Estimating Material Usage of Road Infrastructure in US Cities

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ABSTRACT

This paper examines patterns that emerge in cities and proposes a link between these patterns and material usage. This approach considers road infrastructure in cities to be a structured complex system, with properties that can be described mathematically. A general methodology is proposed and applied using data from 40 US cities. By identifying a road scaling pattern and its range of variation, material usage of road infrastructure can be estimated based on the distance from the urban center. The results of this analysis are visualized spatially providing an intuitive way of understanding these patterns. A preliminary estimate of material consumption is made, with suggestions for future improvement.

Contents

Background

The goal of this paper is to identify a relationship that can be used to describe road infrastructure as a function of distance from the city center. By identifying this relationship and the parameters of variation, a theoretical approach to calculate the amount of material required for road infrastructure is proposed. This approach proposes a general method that can be used to estimate the material resources required for road infrastructure in US cities. The conceptual background for this work is discussed in this section; the following sections discuss the methodology used, the relationship observed, and how this relationship can be linked to material requirements for road infrastructure.

Urban Metabolism

The concept of urban metabolism was first described by Wolman (1969) as a means to estimate material and energy flows in cities. This concept was further advanced by Fischer-Kowalski (1998) and Fischer-Kowalski (1998) who examine the concept of societal metabolism. This concept considers the material and energy requirements necessary for human society. Urban metabolism can assist with identifying material and energy flows, and these flows can be used to characterize cities. Similar to a living organism, 'cities transform raw materials, fuel, and water into the built environment, human biomass and waste' (Decker et al., 2000). Studying the urban metabolism provides an understanding of these transformations, as well as enabling measures of resource efficiency. An example of such a measure is considering the 'degree of circularity of resource streams' suggested by Kennedy (2007). These studies inform how well equipped the local, or global, capacity of the planet can fulfill our demands (Giradet, 1992). Characterizing the resource consumption of urban zones as a complex set of metabolic functions requires a broad perspective and a diversity of methods. This work is one method which can contribute to a better understanding of the resources required for infrastructure in cities.

Cities and Complexity

Batty (2008) considers complexity theory to have the potential to enrich current approaches to city planning and replace traditional top-down strategies with realistic city plans that consider urban processes from a variety of scales. Recent integrated theories of how cities evolve, combine urban economics and transportation behavior, approaches in network science, and fractal geometry (Batty, 2008). West et al. (1997) examined scaling patterns in cities, and considered the parallel scaling relationships between cities and biological organisms. Bettencourt et al. (2007) observed that as cities grow in size, physical networks tend to grow more slowly, due to economies of scale. As a result, the physical infrastructure required does not increase as quickly as the population. For example, Bettencourt et al. (2007) observe the scaling parameter for *Road Surface* to be 0.83 (where *Road Surface*, R, and *Population*, P, are related using the relationship, $R \approx P^{0.83}$).

Meso-scale City Patterns

Historically, a relationship between the distance from the CBD and the population density has been observed, which is referred to as a population density gradient[1] which has been discussed in the literature (Clark, 1951; Ingram, 1998; Bertraud, 2004; Marshall, 2007). Ingram (1998) observes that this density gradient is becoming flatter over time, and Marshall (2007) observes that 'newcomers to urban areas occupy about twice the land area per capita of existing residents'. This is important when considering future urban growth as the physical area of the city does not grow linearly as a function of the number of people.

Road scaling patterns have been previously examined by Samaniego and Moses (2008) but the authors are not aware of other studies that have identified parameters to describe road density gradients in US cities.

Macro-scale City Patterns

Scaling patterns have been observed in cities since the 1920s (Rossi-Hansberg, 2005), however Zipf (1972) was the first to observe that there was a relationship between the population of a city, and the rank of a city. When cities are ranked according to size, Zipf observed that the frequency of cities with a given size is inversely proportional to their rank in a population-size hierarchy (Zipf, 1972). For a city of size p, with a rank $r(p)$, the relationship can be expressed as:

$$\frac{log\, r(p)}{log\,(p)} \approx \zeta \tag{1}$$

with the expected value of $\zeta = -1$. Equation 1 predicts that the population of the second largest city is equal to half the population of the first. This relationship is illustrated for US cities in Figure 1 using a natural logarthmic scale[2]. While there is some discussion amongst the literature questioning if this observation is representative of all urban areas[3], it appears to be appropriate for large cities (Bettencourt et al., 2007; Batty, 2005).

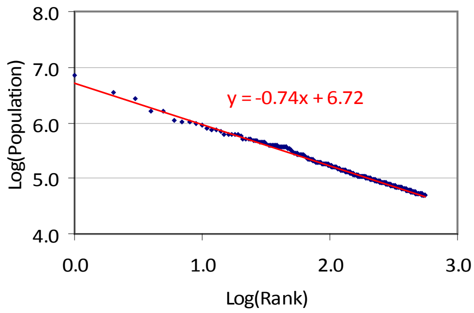

Figure 1: 500 largest US cities (US Census 2000)

The overall metropolitan size is considered to be influenced by a combination of factors, such as climate (Glaeser et al., 2001), innovation cycles (Bettencourt et al., 2007), randomness (Gabaix, 1999) and transportation technology (Hanson and Giuliano, 2004). Glaeser (1998) refers to two opposing forces that influence the urban size, *agglomerating forces* which cause concentration in density (reduced transportation costs, information spillovers, learning), and *congesting forces* which disperse this density (such as living and pollution costs, and crime). As well as physical scaling relationships, Bettencourt et al. (2007) refer to the increasing returns to scale with regards to innovation in cities (measured by patents, inventors, R & D), while (Gabaix, 1999) explains the basis for Zipf's law due to random growth patterns. This pattern (Zipf's Law) can be used to estimate the resource usage for groupings of cities, when more detailed intracity patterns are identified.

