100

Building density of parcels and block-faces from a syntactical, morphological and planning perspective

Alice Vialard
Georgia Institute of Technology
alicevial@gmail.com

Ann Carpenter
Georgia Institute of Technology
acarpenter@gatech.edu

Abstract

In a sprawling metropolitan area such as Atlanta, sustainability can be achieved by building upon the potential of a site. Potential can be found in the availability of land that creates opportunities for new buildings, but can also be found in planning guidelines, the morphological conditions of parcels and blocks, and the syntactical accessibility provided by the street network. While buildings and land uses can be changed and do change over time to accommodate new functions, the street network remains fairly stable and unchanged.

While many studies of urban development have focused on the block or street segment, in this paper we focus on the finer scales of the parcel and the block-face. Using City of Atlanta data, this paper seeks to understand the relationships between parcel and block-face building density and planning, morphological, and syntactical variables, taking into account several control variables.

Descriptive and inferential statistics are presented, including model results that describe the effects of planning, morphological, and syntactical variables on building density. Results support the hypothesis that connectivity, centrality, local and global street density, block size, access to diverse land uses, and land value have mixed effects on building density, depending on the scale of analysis and the land uses present. The results have important implications for land use and zoning policy. For example, accessibility and visibility are required at varying levels for different types of land uses, warranting an analysis of reach in assigning land use and zoning overlays to parcels. Additional findings include that different types of land uses require different types of building density and street connectivity, that parcel coverage is highly correlated to high local and global street density, and that street network diversity encourages density.

Keywords

Building density, block-face, land use.

1. Introduction

The street network is fundamental to urban development. Largely stable, relative to other urban elements such as parcel size and land use, syntactic properties of streets have been shown to influence

land use distribution (Ortiz-Chao & Hillier, 2007), commercial frontage density (Scoppa & Peponis, 2015), and to improve density and diversity through generation of "spatial capital" (Marcus, 2010). Specific land uses are associated with different building configurations and density (Martin & March, 1972; Steadman, 2014) and it has been argued that land use controls and land value influence the density of development (Alonso, 1964; Pendall, 1999).

This paper examines building density at two scales. Part 1 investigates the role of parcel characteristics on building density at the scale of analysis of the parcel. Part 2 provides a similar analysis of building density at the block-face scale of analysis. Both Part 1 and Part 2 use the City of Atlanta as a study area. This geography is roughly 350 square kilometres in area, with a population of 450,000, and is the most central and largest municipality in the Atlanta metropolitan region (see Figure 1).

Figure 1: Study area boundaries

Parcels both determine and are shaped by buildings and land uses, while streets facilitate the distribution of activities and goods across the entire metropolitan area and provide access to local destinations. The property limit of the parcel, what we call the block-face, is influenced by both the building and the street (Vialard, 2013). In the current literature, the concept of the block-face is implicitly present but has not been quantitatively studied; instead, data are generally parsed to the parcel, block, street, or even larger area of land. The two main assets of the block-face are that it can distinguish the two sides of a street segment as well as the different sides of a block. It is also the interface that relates

the global structure of cities (the street network) to local design decisions (buildings within a parcel). Figure 2 shows both the parcel and block-face for a small area of Atlanta.

Figure 2: Comparison of parcel and block-face units of analysis

Building density, the dependent variable in this analysis, is measured by parcel coverage (Berghauser Pont & Haupt, 2010) and block-face frontage (Talen, 2005). Planning variables include land valuation and zoning Floor Area Ratio (FAR). Morphological variables include parcel and block size and shape. Connectivity variables include metric and directional reach (Peponis, Bafna, & Zhang, 2008). Control variables that account for attraction include the presence of sidewalks, distance to the Central Business District (CBD) (Mills, 1970), and distance to the closest highway exits.

The most comprehensive way of looking at the city is to take into account both the parcel and the block-face scales. This paper shows that certain properties of streets are associated with or favour specific building density and land uses. Results show that connectivity, centrality, local and global street density, block size, access to diverse land uses, and land value have mixed effects on building density, depending on the scale of analysis and the land uses present.

2. Literature Review

There are several known influences on building density. The distance from the centre of a metropolitan area, a major tenet of Christaller's (1933) central place theory of geography, is only one of several factors linked with an exponential, negative decrease in density (Mills, 1970). For example, at a fundamental level the size of blocks matters in local densification and creates a two-way dynamic wherein parcels also impact block subdivision or amalgamation (Siksna, 1997). Land use controls and land value also impact building density, ultimately leading to sprawl when governments rely on controls such as zoning and building permit limitations and fiscal arrangements such as ad valorem property taxes (Pendall, 1999). Low-density zoning and other land use controls that curb density also contribute to exclusionary housing

patterns wherein racial and ethnic minorities are disproportionately excluded from housing markets (Pendall, 2000). In response to these practices, the Miami 21 Zoning Code (developed by Duany Plater-Zyberk) is an example of form-based code, which takes into account different types of streets in assigning land uses to parcels. The use, height and density of building are decided based on the importance of the street.

