Original Article

Understanding the link between street connectivity, land use and pedestrian flows

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Abstract The distribution of pedestrian movement by street segment in three areas in Atlanta is modeled in relation to measures of street connectivity and land use. Although land use accounts for the pronounced differences in average pedestrian volumes per area, the connectivity of the street network affects the distribution of pedestrians on a street-by-street basis within each of them. The measures of connectivity that are used describe the density of street connections and the extent to which streets are sinuous or aligned. This study enhances previous findings, particularly those using space syntax, by better controlling for the effects of land use as compared to the effects of street connectivity and network layout. Asserting the independent role of street network design is important given that streets act as the long-term framework within which land uses change over time. The measures of street connectivity are easy to implement on a GIS platform to support the evaluation and development of designs and regulatory frameworks that promote walking, whether it be in the interest of public health, in reducing automobile dependence or in supporting vibrant urban communities.
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Introduction: Does the Spatial Structure of Street Networks have Independent Effects on Pedestrian Movement?

The reduction of automobile dependence and the inducement of non-auto commuting have emerged as commonly shared city planning and urban design aims. Along with the ideals of smart growth and new urbanism, they are reshaping urban form across the United States. The studies of impact of the built environment on individual travel behavior that are reviewed below have generally focused on population densities, land use mix and the qualities of urban design. The latter has often been treated with reference to the immediate condition of individual streets, ranging from the dimensions and design of sidewalks to the frontages of retail or the prevailing levels of environmental comfort that may encourage pedestrian movement (Badland and Schofield, 2005; Ewing *et al*, 2006; Gehl *et al*, 2006; Ewing and Handy, 2009). Pedestrian safety, of course, is also shown to be a major factor in determining physical activity levels (Boarnet *et al*, 2005). Safe and pleasant conditions encourage walking (Brown *et al*, 2007).

These are undoubtedly important factors. However, an intuitive distinction can be drawn between urban environments in which pedestrian presence and walking are contained within a well-circumscribed enclave (that is, a shopping mall or a small pedestrian-friendly development) or directed towards well-defined local destinations (that is, a school or a transit station) and environments where pedestrian movement is distributed over larger areas, with a mixture of longer and shorter pedestrian paths, multiple and overlapping rather than converging trajectories and varied intensities. It would seem that in order to understand the latter and design towards them, equal attention must be paid to the structure of street networks and street connectivity as is paid to street section design and the qualitative properties of specific street segments. Even so, the larger question remains: how do the spatial structure of street networks and street connectivity interact with other important factors such as land use? In terms of planning practice, how far should we give priority to subdivision regulations, aimed at producing desirable long-term network properties, over zoning regulations, aimed at producing desirable patterns of land use and development density? These questions are of critical importance to the interface between planning and urban design.

By adopting appropriate measures of connectivity, which are sensitive to the spatial structure of street networks, this article clarifies how street network design affects the distribution of pedestrian movement at the scale of the square mile rather than the scale of a few urban blocks. In doing so, it enriches a considerable body of literature that points to a relationship between the distribution of pedestrian movement and the spatial structure of street networks. The more distinct contribution of this article arises from explicitly controlling for the effects of land use at a grain that is fine enough to be commensurate with the grain at which street connectivity is measured. It is suggested that, although land uses impact the average densities of movement over an area, the configuration of the street network is the main independent variable affecting the distribution of movement by street. As discussed in the concluding section, this reinforces the importance of street network design as the long-term framework that impacts the evolution of important aspects of urban function, including walkability, and patterns of land use that benefit from walkability.

How is Street Connectivity Measured?

There is a growing body of research on the role of street networks and their layout. From the point of view of the connectivity measures used, the literature can be conveniently classified into four groups of studies.

A first group of studies resorts to intuitively obvious typological distinctions between rectilinear, curvilinear and cul-de-sac layouts (Southworth and Owens, 1993; Crane and Crepeau, 1998; Ewing and Cervero, 2001); traditional, early modern and late modern neighborhoods (Handy 1996); or traditional and suburban planned units (Ewing *et al*, 1994; Handy *et al*, 2005; Rodríguez *et al*, 2006). These typological distinctions are then supported by measures of the average properties of street networks, such as the number of intersections or cul-de-sacs by unit area.