Methodology

In this analysis, 40 US cities were analyzed (Table 1). The following two sub-sections describe the data used and the analytical techniques applied.

Data

Data from the US census population[4] and US road vector files (*TIGER* line files)[5] were used. All calculations involving population data were performed on data at the census block level (the smallest level of aggregation). The

[1]The structure of this relationship is $y = Ae^{br}$ where y is the population density, r is the distance from the urban center, and A and b are parameters for each city.

[2]The slope of the curve in Figure 1 is different from the predicted slope of -1.

[3]Decker et al. (2007) argue that when smaller cities are included that the behavior is more appropriately described using a log-normal relationship rather than a log/log relationship.

[4]`http://www.census.gov` - Year 2000

[5]`ftp://ftp2.census.gov/geo/tiger` - Year 2009

center of the city was defined as the area with the highest service density, using point data that identified the location of services[6]. These services were chosen based on the US Green Building Council's list of diverse uses that contribute to the formation of a community[7]. These services were identified using the North American Industrial Classification System[8] and are listed in Appendix A.

Table 1: List of cities analyzed (Data: US Census 2000)

Cities	Population $[10^6]$	Radius $[km]$	Gross Density $[Pers/km]$
Philadelphia	18.15	80	45.5
New York	18.06	80	42.0
Los Angeles	13.66	80	32.1
Chicago	8.64	73	35.8
San Francisco	6.47	80	19.4
Boston	5.21	80	16.4
Dallas	4.76	62	18.2
Detroit	4.52	66	25.2
Providence	4.40	80	11.4
Houston	4.03	48	32.8
Atlanta	3.67	55	20.0
Seattle	3.15	57	18.2
Phoenix	2.98	40	41.1
Cleveland	2.80	60	18.9
Springfield	2.67	80	7.1
Minneapolis	2.46	36	46.3
Saint Louis	2.15	39	31.7
Denver	2.11	33	51.8
Pittsburgh	1.99	44	20.5
Portland	1.72	33	41.5
Cincinatti	1.63	37	28.6
Milwaukee	1.57	44	28.5
Kansas City	1.46	32	38.8
San Antonio	1.35	26	65.6
Orlando	1.33	30	42.2
Charlotte-Gastonia	1.32	42	16.0
Indianapolis	1.20	29	44.1
Columbus	1.19	26	55.9
Greensboro	1.13	52	7.5
Austin	0.98	31	28.3
Memphis	0.97	29	34.0
Louisville	0.87	24	52.6
Nashville	0.82	31	23.7
Oklahoma	0.79	25	43.2
Richmond-Petersburg	0.76	26	37.1
Tulsa	0.62	24	35.2
Lawrence	0.57	19	71.7
Knoxville	0.54	29	19.2
Flint	0.40	21	36.2
Flagstaff	0.04	7	67.9

Analysis

The population and road density gradients were estimated using a script written in the Python programming language. This script used ArcGIS to perform the analysis and is available for download from here[9].

The density of services was calculated for each city using gridcells at a 200m resolution, by counting the number of services that were within a 1.5 km radius of each gridcell. The US Census Metropolitan Statistical Area[10] was used as an initial boundary for each city. Then, gridcells with values that were within the highest 5% were converted into polygons which are considered to represent the city center. These center points were then used for all subsequent population and road analysis. The service density and center point for Atlanta is illustrated in Figure 2.

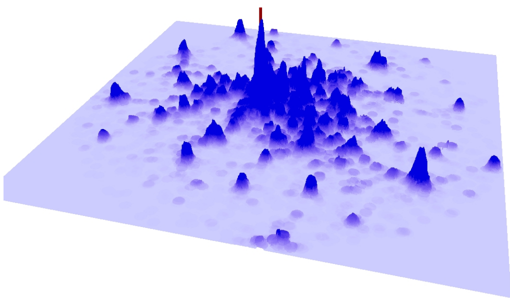

Figure 2: Atlanta service density, with the peak density marked with red.

To calculate the population density, a radial buffer was created at 1km intervals from the city-center, and all census blocks that were within, or intersected the buffer, were summed, up to a maximum radial distance of 80 km. For census blocks that were intersected by the buffer, the fraction of area that fell within the buffer was used to estimate the number of people living there using the following equation:

$$pop_{new} = (area_{new}/area_{old}) \times pop_{old} \qquad (2)$$

Equation 2 assumes that the number of people living in each census block is uniformly distributed. The boundary of the city was defined using a minimum threshold criteria of 100 persons/km^2, or a maximum radius of 80 km. A radius of 80 km was chosen as it was sufficiently large to encompass most cities, and for large cities that extend beyond a radius of 80 km, it provided a representative

[6] http://www.esri.com/software/bao

[7] This list is part of the guidelines for LEED for Neighborhood Development.

[8] http://www.census.gov/eos/www/naics/

[9] http://www.urbmet.org/analysis
This script can be run directly on these public datasets if ArcGIS is available to the user, once a polygon identifying the city center is provided. Polygons used in this analysis are also available for download from this link.

