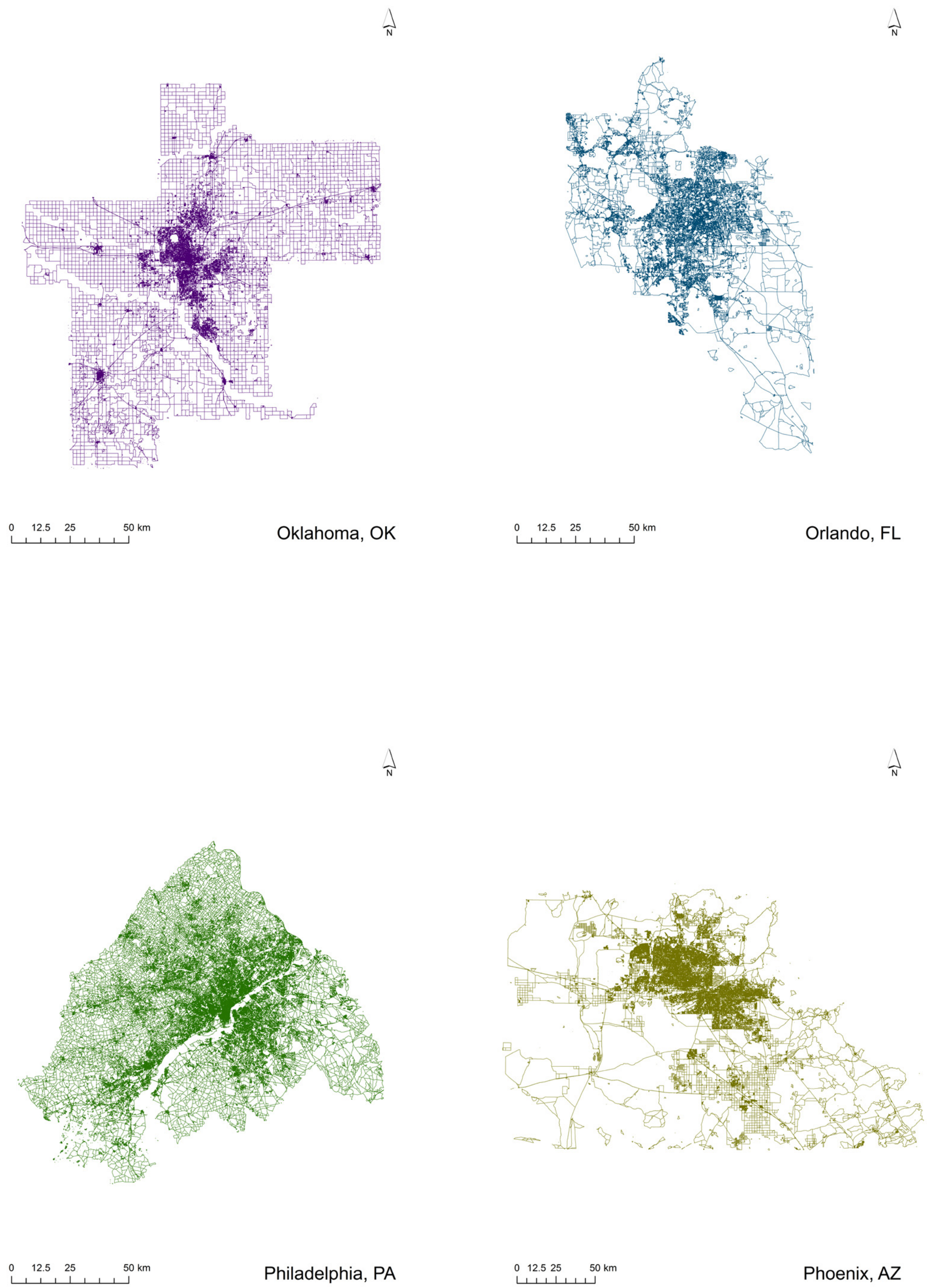

N
0 12.5 25 50 km
Louisville, KY

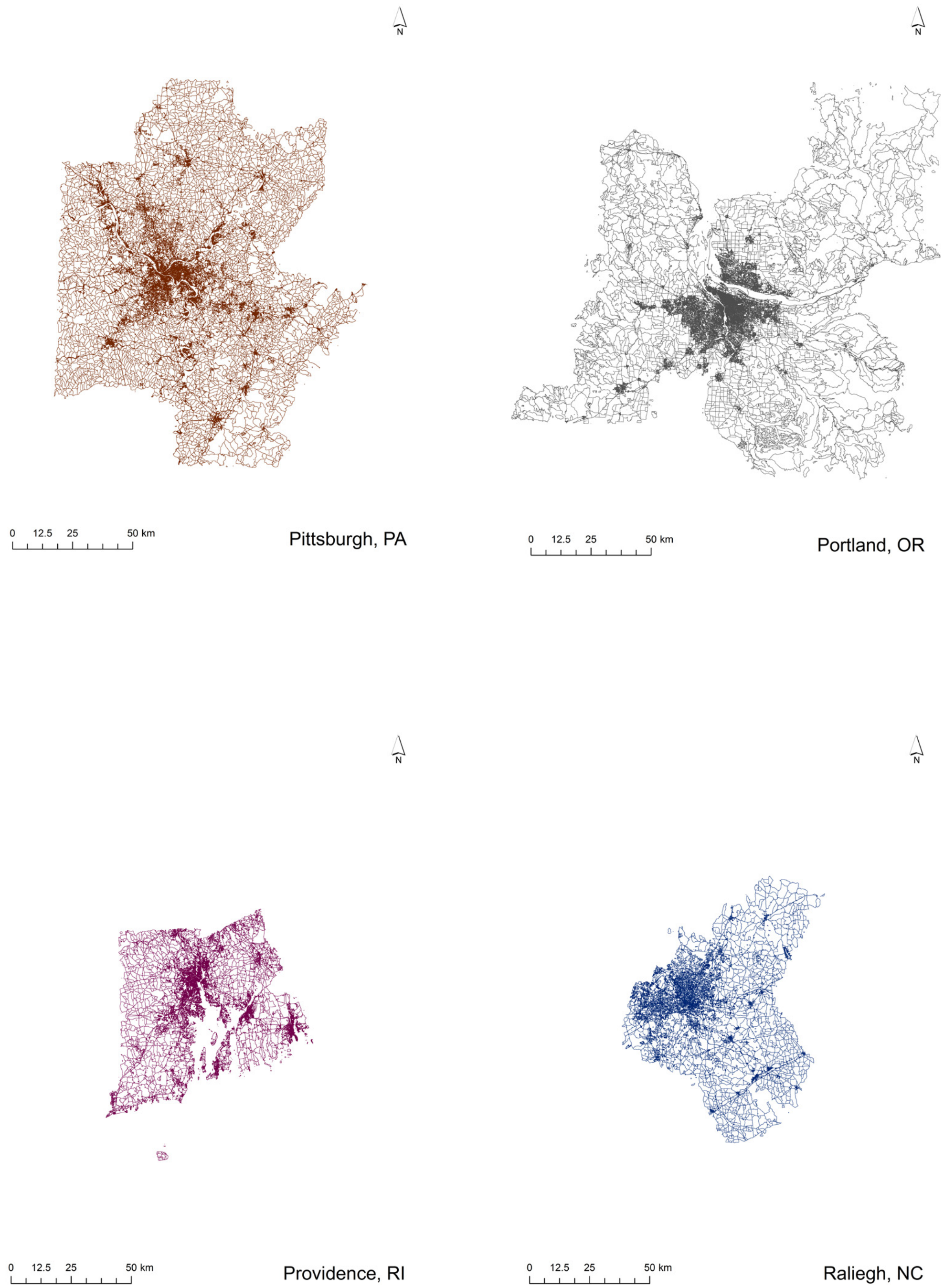

N
0 12.5 25 50 km
Memphis, TN


N
0 12.5 25 50 km
Miami, FL

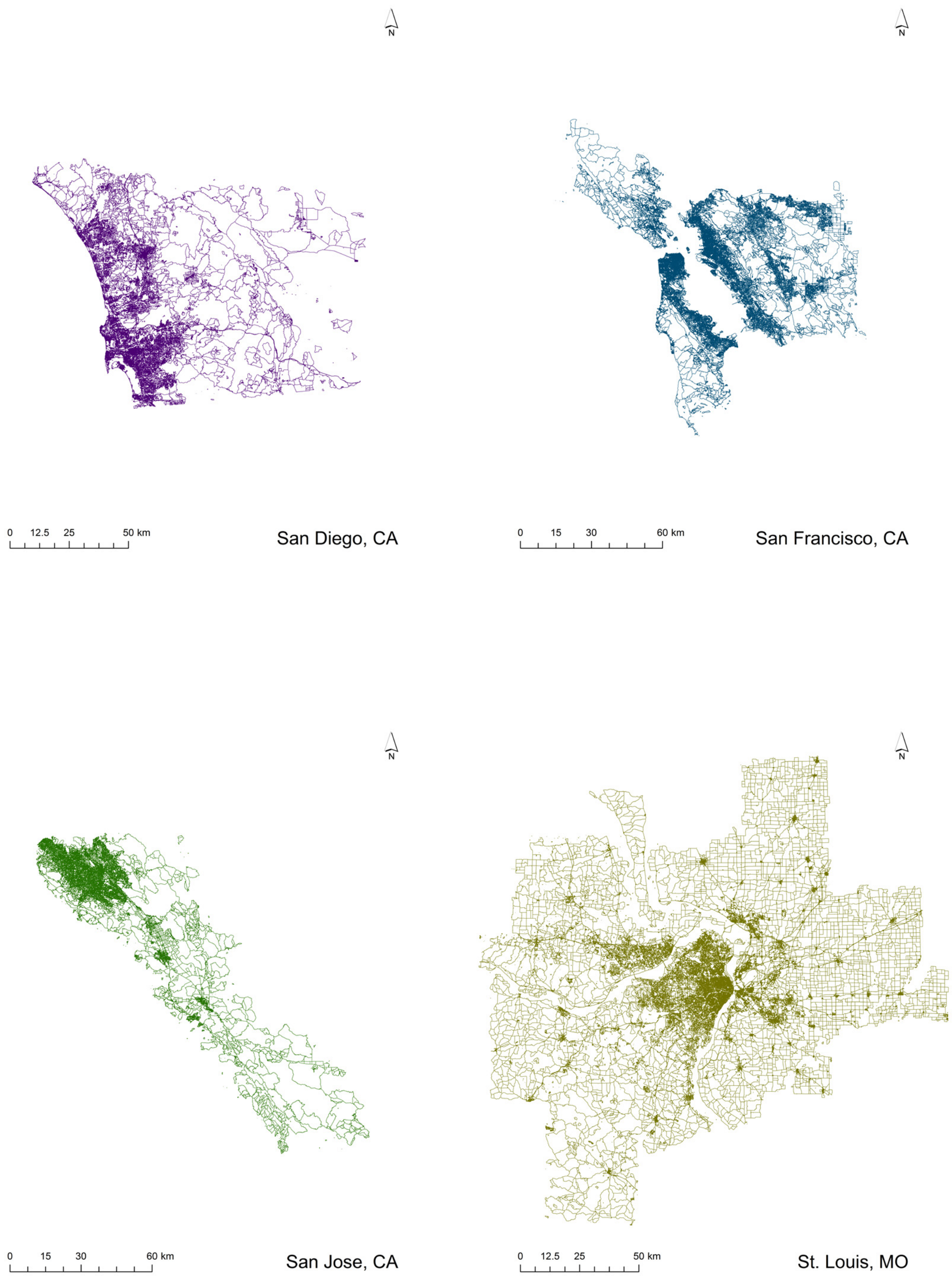

N
0 12.5 25 50 km
Milwaukee, WI


N
0 12.5 25 50 km
Minneapolis, MN
N
0 12.5 25 50 km
Nashville, TN
N
0 12.5 25 50 km
New Orleans, LA
N
0 12.5 25 50 km
New York, NY


N
0 12.5 25 50 km
Oklahoma, OK
N
0 12.5 25 50 km
Orlando, FL
N
0 12.5 25 50 km
Philadelphia, PA
N
0 12.5 25 50 km
Phoenix, AZ


N
0 12.5 25 50 km
Pittsburgh, PA
N
0 12.5 25 50 km
Portland, OR
N
0 12.5 25 50 km
Providence, RI
N
0 12.5 25 50 km
Raliegh, NC


N
0 12.5 25 50 km
Rochester, NY
N
0 12.5 25 50 km
Sacramento, CA
N
0 12.525 50 km
Salt Lake, UT
N
0 12.5 25 50 km
San Antonio, TX