A second group of studies directly discusses the connectivity of street networks as a factor that affects accessibility and walking. The measures used are similar to those employed by the first group and include the density of street intersections per area (Frank *et al*, 2005; Lee and Moudon, 2006; Kerr *et al*, 2007), block size per area (Hess *et al*, 1999; Krizek, 2000), cul-de-sacs per road mile (Handy, 1996) or per area, proportion of four-way intersections (Cervero and Kockelman, 1997; Greenwald and Boarnet, 2001; Parks and Schofer, 2006), the ratio of intersections to cul-de-sacs (Song and Knaap, 2004), the links–nodes ratio (APA, 2006) or the average distance between intersections (Handy *et al*, 2003; Rodríguez *et al*, 2006).

A third, smaller group of studies uses more discriminating measures that can, in principle, characterize a particular location within a network. The walking catchment area around a destination (or walk-shed) of particular importance (Hess, 1997; Hess *et al*, 1999; Aultman-Hall *et al*, 1997) is one such measure. The directness of available routes from various surrounding origins to destinations of importance is another. Route directness, or sinuosity, is usually expressed as a ratio of minimum network distance over straight line (crow flies) distance (Hess, 1997; Randall and Baetz, 2001; Handy *et al*, 2003; Lee and Moudon, 2006).

The fourth group of studies, associated with space syntax (Hillier, 1996; Peponis and Wineman, 2002), takes a configurational approach. This involves measuring the accessibility of all parts of a network under consideration from each individual street element. The intent is to provide a generalized description of spatial structure and connectivity hierarchy without evoking information about land use or making assumptions about desirable or typical trips. Two key measures are integration and choice. Integration describes how accessible each street line is from all other parts of the network based on the number of direction changes. As a measure of relative accessibility, integration is calibrated so that systems with different numbers of constituent street lines can be directly compared. Choice describes how many shortest paths between all possible paired origins and destinations go through each space. In this case 'shortest' can refer to either 'shortest trip length' or 'fewest direction changes' as specified in each study.

The choice of connectivity measures is critical. It affects the grain of theories regarding the relationship between network design and functional consequence, including the impact of network design on walking. Measures that emphasize the average properties of areas can be useful in supporting general guidelines and policies, but cannot inform design decisions about alternative street alignments or alternative ways of fronting and orienting developments. By implication, the measures of connectivity we choose also affect the interface between urban design and planning. Understanding how pedestrian movement is distributed over an area is important to urban development and urban design, because it helps determine the potential character of individual streets. Namely, whether they are intended to act as vibrant hubs of urban life or be quieter; whether they are intended to bring together passing pedestrians on diverse trajectories and distant ranges of walking or be limited to the visitors of local establishments.

The measures of connectivity adopted in this article were originally proposed by Peponis *et al* (2008). They are intended to discriminate between individual street segments, much like space syntax discriminates between individual street lines. At the same time, when averaged over an area, they are strongly correlated with the measures typically used by the second group of studies mentioned above. The choice of measures is motivated by their simplicity, compared to standard space syntax measures and also by the convenience of using readily available GIS-based street centerline maps, which can be associated with GIS-based measures of land use. The two measures, metric reach and directional reach, are illustrated in Figure 1.

Metric reach is very similar to walking catchment areas. It is a measure of the total street length accessible within a specific walking distance from the center of each street segment in an urban network (Peponis *et al*, 2008). In essence, metric reach is another way of expressing the density of streets per unit area and the density of intersections per unit area (Peponis *et al*, 2007), with the advantage that the value associated with proximate street segments can differ according to their exact location within the street network.

Directional reach is a measure of the total street length accessible within a specific number of direction changes from the center of each street segment in an urban network (Peponis *et al*, 2008). Whereas metric reach extends uniformly along the streets surrounding a given street segment, directional reach may extend much less uniformly, because it is sensitive to the shape and alignment of streets, not merely to their density (Hillier, 1999).

The decision to include a measure sensitive to the sinuosity of the network is motivated by two considerations. First, as will be reviewed below, space syntax studies have shown that pedestrian movement is distributed according to integration, essentially a measure of directional accessibility. Second, a body of literature on spatial cognition shows that direction changes are critical to the way in which environments are understood, and contribute to the cognitive (as opposed to the physical) effort (Sadalla and Magel, 1980; Montello, 1991; Bailenson *et al*, 2000; Crowe *et al*, 2000; Jansen-Osmann and Wiedenbauer, 2004; Kim and Penn, 2004; Hillier and Iida, 2005) associated with walking, particularly walking in partly or fully unfamiliar surroundings. This is confirmed by research findings (Moeser, 1988; O'Neill, 1991; Conroy-Dalton, 2003) indicating that people orient themselves with respect to frames of reference that are as linear as possible.