[10] http://www.census.gov/geo/www/cob/bdy_files.html

sample[11]. In this paper, we use the city name loosely, as the definition does not consider political boundaries, but it is used to identify the general area similar to the census defined city boundary.

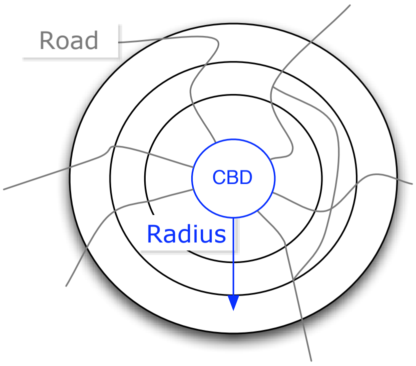

Figure 3: Schematic of the analytical technique used to measure the radial distribution of population and roads

For road calculations, the length of road that fell within each buffer and the road type, was recorded. This study used the US Census road classifications listed in Appendix B. This paper considered primary, secondary and local roads, and a schematic of this analysis is illustrated in Figure 3.

Results

The two patterns examined here are the population gradient and the road gradient in US cities. As mentioned previously, the existence of population density gradients in cities have been widely observed and studied, but are reproduced here with an analytical method that can be examined and easily replicated (Footnote 9).

Population Gradient

Let us consider the population density gradient in greater detail. Clark (1951) observed, and was instrumental in formalizing the concept of a population density gradient within cities. This approach measured the concentration of people as function of distance from the city center. The structure of this relationship is shown in in Equation 3:

$$y = Ae^{br} \tag{3}$$

where y is the population density, r is the radius from the urban center, and A and b are parameters for each city. The population density gradient was estimated for the 40 cities in this study (Figure 4) by fitting a curve using Equation 3 to measured data. The parameters for this curve are listed in Table 4, with the associated R-squared, p-value and t-statistic, and all values are significant at a 99% confidence interval.

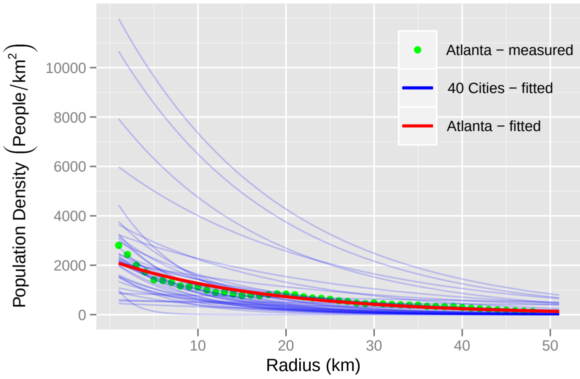

Figure 4: Population density gradient of 40 US cities

Using the original census data at the block level, the population density for Atlanta is visualized in Figure 5, with the estimated population density gradient illustrated in Figure 6, using a curve of the form described in Equation 3, and with the parameters listed in Table 4.

Road Gradient

Figure 7 illustrates the length of road as a function of distance from the city center, when measured radially. A linear relationship was found, with the slope of the curve varying from 134 (Flagstaff) to 1041 (Los Angles). The R^2 value is > 0.99 with the exception of Boston (R^2 = 0.70) and all values are significant at a 99% confidence interval.

This pattern does not control for area, so road density measures for each city were also examined. The total road density decreases as the radius increases, and based on a variety of curve fitting estimates, this relationship was ob-

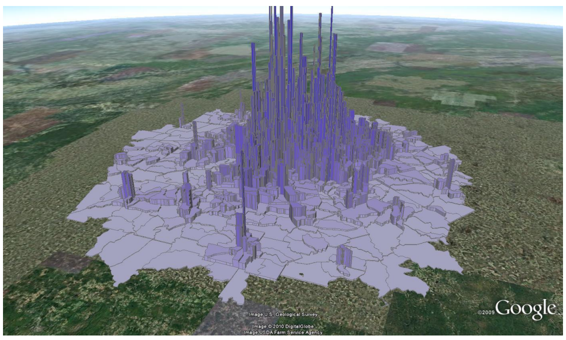

Figure 5: Population density of Atlanta (Data: US Census Blocks)

[11]This explains why Philadelphia has a higher population than New York (Table 1).

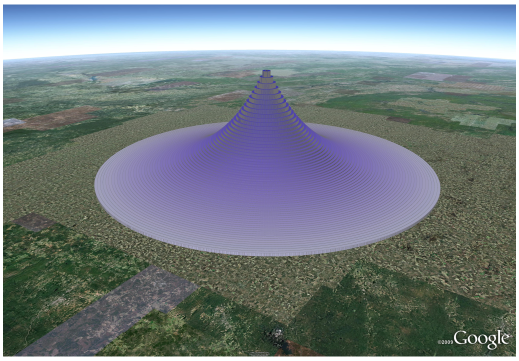

Figure 6: Population density gradient of Atlanta using estimated parameters

served to follow a power law with the following structure:

$$y = Ar^b \tag{4}$$

where y is the road density, r is the radius from the urban center, and A and b are parameters for each city (see Figure 8 and Table 5). This pattern of behavior makes it possible to estimate the total road length for any city, once the radius is specified[12].

A similar relationship was observed for local roads, and Equation 4 best described this relationship. The fitted curves are illustrated in Figure 9 with the values summarized in Table 6.

Material Requirements

In this section, we estimate the amount of material required for local road construction as a function of distance from the city-center by applying the relationship

[12]This is true for cities where a radial measure is appropriate. For cities that do not have an identifiable central place, this approach is not applicable.