The most accurate way to measure the urban form at ground level has been the topic of various studies. Talen (2003) posited that the level of aggregation of geographical units matters for capturing variation and diversity. For the case of walkability, this has been shown to be the parcel level of aggregation (Lee & Moudon, 2006), although this varies according to what the dependent variable may be. The scale at which land use mix is calculated also matters, with mixes of use along streets being most important for walking and accessibility in general and mix of uses within settlements most important for travel mode choice (Carmona, 2001).

Similarly, how density is measured has implications. Common measures like floor area ratio (FAR) capture intensity while ground areas capture intensity and compactness (Berghauser Pont & Haupt, 2004). When density is measured by block dimensions and building configurations on the block, or a matrix called “spacemate” that encompasses block area, open space area, ground floor area, and total floor area, there is a strong relationship to building functions (Berghauser Pont & Haupt, 2010). The shape of urban blocks impacts building density, although this work negates the effects of the streets that bound the block.

In this paper, we provide a systematic method to characterise the importance of the street with syntax measures as a response to previous conceptions of the city and the often unfortunate land use controls that have been developed based on this past work. The measures we propose are meant to complement the idea of “spatial capital” advanced by Marcus (2010), as we seek to refine the known factors that create an urban form with variations in accessibility and diversity that in turn affect the social realm.

3. Analysis

Part 1 and Part 2 both involve ordinary least squares (OLS) stepwise regression models with building density as the dependent variable. The models were run at the scale of the parcel and the block-face. In both Part 1 and Part 2, a principal components analysis of the independent variables was first conducted to combine related variables and improve the model results. As shown in Figure 3, the independent variables included measures chosen based on their internal and external properties relative to streets, buildings, parcels, blocks, and, ultimately, block-faces.

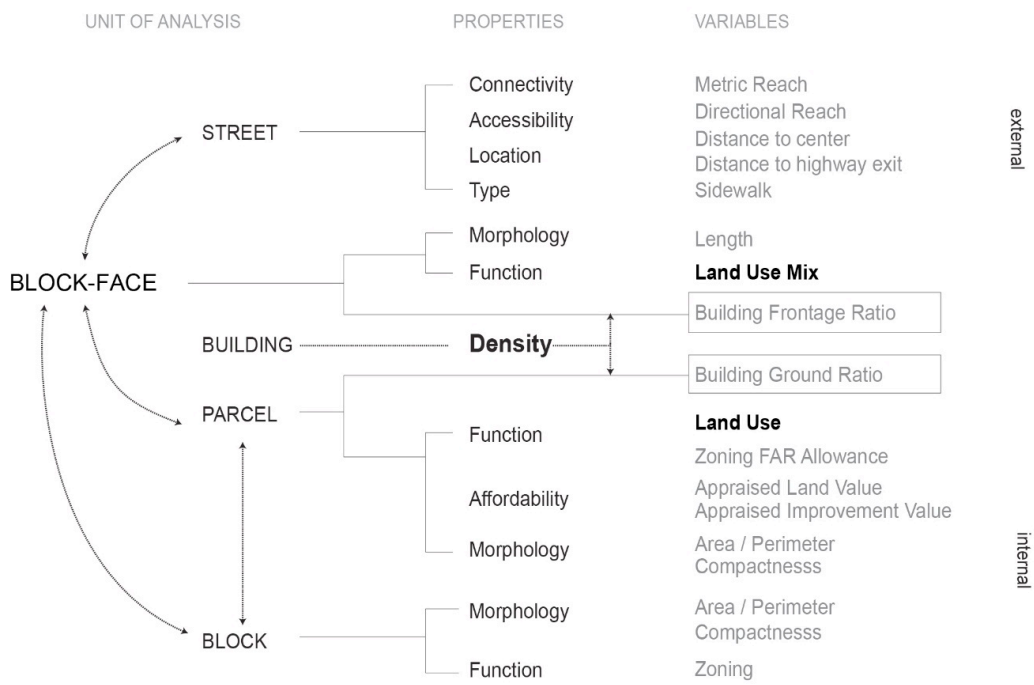

Figure 3: Syntactical, morphological and planning variables and their association to the urban unit of analysis

4. Part 1: The Effect of Parcels on Building Density

For the Part 1 analysis, three measures of building density were considered: the total amount of square footage on the parcel, the ground coverage of the parcel, and finally the built ground ratio. These measures were all derived from City of Atlanta parcel and road network shapefiles and tabular data, compiled geographically in GIS software. It was found that the three measures responded differently to planning, morphological, and syntactic parameters: square footage is more strongly correlated with land value, ground coverage is more strongly correlated with the size of the parcel and the built ground ratio is more strongly correlated to the street structure, or syntactical properties. These measures highlight the differences between the intensity of the building density and the capacity for density (Pont & Haupt, 2004). It was determined that built ground ratio was the most suitable choice for the dependent variable, as this captures the carrying capacity potential for the parcel. Data used for this measure were also collected in the same time period as the data used for the independent variables, resulting in a more comparable measure.