Urban Form and Pedestrian Movement

There is a growing body of literature discussing how density, land use and street connectivity affect walking. Higher population densities are generally associated with more walking (Agrawal and Schimek, 2007). Compact developments with higher densities degenerate vehicle trips and encourage non-motorized travel by reducing the distance between origins and destinations, by offering a wider variety of choices for commuting and a better quality of transit services, and by triggering changes in the overall travel pattern of households (Ewing *et al*, 1994; Holtzclaw, 1994; Cervero and Kockelman, 1997). Recent policy initiatives have proposed strategies of development aimed at reducing auto-dependence rates by encouraging denser development infrastructure (Washington State Growth Management Act; Central Puget Sound Vision). Findings from previous research have demonstrated that there is an inverse relationship between density and

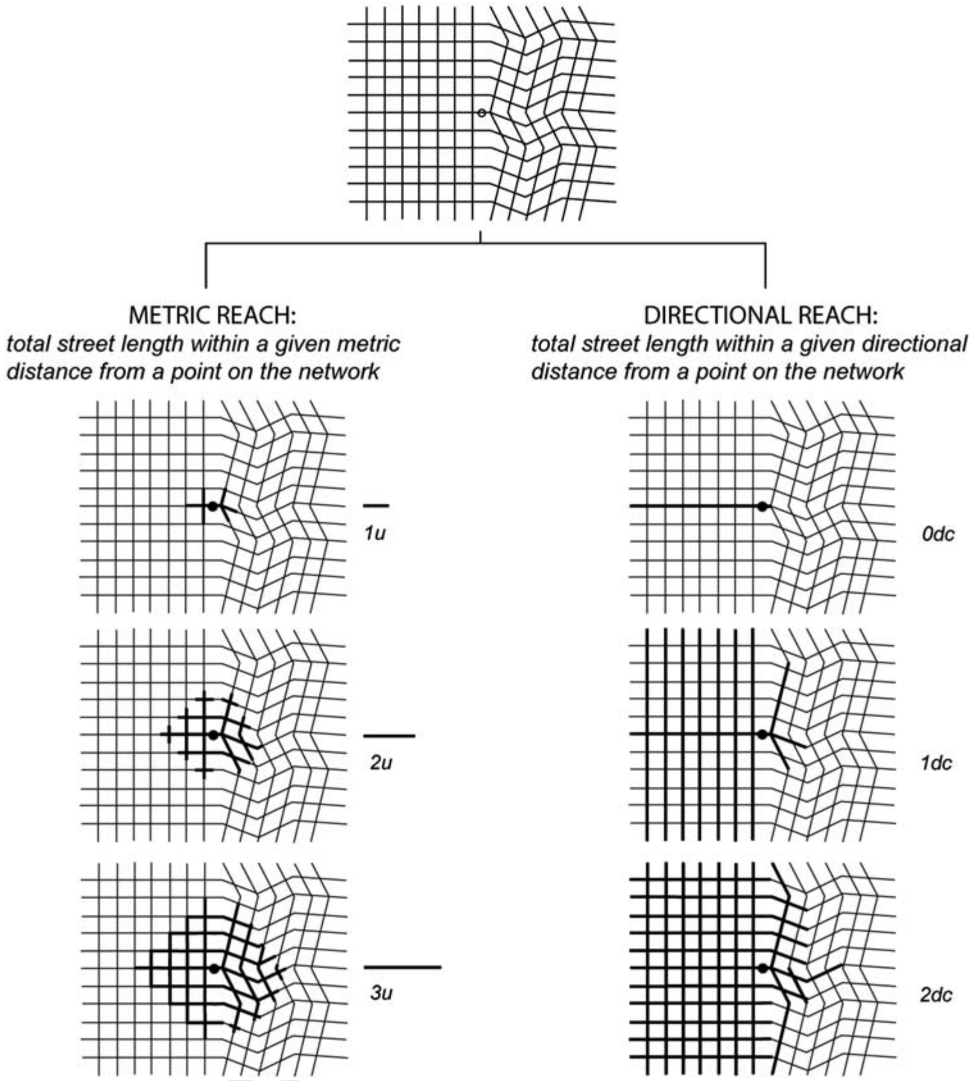

Figure 1: Diagrammatic definition of GIS-based connectivity measures. Adapted from Peponis *et al*, 2008.

vehicle miles traveled and a positive association between density and transit usage and walking trips (Dunphy and Fisher, 1996; Lopez-Zetina *et al*, 2005). However, some researchers warn that density and land use mix do not directly affect long-distance vehicle trip generation even though they may encourage short-distance walking (Boarnet and Crane, 2001).