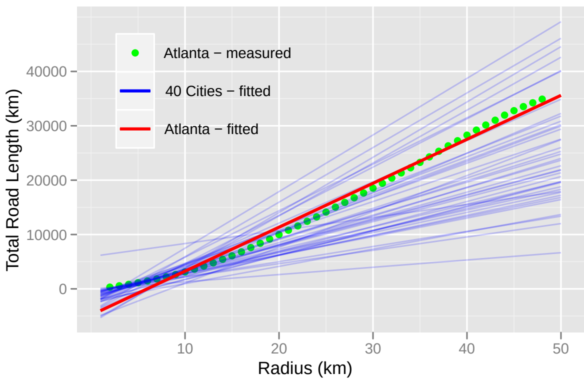

Figure 7: Cumulative length of all roads from the city center

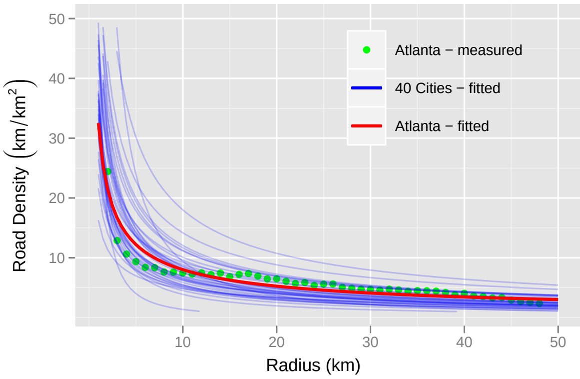

Figure 8: Road density gradient for all roads (Primary, Secondary and Local)

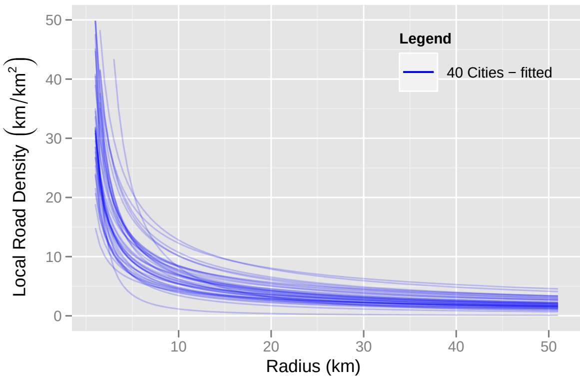

Figure 9: Road density of local roads

described in Equation 4. This material quantity can be calculated by multiplying the road-density by the area examined, and by the cross-sectional area of a typical road:

$$Material = Ar^b \times Area \times Cross\text{-}Section \tag{5}$$

To estimate this material value, an average width of local roads of 7.62 m is used[13]. Using values from Chudley and Greeno (2008), the cross-section of a road of this type typically requires 125 mm of gravel and 60 mm asphalt.

The specific road construction material used for secondary and local roads depends on state construction standards and local ground conditions. The cross-sectional area of asphalt for a local road is 0.4572 m^2; for gravel it is 0.9525 m^2. A sample calculation of material required for local roads in Atlanta is shown in Table 2. This illustrates the amount of construction material as a function of distance from the center.

[13]This road width value is based on a summary of guidelines for local road construction for the state of Massachusetts.

Table 2: Calculation of local road material requirement for 1 km^2, considering distance from city center.

Distance $[km]$	**Road Length** $[m]$	**Asphalt** $[m^3]$	**Gravel** $[m^3]$
10	6862	3137.56	6536.59
30	3585	1639.13	3414.86

Discussion

City Typologies

When cities with similar levels of gross population density are compared, the local road per capita can be significantly different. Figure 10 illustrates local road patterns for two cities of similar population densities. However, the measured population density at 5 km from the city center for these cities is 1929 people/km^2 for Dallas, and 4797 people/km^2 for Boston, while the local road-length in Boston is 3.86 km/person, and in Dallas it is 12.03 km/person. This suggests that the local road length is a more sensitive measure for estimating the overall compactness of a city, rather than a gross population density measure. When considering local roads, the resources required can be directly attributed to the local population, as it is assumed that they are the primary users of these roads.

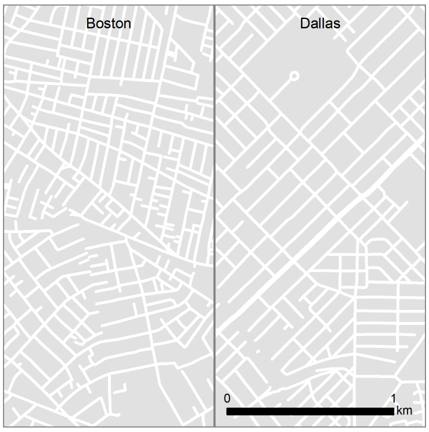

Figure 10: Local road patterns for cities with similar gross population densities; Boston 16.4 people/km^2 (left) and Dallas 18.2 people/km^2 (right) at 5 km from the city center.

Newman and Kenworthy (1989) use the linear miles of road per capita to categorize cities (Figure 11). They argue that this measure can illustrate what the primary transportation mode is. This paper demonstrates the importance of considering how this value varies within the city, which a typology classification should consider.