N
0 12.5 25 50 km
San Diego, CA
N
0 15 30 60 km
San Francisco, CA
N
0 15 30 60 km
San Jose, CA
N
0 12.5 25 50 km
St. Louis, MO

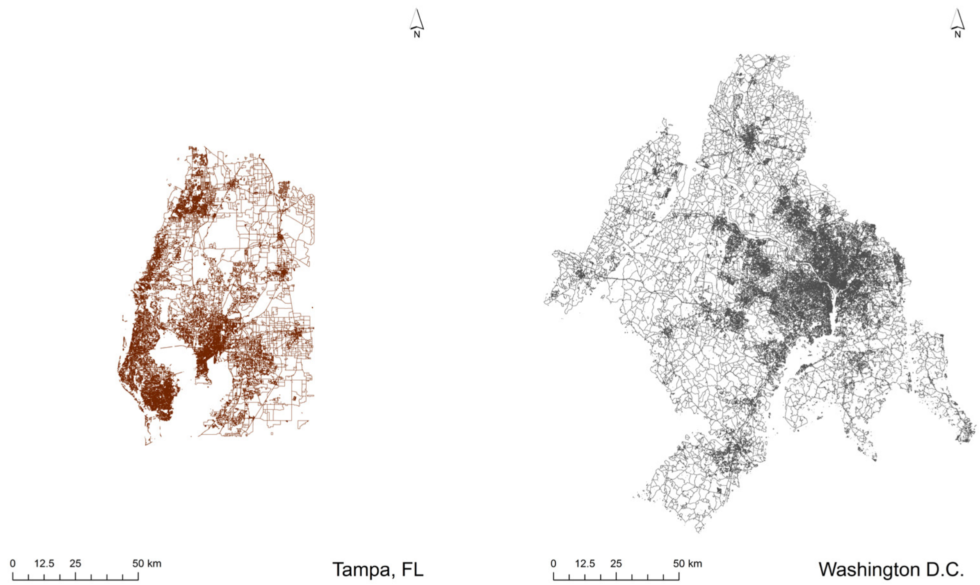


Figure C. Relative sizes and shapes of the 50 urban road polygons analyzed in this study.

D. Area, point, and line thresholds for 50 U.S. urban road systems

Urban Area, State	Area Threshold (m)	Line Threshold (m)	Point Threshold (m)
Atlanta, GA	872	610	270
Austin, TX	794	666	272
Baltimore, MD	390	352	153
Boston, MA	480	353	174
Buffalo, NY	971	615	270
Carson, NV	156	778	279
Charlotte, NC	672	627	267
Chicago, IL	984	321	179
Cincinnati, OH	745	668	249
Cleveland, OH	821	479	251
Columbus, OH	907	722	267
Dallas, TX	971	472	215
Denver, CO	1671	654	241
Detroit, MI	751	381	204
Grand Rapids, MI	792	926	395
Hartford, CT	545	514	245
Honolulu, HI	454	361	178
Houston, TX	904	450	210
Indianapolis, IN	863	575	213
Jacksonville, FL	923	670	271
Kansas City, KS	1028	793	282
Las Vegas, NV	1330	484	181
Lewiston, ID	663	980	727
Los Angeles, CA	962	230	152
Louisville, KY	767	879	327
Memphis, TN	960	891	348
Miami, FL	1660	248	174
Milwaukee, WI	700	386	212
Minneapolis, MN	904	502	207
Nashville, TN	868	919	383
New Orleans, LA	699	372	189
New York, NY	501	282	170
Oklahoma, OK	955	828	296
Orlando, FL	1374	418	200
Philadelphia, PA	648	378	197
Phoenix, AZ	1200	535	221
Pittsburgh, PA	707	596	267
Portland, OR	787	722	270
Providence, RI	531	444	201
Raliegh, NC	637	562	231
Rochester, NY	881	874	380

D. Area, point, and line thresholds for 50 U.S. urban road systems continued

Urban Area, State	Area Threshold (m)	Line Threshold (m)	Point Threshold (m)
Sacramento, CA	821	627	260
Salt Lake, UT	1033	957	397
San Antonio, TX	875	806	347
San Diego, CA	1129	413	186
San Francisco, CA	640	272	155
San Jose, CA	773	478	195
St. Louis, MO	880	753	287
Tampa, FL	756	315	180
Washington D.C.	467	361	162