In order to determine the effects of parcel and block-face properties on building density, several independent variables were identified in the literature. Many of these were found to be highly correlated in Atlanta, such as density and distance to central business district. Therefore, a principal components analysis was first conducted on the individual independent variables. Principal components are used to reduce auto-correlation and the number of variables. Twelve independent variables were chosen for the principal component factor analysis. These were chosen from three major types of influences known to impact building density in the literature: planning, morphological, and syntactic. Planning measures included appraised land value, appraised improvement value, total appraised value, and maximum floor area ratio (FAR) as dictated under current zoning regulations. Morphological measures included parcel area, perimeter, and compactness. Syntactic measures included metric reach at distances of one quarter mile, one mile, and five miles and directional reach for zero and two turns, with an angular threshold of

10 degrees. Metric reach characterizes density of streets that are available within a set distance, while directional reach depicts ease of access and the tendency for the street network to align, Normalized Angular Choice (Hillier, Yang, & Turner, 2012) provides a combined measure of accessibility and street density. But for the purpose of this analysis, both aspects are differentiated with the use of two measures, Other measures included the presence of sidewalks in front of the parcel, distance to the nearest highway exit (which in Atlanta also serves as proxy for the closest subway station), and distance to the downtown Atlanta central business district (CBD). Several of these variables are plotted in Figure 4, which shows data for a small section of Atlanta.

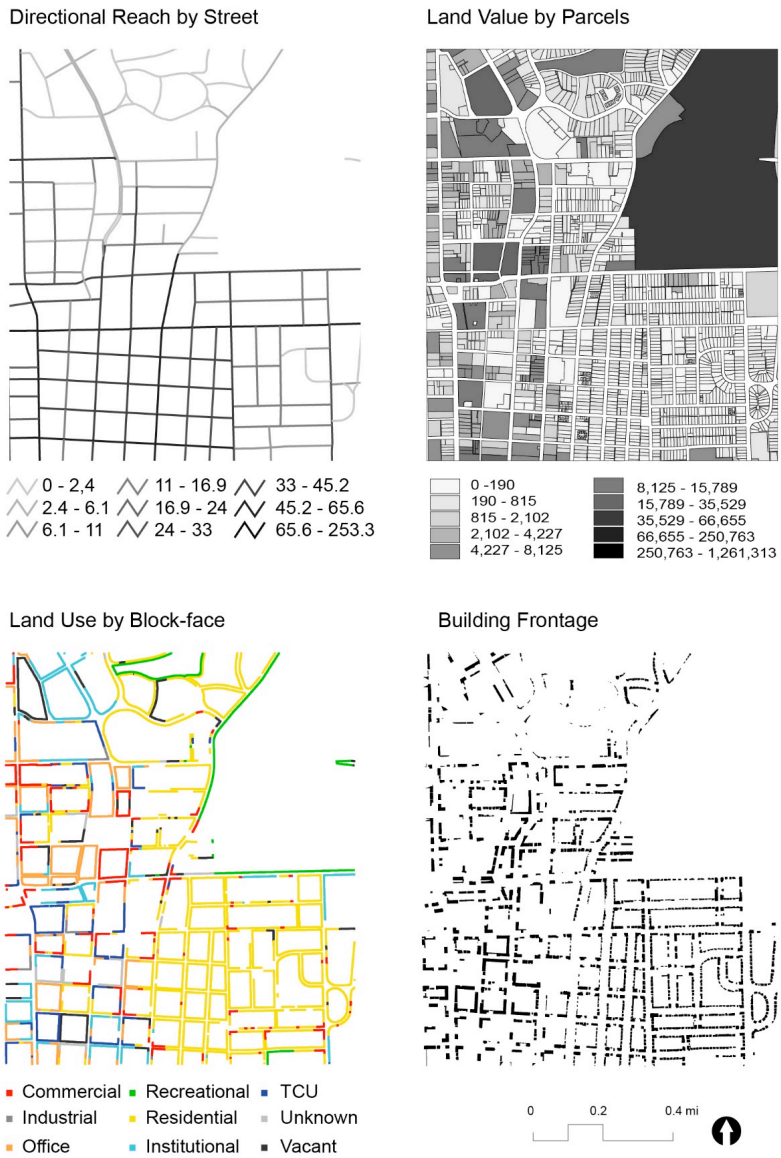

Figure 4: Examples of three independent and one dependent variables shown for a detailed section of Atlanta

Results of the principal components factor analysis for the independent variables is shown below in Table 1. Five principal components were determined, which are represented in bold font, grouped by column.