Considering the amount of roads per person, the actual

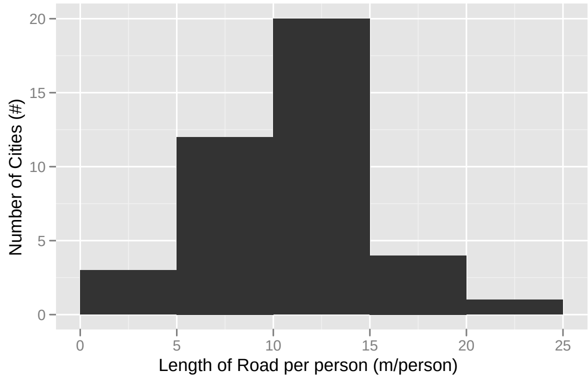

Figure 11: Proposed city typology

required amount of infrastructure based on the households location can be attributed to local roads. An estimated function to describe this relationship of local roads per person is defined in Figure 12. This concept is expanded upon by measuring local roads using the Gini coefficient for each city, so that a measure of the statistical dispersion of local roads per person can be considered.

Relevance for Urban Simulation

To estimate material flows due to infrastructure, Brand (2006) states that European cities replace 2 to 3% of their material fabric each year. This is due to the demolition and rebuilding of buildings, roads, and other construction

One consideration that Ewing and Rong (2008) highlight is the consequence of the interactions between higher-density developments when compared to urban sprawl. They consider how higher density settlements require more air-conditioning due to the urban heat island effect, and examine whether this outweighs the savings resulting from high-density development. They observe that it has a double benefit as people live in smaller dwellings ('typically reducing transportation energy use and emissions by 20 to 40 percent relative to sprawl' with a 'comparable percentage impact on residential energy use and emissions').

Many studies refer to cost savings for infrastructure at high densities (Ewing, 1997) and the associated trade-offs. For areas of low-population density the use of septic tanks, open drainage and rural cross sections may cause the cost per area to slope downwards while for areas of extremely high densities, the need for special high-rise structures and infrastructure arises Ewing (1997). The exact shape of the cost function is hard to estimate, as are the material requirements.

For material and cost to be considered per capita, a measure of the unit of service provided by the infrastructure needs to be defined so that an efficiency baseline can

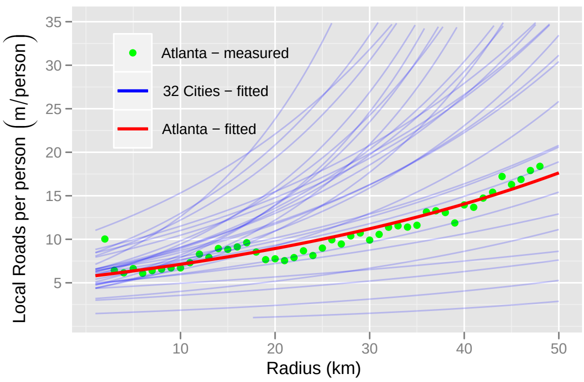

Figure 12: Road density gradient for Local roads

be calculated. Shin et al. (2009) examines this with regard to the functionality of the land area, and illustrates that when private auto is the dominant mode choice, buildings need to be taller so that they can provide more productive area, due to the space required for road area.

The Gini coefficient enables an estimate of infrastructure 'equality' to be calculated. The values for each city are listed in Table 3 [14]. This provides a measure of the infrastructure equality within the city, within a range of 0 - 1, where 0 is the most equal distribution and 1 is the most unequal distribution. The interpretation of this data is that there is a correlation between local road length per person and the Gini coefficient. Cities with a high Gini coefficient have a low local road/person, while the inverse is also true. This can be explained by larger cities having concentrations of population near the center, while lower-density cities have a similar amount of roads per person, irrespective of the distance from the center.

Table 3: Local road distribution within cities, where b is the exponent for local roads

City Names	m Road / Person	Gini Coef.	*b*
Flagstaff	24.16	-	0.05
Greensboro	19.59	0.06	-
Knoxville	18.90	0.12	0.04
Charlotte-Gastonia	15.95	0.15	0.03
Richmond-Petersburg	15.59	0.17	0.06
Tulsa	14.00	0.11	0.05
Pittsburgh	13.72	0.22	0.04
Nashville	13.53	0.10	0.03
Oklahoma	13.25	0.10	-
Seattle	12.32	0.19	0.02
Kansas City	12.21	0.07	0.03
Flint	12.17	0.06	0.05
Dallas	12.03	0.20	0.02
Indianapolis	11.93	0.14	0.05
Saint Louis	11.40	0.14	0.03
Memphis	10.86	0.08	-
Providence	10.85	0.13	0.03
Austin	10.83	0.20	0.03
Orlando	10.82	0.12	0.04
Atlanta	10.63	0.14	0.02
Houston	10.60	0.12	0.02
Phoenix	10.40	0.12	-
Cincinatti	10.28	0.18	0.04
Louisville	10.23	0.09	0.05
Portland	10.08	0.12	0.04
Minneapolis	9.84	0.17	0.05
Cleveland	9.50	0.07	-
San Antonio	9.41	0.20	0.02
Denver	9.07	0.08	-
Columbus	8.98	0.15	0.05
Milwaukee	8.98	0.11	0.06
Detroit	8.92	0.23	0.03
Lawrence	8.56	0.17	0.02
Springfield	8.50	-	-
San Francisco	7.72	0.15	0.01
Chicago	7.48	0.25	0.03
Los Angeles	5.84	0.21	0.02
Boston	3.86	-	-
New York	3.45	0.35	-
Philadelphia	1.91	0.39	0.03
Mean	10.96	-	-
Standard Deviation	4.14	-	-

Future Work

This work can benefit from remote-sensing data that can be used to identify the types of materials used for road construction, and the widths of roads. This data is currently lacking in national US databases, so identifying the road type would be useful in calculations of albedo, and identifying impermeable surfaces. The predicted amount of material in roads could also be validated using remote sensing.