Research also suggests that land use patterns play a significant role in encouraging walks. The presence of retail within neighborhoods has a stronger impact on mode choice for non-work trips than density (Cervero and Kockelman, 1997). Development patterns have a significant impact on household travel behavior beyond their relationship with the socio-demographic characteristics of households (Ewing, 1995). Higher levels of mix-use and the presence of retail activities near residences increase non-work trips and induce non-auto commuting (Holtzclaw, 1994; Cervero, 1996). Increased levels of land use mix at the trip origins and destinations yield in increase in walking (Cervero, 1988; Frank and Pivo, 1994). Similarly, mixed land use neighborhoods help increase walking with a concomitant reduction in body mass index (Frank *et al*, 2006).

The impact of street networks on walking has generally been analyzed on the basis of the average properties of areas, as well as route directness, as reviewed earlier. It is suggested that shorter distances between intersections, smaller block sizes and more direct paths encourage walking. Walking to stores is more likely when paths are shorter and more direct as a result of higher intersection and street densities (Handy, 1996). Walking to neighborhood centers is more likely when urban blocks are smaller, intersections are denser and pedestrian sidewalks are available (Hess *et al*, 1999). Where there is a choice, people prefer to walk on 'main streets' (Hess *et al*, 1999). Children are more likely to walk to school when street connections are denser and population density is higher (Bejleri *et al*, 2009). Shorter distances to stores/markets and eating/drinking places are associated with more walking (Lee and Moudon, 2006), which in turn is shown to substitute for longer automobile trips (Ewing and Cervero, 2001). Some studies, however, question whether street network characteristics enhance walking once density and land use are controlled for (Crane and Crepeau, 1998).

In general, the studies reviewed here seek to establish how population density, land use and street network connectivity impact the amount of walking. Typically, walking is of interest either as a means of affecting travel mode splits and reducing vehicular travel, or as a means of contributing to health. Sometimes, walking is seen as of value in its own right, as an indicator of an urban lifestyle. The intent is to develop and evaluate policies, guidelines and practices that will encourage people to walk.

A different group of studies, using space syntax, looks at the distribution of walking within an area on a street-by-street basis. The aim is to determine whether and how the distribution is affected by the hierarchy of network accessibility. One practical motivation is to support the appropriate design of paths and streets as part of urban developments or redevelopments. For example, one question asked is how the street network can be designed so as to ensure that some places, intended as retail hubs, commercial uses or local centers, will be more likely to attract higher densities of movement, whereas others, intended for residential uses, will remain quieter (Hillier, 1993). Another question asked is how to achieve a desirable mix of high and low intensity of pedestrian movement without creating isolated enclaves (Hillier, 1988).

In traditional residential areas in London, pedestrian movement densities were found to be correlated with the integration of streets within the surrounding street network (Hillier *et al*, 1987), whereas this correlation broke down in housing estates where the internal path structure was excessively fragmented and labyrinthine. The association between pedestrian movement densities and integration was subsequently confirmed by more extensive studies in London (Hillier *et al*, 1993), in Greek Cities (Peponis *et al*, 1989), in Dutch cities (Read, 1999), in Istanbul (Kubat *et al*, 2005) or in Atlanta (Peponis *et al*, 1997). On the basis of the confirmation that the correlation holds in a variety of urban conditions, Hillier and his team have argued that there is a natural propensity for movement to be drawn towards syntactically more accessible streets. It has been hypothesized that, at least in part, this reflects cognitive factors associated with the way in which environments are understood (Penn, 2003; Kim and Penn, 2004) and navigated (Hillier and Iida, 2005). Regardless of the possible cognitive explanation of this phenomenon, the association between movement densities and integration is held to have important implications for the economy of land uses (Hillier *et al*, 1993), as well as for urban culture (Hillier, 1989; Peponis, 1989; Hillier, 2002; Hillier and Netto, 2002). It is argued that streets that attract more movement by virtue of their syntactic accessibility also attract land uses that are dependent on movement, such as retail, which in turn multiplies their attraction value, turning an otherwise linear relationship into a logarithmic one (Hillier *et al*, 1993). It is also shown that at least in some cases, streets with commercial uses continue to attract proportionately higher levels of movement even at times of the day or the week when retail premises are shut, which indicates that the correlation holds independent of the functional impact of land use (Peponis *et al*, 1989) – land use can still exercise effects on movement by making some streets more familiar than others over time. However, the hypothesis that street configuration independently affects the distribution of movement in an area has not typically been tested by controlling in a systematic way for land use variations. This is important as typically more accessible locations are associated with commercial and retail land uses. This study is intended as a contribution towards filling this gap.