	Independent Variables	**Prin1**	**Prin2**	**Prin3**	**Prin4**	**Prin5**	
Planning	Appraised Land Value (2014)	0.017	**0.772**	0.042	-0.003	-0.005	Land Value
	Appraised Improvement Value (2014)	0.039	**0.856**	0.017	0.001	0.006	
	Total Appraised Value	0.035	**0.997**	0.033	-0.001	0.002	
	Zoning FAR Allowance	0.063	-0.000	-0.025	0.027	**0.988**	Zoning FAR Allowance
Morphology	Parcel Area	-0.104	0.055	**0.857**	0.052	0.075	Parcel Morphology
	Parcel Perimeter	-0.197	0.076	**0.914**	0.054	0.026	
	Parcel Compactness	-0.206	0.023	**-0.459**	0.051	0.117	
Other	Presence of Sidewalk	**0.642**	0.009	0.034	0.143	0.011	Street density and Location
	Distance to Highway Exit	**-0.588**	-0.030	-0.006	-0.067	-0.009	
	Distance to CBD	**-0.904**	-0.013	0.021	-0.015	-0.009	
Syntax	Metric Reach 0.25 Miles	**0.791**	0.028	-0.090	0.171	0.030	
	Metric Reach 1 Mile	**0.918**	0.029	-0.019	0.152	0.021	
	Metric Reach 5 Miles	**0.932**	0.013	-0.007	0.057	-0.000	
	Directional Reach 0 Turns	0.114	-0.001	0.041	**0.946**	0.009	Accessibility and Intelligibility
	Directional Reach 2 Turns	0.390	-0.004	-0.002	**0.862**	0.032	
		Street Density and Location	Land Value	Parcel Morphology	Accessibility and Intelligibility	Zoning FAR Allowance	

Table 1: List of independent variables and results for five principal component factor analysis for 15 input variables

The principal components analysis resulted in five distinct groupings of variables. These included "street density and location" (labelled Prin1 in Table 1), which is mostly defined by metric reach with radius 0.25, 1, and 5 miles and the distances to the CBD and highway exits; "land value" (Prin2), which is defined mainly by appraised land value, appraised improvement value, and total appraised value; "parcel morphology" (Prin3), which encompasses the parcel area, perimeter, and parcel compactness; "accessibility and intelligibility" (Prin4), which includes both directional reach with no change of direction and with two turns; and "zoning density allowance" (Prin5), which represents only the zoning FAR.

Once the independent variables were combined using the principal components analysis, an OLS stepwise regression model was conducted to determine the impact of the factors on building density. The model was run first using the entire set of parcels (n=104,800) and then using only built parcels (n=84,280). An analysis excluding unbuilt parcels was conducted because the amount of vacant land in Atlanta is very high (particularly in low-density and industrial areas) and due to the focus on building density, empty parcels (and those with less than 10 square meters of building footprints) skewed the analysis when included. The results of each model are summarised in Table 2.

		R^2	Term	Principal components	Std Error	t Ratio	Prob>|t|	Std Beta	VIF
All Parcels (n=82,623)	Building Density	0.24	Prin1	Street Density and Location	0.0203	155.58	<.0001	0.4818	1.05
			Prin3	Parcel Morphology	0.0465	-42.04	<.0001	-0.1457	1.31
			Prin5	Zoning FAR allowance	0.0513	11.72	<.0001	0.0355	1.00
			Prin2	Land Value	0.0735	7.64	<.0001	0.0265	1.31
			Prin4	*Accessibility and Intelligibility* [1]	*0.0403*	*0.35*	*0.7239*	*0.0011*	*1.08*
Built Parcels (n=71,102)	Building Density	0.41	Prin1	Street Density and Location	0.0186	215.10	<.0001	0.6396	1.06
			Prin3	Parcel Morphology	0.0456	-52.61	<.0001	-0.1813	1.43
			Prin2	Land Value	0.0746	17.93	<.0001	0.0616	1.42
			Prin5	Zoning FAR allowance	0.0443	10.16	<.0001	0.0293	1.00
			Prin4	*Accessibility and Intelligibility*	*0.0372*	*-1.78*	*0.0753*	*-0.0054*	*1.11*

[1] *Variables that were not significant are in italics.*

Table 2: OLS regression model results for building density at the parcel level.

Based on an R-squared value of 0.24, the model explains 24 percent of variation in building density (R^2= 0.24, n=82,623, p<0.0001*) for all parcels. Based on an R-squared value of 0.41, the model explains 41 percent of variation in building density (R^2= 0.41, n=71,102, p<.0001*) for only built parcels. Overall the two most significant factors were the street density and location (Prin1) and parcel morphology (Prin3). The positive influence of street density and location, based on the component variables of presence of sidewalks and the distance to the CBD and highway exits, indicates the importance of walkability and centrality for building density. The negative influence of parcel morphology indicates that larger and less compact parcels cause lower building densities. Land value (Prin2) also impacts the building density and slightly prevails over zoning FAR allowance when the parcels are built. Accessibility and intelligibility are not significant in both cases, despite being shown as related to commercial frontage density (Scoppa &Peponis). Therefore the next step distinguished by land use.