Conclusions

This paper illustrated a method of estimating the material resources required for infrastructure within a city, and how these resources can be related to the population. As both population and road density are shown to be functions of distance from the city-center, they can be related to each other, so that a relationship between road length and population density can be observed. This provides a means to estimate the material required for road construction in cities. It is hoped that this methodology and these results contribute to the understanding of the resources required for cities.

Acknowledgments

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[14]The values for Flagstaff, Lawrence and Boston were ignored as they were negative and the Gini coefficient measure is from 0-1 by construction

program.

Table 4: Population density parameters (Data: US Census 2000)

City Names	**A** [Person/km^2]	**b** [$1/km$]	**Adj.-R-Sq.**	**p-value**	**t-test**
Minneapolis	4,147.5	-0.10	0.9518	0.0000	-26.30
Kansas City	2,434.1	-0.09	0.9232	0.0000	-19.32
Saint Louis	2,669.5	-0.08	0.9575	0.0000	-29.29
Dallas	2,397.6	-0.05	0.9700	0.0000	-44.45
Houston	3,162.2	-0.07	0.9406	0.0000	-27.29
Atlanta	2,199.6	-0.06	0.9721	0.0000	-43.38
Indianapolis	2,423.9	-0.10	0.9308	0.0000	-19.43
Pittsburgh	2,247.9	-0.08	0.9320	0.0000	-24.29
Phoenix	2,347.0	-0.07	0.7315	0.0000	-10.36
Memphis	1,680.4	-0.09	0.9262	0.0000	-18.78
San Antonio	3,696.3	-0.13	0.8790	0.0000	-13.51
Detroit	3,845.0	-0.05	0.9460	0.0000	-33.75
Columbus	3,100.3	-0.12	0.9083	0.0000	-15.77
Cincinatti	2,516.3	-0.09	0.9690	0.0000	-33.55
Orlando	2,342.9	-0.10	0.9360	0.0000	-20.62
Nashville	1,466.6	-0.09	0.9670	0.0000	-29.67
Oklahoma	1,794.7	-0.11	0.8623	0.0000	-12.30
Denver	5,005.4	-0.12	0.9100	0.0000	-18.02
Charlotte-Gastonia	1,147.5	-0.06	0.8840	0.0000	-17.70
Louisville	2,716.9	-0.13	0.9576	0.0000	-22.80
Richmond-Petersburg	2,233.4	-0.12	0.9786	0.0000	-33.87
Portland	3,448.7	-0.11	0.9107	0.0000	-18.09
Seattle	2,613.3	-0.06	0.9481	0.0000	-32.01
Los Angeles	6,249.1	-0.04	0.9347	0.0000	-33.63
Flagstaff	1,647.8	-0.50	0.9991	0.0000	-81.95
Austin	2,236.6	-0.11	0.9670	0.0000	-29.69
Philadelphia	12,647.7	-0.05	0.9450	0.0000	-36.87
New York	11,263.3	-0.06	0.9285	0.0000	-32.04
Springfield	613.1	-0.02	0.5302	0.0000	-9.49
Cleveland	2,155.2	-0.05	0.8353	0.0000	-17.33
Lawrence	869.4	-0.01	0.1194	0.0010	-3.42
Boston	2,193.1	-0.03	0.7350	0.0000	-14.83
Providence	558.0	-0.01	0.0310	0.0642	-1.88
Chicago	8,387.3	-0.06	0.9558	0.0000	-39.47
Milwaukee	3,444.6	-0.09	0.9110	0.0000	-21.00
Greensboro	469.1	-0.04	0.5444	0.0000	-7.87
Flint	1,828.2	-0.16	0.9840	0.0000	-35.06
San Francisco	3,355.4	-0.04	0.7800	0.0000	-16.77
Tulsa	1,698.9	-0.12	0.9755	0.0000	-30.30
Knoxville	988.1	-0.09	0.9223	0.0000	-18.26
Mean	3056.05	-0.09	0.002	-	-
Standard Deviation	2555.17	0.08	0.010	-	-

Table 5: Road density parameters for all roads (Data: US Tiger Files 2008)