Analytical Framework

To address how street connectivity affects the distribution of pedestrian movement, it was necessary to compile data from different sources and merge them into a single database. Data on actual pedestrian volumes were recorded by conducting on-site observations in three urban areas. Land use data were acquired from the 1999 and 2000 US census tracts. Parcel-based data were categorized into residential (single family and multi-family housing) and non-residential (office, retail, institution, recreation, industrial) for the purpose of distinguishing between the effects of each on the distribution of movement. Gross densities of land use were measured at three different scales. First, land use density was calculated as a linear measure at the street segment scale by computing residential and non-residential building square feet associated with each individual street segment, and relativized by segment length: square feet of development per 100 m of street length. Second, land use density was calculated as a surface measure at the street network that is accessible within 1-, 0.5- and 0.25-mile walking distances from the mid-point of each street segment. Third, land use density was calculated for 1-, 0.5- and 0.25-mile rings around the mid-point of each street segment. Figure 2 demonstrates the three ways in which development densities were associated with street segments.

Metric and directional reach were computed on the basis of ESRI 2003 street centerline maps using a GIS-based software developed by Zhang at Georgia Tech. Metric reach was computed for 1-, 0.5- and 0.25-mile walking distance thresholds. The use of 1 mile as the upper threshold is based on research findings showing that comfortable walking distances rarely extend beyond the mile (Stringham, 1982; Bernick and Cervero, 1997). Directional reach was computed for two direction changes subject to a 10° angle threshold. The 10° angle threshold was based on research showing that people are sensitive to direction changes of this magnitude (Sadalla and Montello, 1989; Montello, 1991), and also on a desire to set the threshold low enough to make the analysis sensitive to street sinuosity. The decision to compute for two direction changes was based on prior syntactic research indicating that integration computed for two direction changes is often a better predictor of movement than integration computed for more direction changes (Hillier, 1996).

The average directional distance of the street segments within metric reach was also computed. Thus, each street segment is associated with seven primary connectivity measures (metric reach for 1-mile, 0.5-mile and 0.25-mile walking ranges; directional reach for two direction changes; and directional distances associated with metric reach) and seven measures of land use density (square footage of development on parcels attached to individual street segments relativized for segment length; on parcels accessible by walking along the network for 1-, 0.5- and 0.25-mile distances; and finally parcels contained within circular buffers of 1-, 0.5- and 0.25-mile radii). A composite connectivity measure was also added to calculate the ratio of metric reach to the average directional distance associated with it. This composite variable takes higher values as street density increases and as access to streets becomes more direct.

Pedestrian count data were collected for samples of spaces in three areas in Atlanta. Atlanta is not a pedestrian-friendly city. The results of an