	R^2	Term	Principal components	Std Error	t Ratio	Prob>|t|	Std Beta	VIF
Commercial (n=2,013)	0.30	Prin1	Street Density and Location	0.2315	28.00	<.0001*	0.5484	1.11
		Prin4	Accessibility and Intelligibility	0.3329	-8.34	<.0001*	-0.1766	1.29
		Prin3	Parcel Morphology	0.4114	-7.80	<.0001*	-0.1753	1.45
		Prin2	Land Value	0.4753	3.78	0.0002*	0.0838	1.42
		Prin5	Zoning FAR Allowance	0.2816	-2.09	0.0370*	-0.0390	1.01
Industrial (n=512)	0.17	Prin3	Parcel Morphology	0.4696	-6.45	<.0001*	-0.2709	1.08
		Prin1	Street Density and Location	0.4305	5.45	<.0001*	0.2339	1.13
		Prin2	Land Value	0.5979	-2.55	0.0111*	-0.1071	1.08
		Prin4	*Accessibility and Intelligibility*	*0.5878*	*0.88*	*0.3775*	*0.0380*	*1.13*
		Prin5	*Zoning FAR Allowance*	*0.8105*	*-0.56*	*0.5778*	*-0.0226*	*1.01*
Institutional (n=1,368)	0.35	Prin1	Street Density and Location	0.1923	24.33	<.0001*	0.5589	1.10
		Prin3	Parcel Morphology	0.2085	-6.59	<.0001*	-0.1624	1.27
		Prin4	Accessibility and Intelligibility	0.3185	-3.48	0.0005*	-0.0828	1.18
		Prin5	Zoning FAR Allowance	0.4636	2.31	0.0210*	0.0512	1.03
		Prin2	Land Value	0.2201	2.02	0.0437*	0.0469	1.13
Office (n=404)	0.31	Prin1	Street Density and Location	0.4897	12.65	<.0001*	0.5630	1.14
		Prin4	Accessibility and Intelligibility	0.8857	-5.11	<.0001*	-0.2511	1.39
		Prin3	*Parcel Morphology*	*1.1463*	*-1.16*	*0.2451*	*-0.0642*	*1.74*
		Prin2	*Land Value*	*0.4014*	*-0.36*	*0.7190*	*-0.0185*	*1.52*
		Prin5	*Zoning FAR Allowance*	*0.5932*	*0.01*	*0.9920*	*0.0004*	*1.02*
Recreational (n=49)	0.25	Prin1	Street Density and Location	1.3185	2.10	0.0415*	0.3827	1.89
		Prin3	*Parcel Morphology*	*1.9456*	*-1.10*	*0.2786*	*-0.9898*	*46.47*
		Prin5	*Zoning FAR Allowance*	*10.042*	*1.69*	*0.0978*	*0.8041*	*12.90*
		Prin4	*Accessibility*	*2.8122*	*0.99*	*0.3298*	*0.5257*	*16.24*
		Prin2	*Land Value*	*4.7216*	*0.69*	*0.4943*	*0.6266*	*47.18*

Residential (n=62,877)	0.47	Prin1	Street Density and Location	0.0214	172.1	<.0001*	0.6830	1.87
		Prin3	Parcel Morphology	0.0790	-51.44	<.0001*	-0.2727	3.34
		Prin4	Accessibility and Intelligibility	0.0431	13.73	<.0001*	0.0540	1.84
		Prin5	Zoning FAR Allowance	0.0393	9.25	<.0001*	0.0270	1.01
		Prin2	Land Value	0.1957	4.47	<.0001*	0.0233	3.22
TCU (n=207)	0.20	Prin1	Street Density and Location	0.8199	5.85	<.0001*	0.4508	1.50
		Prin5	Zoning FAR Allowance	6.5327	2.62	0.0095*	0.2738	2.76
		Prin4	Accessibility and Intelligibility	1.6341	2.59	0.0102*	0.3120	3.65
		Prin3	Parcel Morphology	1.8390	-3.46	0.0007*	-0.8457	15.07
		Prin2	Land Value	5.4793	3.23	0.0015*	0.9412	21.48
Unknown (n=219)	0.28	Prin1	Street Density And Location	0.5377	8.10	<.0001*	0.5211	1.22
		Prin2	*Land Value*	*0.4310*	*1.56*	*0.1198*	*0.0951*	*1.09*
		Prin4	*Accessibility*	*0.9107*	*-1.20*	*0.2316*	*-0.0800*	*1.31*
		Prin3	*Parcel Morphology*	*0.5975*	*-1.18*	*0.2396*	*-0.0722*	*1.10*
		Prin5	*Zoning FAR Allowance*	*0.6417*	*-0.83*	*0.4059*	*-0.0496*	*1.04*
Vacant (n=3,334)	0.45	Prin1	Street Density And Location	0.1259	44.03	<.0001*	0.7405	1.70
		Prin5	Zoning FAR Allowance	1.6094	9.59	<.0001*	0.2141	3.00
		Prin3	Parcel Morphology	0.4380	-7.41	<.0001*	-0.3133	10.75
		Prin4	Accessibility and Intelligibility	0.2671	5.23	<.0001*	0.1103	2.69
		Prin2	Land Value	1.2120	4.95	<.0001*	0.2339	13.44

Table 3: OLS regression model results for building density at the parcel level by land use categories

In order to determine the differing effects of the independent variables on building density by land use, regression models for only the parcels within each land use category in the parcel dataset were also run with the five principal component factors (street density and location, land value, parcel morphology, accessibility and intelligibility, and zoning FAR) as independent variables and building density as the dependent variable. The ten land use categories as denoted by the City of Atlanta parcel database included commercial, industrial, institutional, office, residential, recreational, open, transportation/communications/utilities (TCU), unknown, and vacant. Results for each model are shown in Table 3, with the principal components listed in order of greatest significance in the model. Because only six parcels were categorised as open space, a model was not run for that land use category due to the insufficient number of degrees of freedom.