City Names	b [-]	A [km/km^2]	Adj.-R-Sq.	p-value	t-test
Minneapolis	-0.523	26.94	0.8243	0.0000	-12.67
Kansas City	-0.614	30.02	0.8509	0.0000	-13.12
Saint Louis	-0.630	32.92	0.9254	0.0000	-21.45
Dallas	-0.557	32.89	0.8788	0.0000	-20.88
Houston	-0.640	45.24	0.8436	0.0000	-15.78
Atlanta	-0.539	25.13	0.8299	0.0000	-16.11
Indianapolis	-0.565	25.10	0.8724	0.0000	-13.63
Pittsburgh	-0.648	32.93	0.9635	0.0000	-33.32
Phoenix	-0.483	25.85	0.6798	0.0000	-9.04
Memphis	-0.592	18.92	0.8888	0.0000	-14.72
San Antonio	-0.710	34.46	0.9316	0.0000	-18.10
Detroit	-0.646	47.12	0.7517	0.0000	-13.96
Columbus	-0.670	26.33	0.8821	0.0000	-13.44
Cincinatti	-0.646	25.81	0.9684	0.0000	-32.76
Orlando	-0.568	23.18	0.8448	0.0000	-12.38
Nashville	-0.721	25.63	0.9850	0.0000	-43.64
Oklahoma	-0.576	22.54	0.9124	0.0000	-15.51
Denver	-0.678	35.97	0.7824	0.0000	-10.61
Charlotte-Gastonia	-0.514	18.57	0.9711	0.0000	-36.70
Louisville	-0.637	23.06	0.9039	0.0000	-14.42
Richmond-Petersburg	-0.542	22.26	0.9365	0.0000	-18.84
Portland	-0.753	39.93	0.8806	0.0000	-15.15
Seattle	-0.616	35.49	0.9134	0.0000	-24.11
Los Angeles	-0.619	52.92	0.9216	0.0000	-30.29
Flagstaff	-1.083	17.65	0.9389	0.0009	-8.82
Austin	-0.682	22.19	0.9599	0.0000	-26.37
Philadelphia	-0.624	24.42	0.8519	0.0000	-21.20
New York	-0.644	43.74	0.7874	0.0000	-17.03
Springfield	-0.683	20.97	0.8785	0.0000	-23.77
Cleveland	-0.565	26.35	0.9245	0.0000	-26.66
Lawrence	-0.679	19.63	0.9486	0.0000	-17.74
Boston	-1.141	104.45	0.4389	0.0000	-5.68
Providence	-1.211	89.72	0.5680	0.0000	-8.49
Chicago	-0.664	73.13	0.8077	0.0000	-17.30
Milwaukee	-0.726	36.92	0.8845	0.0000	-17.97
Greensboro	-0.479	13.52	0.8366	0.0000	-16.03
Flint	-0.802	21.88	0.9472	0.0000	-18.48
San Francisco	-0.615	41.30	0.9086	0.0000	-27.87
Tulsa	-0.663	22.65	0.9707	0.0000	-27.00
Knoxville	-0.537	16.18	0.9688	0.0000	-28.98
Mean	-0.662	33.10	0.000	-	-
Standard Deviation	0.157	18.83	0.000	-	-

Table 6: Local road density parameters (Data: US Tiger Files 2008)

City Names	b [-]	A [km/km^2]	Adj.-R-Sq.	p-value	t-test
Minneapolis	-0.646	34.62	0.8418	0.0000	-13.49
Kansas City	-0.765	40.54	0.8973	0.0000	-16.22
Saint Louis	-0.764	44.72	0.9486	0.0000	-26.15
Dallas	-0.618	35.08	0.8844	0.0000	-21.44
Houston	-0.694	40.89	0.9433	0.0000	-27.67
Atlanta	-0.591	26.76	0.8113	0.0000	-15.13
Indianapolis	-0.668	30.90	0.8828	0.0000	-14.29
Pittsburgh	-0.786	45.18	0.9733	0.0000	-39.16
Phoenix	-0.559	30.21	0.6450	0.0000	-8.37
Memphis	-0.670	21.60	0.8774	0.0000	-13.94
San Antonio	-0.915	50.92	0.9430	0.0000	-19.95
Detroit	-0.714	55.41	0.7619	0.0000	-14.34
Columbus	-0.778	31.94	0.8856	0.0000	-13.67
Cincinatti	-0.769	31.82	0.9691	0.0000	-33.14
Orlando	-0.666	28.61	0.8588	0.0000	-13.09
Nashville	-0.753	24.05	0.9687	0.0000	-29.97
Oklahoma	-0.726	31.32	0.9192	0.0000	-16.21
Denver	-0.820	49.87	0.8213	0.0000	-11.98
Charlotte-Gastonia	-0.584	20.74	0.9699	0.0000	-35.90
Louisville	-0.760	27.76	0.8966	0.0000	-13.85
Richmond-Petersburg	-0.705	28.47	0.9385	0.0000	-19.17
Portland	-0.856	51.08	0.8995	0.0000	-16.69
Seattle	-0.663	39.04	0.9162	0.0000	-24.54
Los Angeles	-0.700	64.13	0.9356	0.0000	-33.68
Flagstaff	-1.615	47.60	0.9561	0.0005	-10.49
Austin	-0.776	26.90	0.9638	0.0000	-27.80
Philadelphia	-0.704	29.63	0.8238	0.0000	-19.12
New York	-0.745	56.39	0.8205	0.0000	-18.91
Springfield	-0.773	23.77	0.8907	0.0000	-25.23
Cleveland	-0.664	31.36	0.9180	0.0000	-25.51
Lawrence	-0.817	25.44	0.9055	0.0000	-12.80
Boston	-1.383	198.33	0.4424	0.0000	-5.72
Providence	-0.755	30.94	0.9432	0.0000	-23.07
Chicago	-0.609	49.83	0.8155	0.0000	-17.74
Milwaukee	-0.890	54.01	0.8996	0.0000	-19.42
Greensboro	-0.553	14.84	0.8194	0.0000	-15.09
Flint	-0.993	33.73	0.9607	0.0000	-21.57
San Francisco	-0.693	49.91	0.9195	0.0000	-29.86
Tulsa	-0.830	31.63	0.9666	0.0000	-25.25
Knoxville	-0.629	18.86	0.9609	0.0000	-25.78
Mean	-0.765	40.22	0.000	-	-
Standard Deviation	0.197	28.23	0.000	-	-

REFERENCES

Batty, M. (2005). *Cities and complexity : Understanding Cities with Cellular Automata, Agent-Based Models, and Fractals*. Cambridge, Mass.: MIT Press.