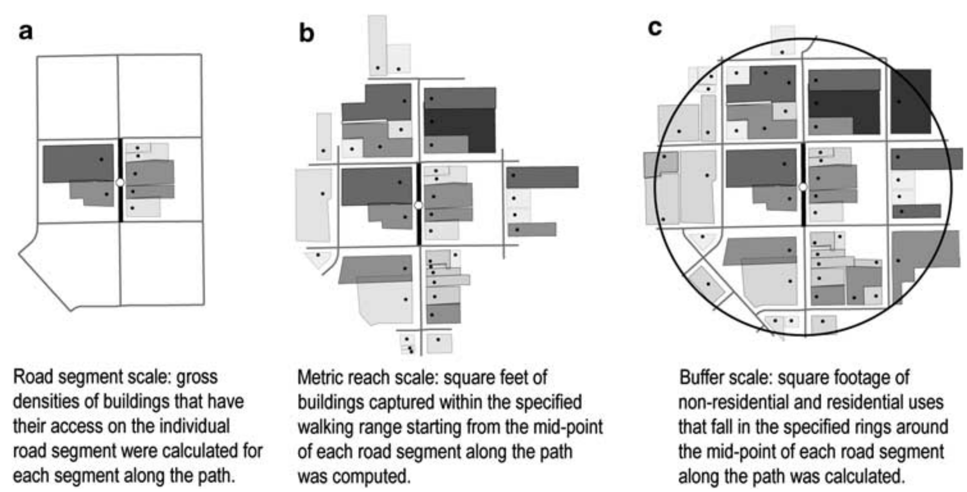

Figure 2: Illustration of three different scales at which land use densities were measured.

earlier study on urban sprawl and health-related issues, where 83 metropolitan areas in the United States were rated in terms of residential density, land use mix, degree of centering and street accessibility, have demonstrated that Atlanta sprawls badly in all dimensions (Ewing *et al*, 2003). Bearing these extremities in mind, the areas were selected to reasonably represent the more pedestrian-friendly environments in the city. The first area, which had been previously studied in the 1990s (Peponis *et al*, 1997), is Downtown Atlanta (average block area 1.7 ha), which includes some of the most densely walked street segments within the city. The second area is Midtown (average block area 3.04 ha), which has recently experienced very rapid mixed-use growth with explicit attempts by the City of Atlanta and Midtown Coalition to encourage walking through the provision of remodeled sidewalks. The third study area is the Virginia Highland neighborhood (average block area 7.5 ha), developed in the early 1900s, which remains a pedestrian-oriented environment attracting visitors to its shops, restaurants and bars.

Population densities calculated according to the 2000 US census for the three areas are 2603, 2726 and 1608 km^2, respectively. These figures do not include estimates of the people who work in each area and commute daily. Figure 3a shows the three areas and marks the observation locations for each.

In the cases of Downtown and Midtown, data were gathered by a moving observer walking at a constant pace and counting the people crossing her path at right angles; in the case of Virginia, Highland data were gathered on the basis of gate counts, counting the people crossing a conceptual line across the street. Twenty rounds of observation during working hours were completed for Downtown and Midtown, and 20 min of observation for each gate were completed in Virginia Highland, distributed over 10 different periods including evening hours when the area attracts more visitors. The reason why gate counts were used in Virginia Highlands instead of counts along a path has to do with the network morphology. The larger size of blocks in this area would have necessitated unreasonably long walking paths if an appropriate sample of measures were to be taken. Figure 3b shows graphically the distribution of movement densities using different line thicknesses for Downtown and Midtown, and circles of different diameters for Virginia Highland.

Analysis

Gross differences between the three areas

Table 1 presents a quantitative profile of the three areas in terms of street connectivity, population density, movement patterns and land use compositions. This preliminary benchmarking demonstrates notable differences between areas. The population densities of the areas, calculated on the basis of the census blocks associated with the street segments for which pedestrian counts were taken, range from 516 to 960 per acre with Downtown and Midtown having similar densities. The median density of moving pedestrians per 100 m or per minute, which is roughly equivalent to 100 m′ walk, is 68.7, 18.9 and 0.9 for Downtown, Midtown and Virginia Highland, respectively, whereas the corresponding means are 122.9, 31.8 and 1.3. The three areas also differ significantly in their average street density. Average metric reach, from high to low, is consistently in descending order from Downtown to Midtown and Virginia Highland for all three radii (1, 0.5, 0.25 mile). However, Midtown has the highest two-directional reach, whereas Downtown and Virginia Highland have similar lower averages. The magnitude of land use densities follows the same order as that of street density. Non-residential land use density is highest at all scales in Downtown, which is primarily a business district, and lowest in Virginia Highland, which is primarily a residential neighborhood. This is consistent with the residential development density, which is highest for Virginia Highland and lowest for Downtown. However, in terms of total building square feet, Downtown and Midtown are found to have similar densities for the 1-mile buffer range.