Based on these results, commercial building density is more responsive to street density and location and accessibility and intelligibility. Industrial building density is affected primarily by the morphology of the parcel, as very large buildings typical of industrial sites require an adequate area and they grow

mostly in a model of horizontal density. Land value was only the third most significant factor in the model. Institutional building density tends to be linked to both street density, parcel morphology, accessibility and intelligibility. Office building density is associated with street density and location, accessibility and intelligibility, due to the location of office space in dense and accessible neighbourhoods in Atlanta. This confirms a similar finding of Kim and Sohn (2002) on offices in Seoul. Residential building density is also linked to street density and location and all other factors were also significant in the model. Recreational building density is only responsive to street density and location.

Overall, for all land uses, building density is primarily linked to the street density and location, the only exception is for the industrial buildings that are more sensitive to the morphology of the parcel. As noted, this is likely because industrial buildings tend to expand horizontally and therefore require an adequate area. There are two groups of parcels that follow distinctly different patterns: accessibility plays a major role for commercial and office land use categories, while parcel morphology comes as a second factor for institutional, recreational, and residential. This can be explained by the ability of the first type of buildings (commercial and office) to densify vertically, which is often not the case for the institutional or recreational buildings. The street network and the location are essential for commercial uses and offices, inclusive of the street superstructure captured by accessibility and intelligibility (Scoppa & Peponis 2015). Residential development in Atlanta includes mostly single-family houses which also promotes horizontal development. In fact, multi-family residential parcels are outnumbered by single-family residential parcels by more than 1,000 to one. Land value and parcel morphology are influential factors common to most types of land use with respect to building density by parcel, with the exceptions of office and recreational land uses. Although the separate modelling of each land use was informative, the block-face level analysis was more instructive in allowing the measurement of land use mix to be utilised as an independent variable.

5. Part 2: The Effect of Block-Faces on Building Density

In Part 1, some limitations existed, such as parcels without streets as boundaries or parcels internally facing parcels within a block and buildings that overlapped across several parcels, either due to alignment issues among disparate data sets or a reconfiguration of parcels not captured in the GIS parcel shapefile. It was also important to show the positive impact of the diversity of land uses along a street on building density. For these reasons, the urban block-face became the second unit of analysis. The block-face represents the morphological unit that distinguishes the urban block disaggregated by each surrounding street, and the city street, disaggregated by each side of the street. We have shown that building density requires different urban design characteristics according to land use at the parcel level. We now focus on the building density at the block-face level.

The block-face, as morphological unit, has been used in only a few urban morphological studies (Purciel et al., 2009). Figure 5 illustrates the different translations from road segments to block-faces. The number of faces per block corresponds to the number of road segments associated to a block with adjustment for internal road segments. In the GIS platform, the block-face is defined by populating the urban block boundary with points every five meters. These points can then be linked to values from the parcel it falls on and to the adjacent street segment. In Figure 5, the distinction between (b) and (e) is the source of the pressure on the boundary: external (b) or internal (e). The variation between number of road segments and number of faces happens when there are internal road segments: dead-ends (e) or more complex internal networks (f).

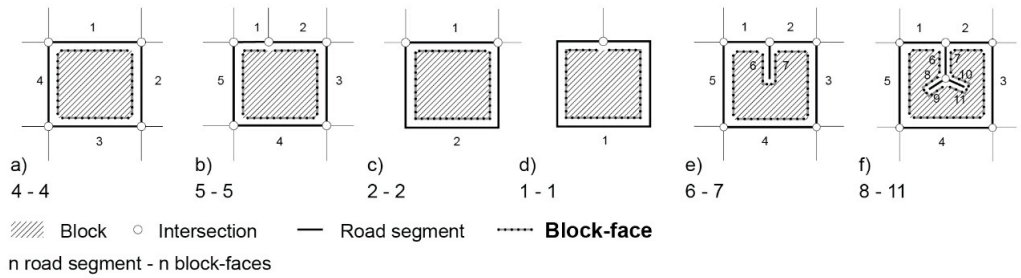

Figure 5: Number of block-faces based on road segment

The building frontage is made of the width of the building footprints that are within a given distance from the block-face (Figure 6). Talen (2005) draws the limit at 9 to 14 meters in the interior of the block from the street for the sense of enclosure to be effectively present. In the case of Atlanta, the chosen distances are 15 meters from the boundary of the block. The building frontage ratio of a block-face is the percentage of its length that is built.