Batty, M. (2008). The size, scale, and shape of cities. *Science 319*(5864), 769.

Bertraud, A. (2004). The spatial organization of cities: Deliberate outcome or unforeseen consequence?

Bettencourt, L. M. A., J. Lobo, D. Helbing, C. Kuhnert, and G. B. West (2007). Growth, innovation, scaling, and the pace of life in cities. *Proceedings of the National Academy of Sciences of the United States of America. 104*(17), 7301–7306.

Brand, S. (2006). City Planet. Technical report, www.strategy-business.com.

Chudley, R. and R. Greeno (2008). *Building construction handbook* (7th ed. ed.). Oxford: Butterworth-Heinemann.

Clark, C. (1951). Urban population densities. *Journal of the Royal Statistical Society 114*, 490–496.

Decker, E. H., A. J. Kerkhoff, and M. E. Moses (2007). Global patterns of city size distributions and their fundamental drivers. *PLoS ONE Issue 9*.

Decker, H., S. Elliott, F. A. Smith, D. R. Blake, and F. S. Rowland (2000). Energy and material flow through the urban ecosystem. *Annual Review of Energy and the Environment 25*, 685–740.

Ewing, R. (1997). Is Los Angeles-style sprawl desirable? *Journal of the American Planning Association 63*(1), 107–126.

Ewing, R. and F. Rong (2008). The impact of urban form on us residential energy use. *Housing Policy Debate 19*(1), 1–30.

Fischer-Kowalski, M. (1998). Society's Metabolism. The Intellectual History of Materials Flow Analysis, Part I, 1860-1970. *Journal of Industrial Ecology 2*(1), 61–78.

Gabaix, X. (1999). Zipf's Law For Cities: An Explanation. *Quarterly Journal of Economics 114*(3), 739–767.

Giradet, H. (1992). *The Gaia Atlas of Cities*. Gaia Books.

Glaeser, E. (1998). Are cities dying? *The Journal of Economic Perspectives 12*(2), 139–160.

Glaeser, E., J. Kolko, and A. Saiz (2001). Consumer city. *Journal of Economic Geography 1*(1), 27.

Hanson, S. and G. Giuliano (2004). *The geography of urban transportation*. Guilford Press.

Ingram, G. (1998). Patterns of metropolitan development: what have we learned? *Urban studies 35*(7), 1019–1035.

Kennedy, C. (2007, April). Urban metabolism.

Marshall, J. D. (2007). Urban land area and population growth: A new scaling relationship for metropolitan expansion. *Urban Studies 44, No. 10*, 1889–1904.

Newman, P. and J. Kenworthy (1989). *Cities and automobile dependence : a sourcebook*. Aldershot, Hants., England; Brookfield, Vt., USA: Gower Technical.

Rossi-Hansberg, E. (2005). A spatial theory of trade. *American Economic Association 95, No. 5*, 1464.

Samaniego, H. and M. Moses (2008). Cities as organisms: Allometric scaling of urban road networks. *Journal of Transport and Land Use 1*, 21–39.

Shin, Y., V. Vuchic, and E. Bruun (2009). Land consumption impacts of a transportation system on a city. *Transportation Research Record: Journal of the Transportation Research Board 2110*(-1), 69–77.

West, G. B., J. H. Brown, and B. J. Enquist (1997). A general model for the origin of allometric scaling laws in biology. *Science No. 5309-122*.

Wolman, A. (1969). The metabolism of cities. *Scientific American*.

Zipf, G. K. (1972). *Human behavior and the principles of least effort : an introduction to human ecology*. New York: Hafner Publishing Company.

Appendix A - NAICS codes

The North American Industry Classification System was used in Table 7 to identify services, that were used to calculate the service density.

Table 7: NAICS Codes

Service	NAICS Code
Bank	521110, 522110
Child care facility	624410
Community/Civic center	624110, 624120
Convenience store	445120,447110, 447110, 447190
Hair Care	812112
Hardware store	444130
Health club or outdoor recreation facility	713940
Laundry/Dry Cleaner	81231, 81232
Library	519120
Medical/Dental office	621111, 621112
Pharmacy (stand-alone)	446110
Place of worship	813110
Police/Fire station	922160, 922120
Post-Office	491110
Restaurant	722110
School	611110
Senior care facility	624120
Supermarket	445110
Theater	512131

Appendix B - Road Nomenclature

`http://www.census.gov/geo/www/tiger/cfcc_to_mtfcc.txt`

Primary roads: Primary roads are generally divided, limited-access highways within the interstate highway system or under state management, and are distinguished by the presence of interchanges. These highways are accessible by ramps and may include some toll highways.

Secondary roads: Secondary roads are main arteries, usually in the U.S. Highway, State Highway or County Highway system. These roads have one or more lanes of traffic in each direction, may or may not be divided, and usually have at-grade intersections with many other roads and driveways. They often have both a local name and a route number.

Local Neighborhood Road, Rural Road, City Street: Generally a paved non-arterial street, road, or byway that usually has a single lane of traffic in each direction. Roads in this feature class may be privately or publicly maintained. Scenic park roads would be included in this feature class, as would (depending on the region of the country) some unpaved roads.