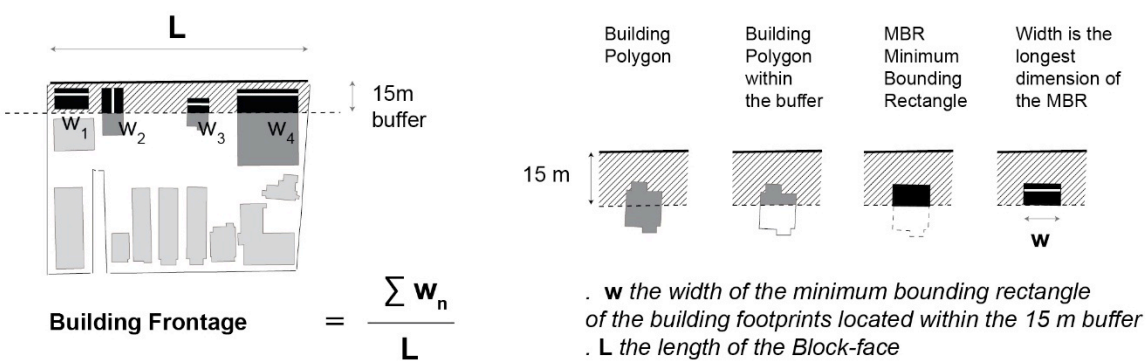

Figure 6: Building frontage ratio is the relationship between the building footprint (j) that is located within 15 meters from the property limit and the length of the block-face

As in Part 1, building density was the dependent variable, in this case using the building frontage ratio measure described above. Measures analogous to those of Part 1 were used for the independent variables, aggregated or recalculated to the block-face unit of analysis. One additional variable used in the block-face analysis was land use mix. Again using City of Atlanta parcel data, the land use mix index was an entropy measure reflecting the evenness of distribution of four land use types (residential, commercial, office, and institutional) that has been used in previous work (Frank, Bradley, Kavage, Chapman, & Lawton, 2008). The land use mix index was calculated as follows where *n* is the number of different land use type classes in the block-face and P_i is the proportion of land in type *i* in the buffer: Land use mix index = $- \sum_{i=1}^{n} P_i * (\ln P_i / \ln n)$. The resulting variable has a variance of 0 (homogeneous land use) to 1 (a perfect mix). A map of this variable calculated for block-faces in the city of Atlanta is shown in Figure 7.

Figure 7: Land use mix values for block-faces

Results of the principal components factor analysis for the independent variables is shown below in Table 4. Six principal components were determined, rather than five as in Part 1. This is due to the addition of land use mix in the model. Variables in each principal component factor are represented in bold font, grouped by column.

Table 4: List of independent variables and results for six principal component factor analysis for 15 input variables

	Independent Variables	**Prin1**	**Prin2**	**Prin3**	**Prin4**	**Prin5**	**Prin6**	
Block Morphology	Block Area	-0.124	**0.926**	-0.004	-0.030	0.016	-0.005	Block Morphology
	Block Perimeter	-0.188	**0.961**	-0.005	-0.046	0.006	-0.003	
	Block Compactness	0.324	**-0.719**	-0.017	0.051	0.047	0.009	
	Block-face Length	**-0.441**	0.205	0.279	0.069	-0.032	0.042	Street Density and Location
Other	Distance to Highway Exit	**-0.631**	0.040	-0.091	-0.096	0.026	-0.057	
	Distance to CBD	**-0.905**	0.100	-0.022	-0.071	-0.020	0.002	
Syntax	Metric Reach 0.25 Miles	**0.759**	-0.267	-0.035	0.153	0.048	0.017	
	Metric Reach 1 Mile	**0.891**	-0.193	0.041	0.175	0.030	0.041	
	Metric Reach 5 Miles	**0.905**	-0.161	0.049	0.120	0.016	0.001	
	Directional Reach 0 Turns	0.083	-0.029	0.056	**0.955**	0.005	0.006	Accessibility and Intelligibility
	Directional Reach 2 Turns	0.318	-0.080	0.050	**0.893**	0.034	0.002	
Planning	N Total Land Uses	-0.014	-0.013	**0.943**	0.038	0.010	0.004	Land Use Mix
	Land Use Mix of Block-face	0.092	-0.005	**0.935**	0.050	0.019	-0.002	
	Average Appraised Value Per Acre	0.054	-0.011	0.006	0.006	0.007	**0.996**	Land Value
	Zoning FAR Allowance	0.043	-0.013	0.022	0.030	**0.996**	0.007	Zoning FAR Allowance
		Street Density and Location	Block Morphology	Land Use Mix	Accessibility	Zoning FAR Allowance	Land Value	

Each principal component associated more highly with one or several variables. For the purpose of clarity we will refer to each component by its most representative meaning that is: street density and location (Prin1), block morphology (Prin2), land use mix (Prin3), accessibility and intelligibility (Prin4), zoning FAR (Prin5), and land value (Prin6).

As in Part 1, once the independent variables were combined using the principal components analysis, an OLS stepwise regression model was conducted to determine the impact of the factors on building density, or building frontage ratio within a distance of 15 meters for block-faces, with the six principal components were used as independent variables. The results of the model are summarised in Table 5, with the principal components listed in order of greatest significance in the model.

Table 5: OLS regression model results for building frontage ratio at the block-face level

	R^2	Term	Principal components	Std Error	t Ratio	Prob>|t|	Std Beta	VIF
Building Density (n=23,285)	0.22	Prin1	Street Density and Location	0.0884	73.97	<.0001*	0.4280	1.00
		Prin4	Accessibility and Intelligibility	0.1660	-23.02	<.0001*	-0.1332	1.00
		Prin3	Land Use Mix	0.1499	19.23	<.0001*	0.1113	1.00
		Prin2	Block Morphology	0.1376	-15.43	<.0001*	-0.0893	1.00
		Prin6	*Land Value*	*0.1967*	*1.52*	*0.1273*	*0.0088*	*1.00*
		Prin5	*Zoning FAR Allowance*	*0.1955*	*-0.80*	*0.4240*	*-0.0046*	*1.00*

**Variables that were not significant are in italics.*

Based on an R-squared value of 0.22, the model explains 22 percent of variation in building frontage within 15 meters from the edge of the parcels (R^2= 0.22, n=23,285, p<.0001*). The most influential components are the syntactical street parameters and the location, followed by accessibility and intelligibility, land use mix by block-face, and the morphology of the block. As in the parcel level analysis, the positive influence of street density and location indicates the importance of walkability and centrality for building density. The negative influence of parcel morphology indicates that larger and less compact parcels cause lower building densities. The negative impact of accessibility and intelligibility was surprising and questions the role of the street superstructure on density. These variables were not significant in the parcel level analysis and the overall effect seems to be related to the nature of the street network in Atlanta, where long connections are rare due to a dendritic street pattern and speculative land development. Interestingly, the value of the land and the maximum floor area ratio allowed by zoning were not significant. This can be explained by the fact that frontage in this case does not take into account the height of building, nor its surface. It is worth noting that the presence of different land uses within a block-face correlates with a higher presence of frontage. The street network is more influential than the shape and size of the block itself although both contribute to an increase of frontage for denser and more regular street pattern as well as a location at proximity to the city centre and to highway exits.

6. Discussion

The above analysis was conducted to determine the impact of planning, morphological, and syntactical characteristics on the building density of parcels (Part 1) and block-faces (Part 2). Based on the results of this analysis, building density at the parcel level and building frontage ratio at the block-face level are variously impacted by planning, morphological, and syntactical characteristics of their surroundings. The most important finding, perhaps, was that the street network density exerted the greatest influence on building density and building frontage ratio in most iterations of the models. However, there is an important distinction to make between superstructure acting as the foreground structure (Hillier, Turner, Yang, & Park, 2007) and street density that locally describes the background structure. A previous study showed that Atlanta starts with a weak superstructure with patches of relative more dense areas (Hillier et al., 2012). However, this article shows that the consolidation of the superstructure can provide a model for densification of a city like Atlanta where the density is, overall, very low. Currently, Atlanta cannot support density everywhere, but densification can and should respond to existing land use and street network properties. One of the findings of this paper is that building density responds differently to street properties by land use: accessibility and intelligibility matters for commercial and office uses, but not for residential (although a separate model for single- and multi-family residential may yield

differing results for multi-family development). Atlanta has indeed identified opportunities for densifying its superstructure, including revitalisation of the Memorial Drive Corridor (inspired by corridor development in the Washington, D.C. region). Based on the findings of this paper, these types of thoroughfares carry syntactic properties that can support greater density for commercial and office uses.

Street density and location measure the potential for movement in and around a space. Therefore, the variation of street properties adjacent to a corridor is also important. The superstructure provides a ground for primarily commercial and office uses and a highly connected local network allows residents to pass from high density and highly accessible streets to adjacent lower-density neighbourhoods.

Surprisingly, FAR restrictions as dictated by City of Atlanta zoning regulations were relatively insignificant determinants of building density. FAR is used to limit or encourage density and intensity of development. Therefore, it was surprising that this tool often employed by urban planners yielded very little influence in the models. This may be because of the lack of nuance in FAR determinations, as several zoning categories often have an identical FAR. This finding indicated the possible need for form based codes in Atlanta in order to preserve low- to middle-density traditional neighbourhoods while allowing for increased development in the urban core and other nodes.

Similarly, the lack of influence of land value in many of the models was surprising. It seems natural that land with a higher value should be developed more intensely. In fact, higher allowable FAR is generally associated with higher land value. When plotted on a map, the highest value parcels clustered in the most developed areas, such as downtown and high profile commercial corridors. However, whether normalising by area (for building frontage ratio) or not (for building density), this measure was not as significant as street network and density or morphology, which points to the power of influence of syntactical and morphological properties.

Overall, this study provides a justification for the creation of high profile commercial corridors in Atlanta and refinement of its zoning code to allow higher land use mix in order to link these thoroughfares with surrounding low-density neighbourhoods.

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