Overall, the initial tabulation suggests a strong correspondence between the average volume of pedestrian movement and the average density of streets and land development. A sample of only three areas does not allow further statistical inference, but intuition suggests that land use and development density are the primary factors affecting average pedestrian densities. As higher development densities are located in areas with denser street networks, it would seem that the association between pedestrian density and street density is a by-product of land use. In the next section, however, the examination of the data at street segment level suggests that street connectivity has a strong role

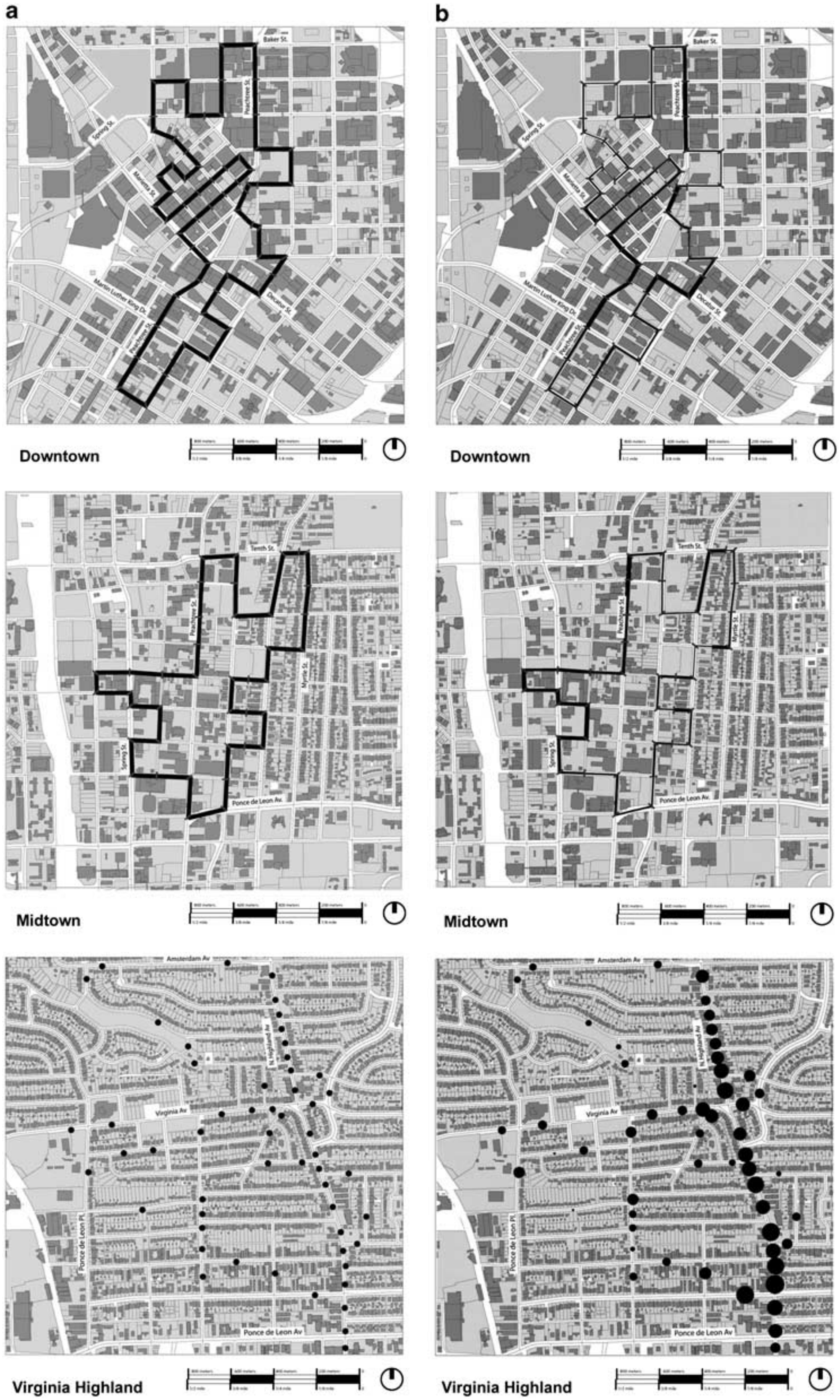

Figure 3: (**a**) Location of pedestrian observations. (**b**) Graphic representation of observed pedestrian densities.

Table 1: Urban form characteristics of areas

	Primarily non-residential Downtown	*Mixed-use Midtown*	*Primarily residential Virginia Highland*
Densities of residential Population and pedestrians			
Average population density per acres	520	960	516
Average number of pedestrians per 100 m	124.6	31.8	1.3
Average natural log of pedestrians per 100 m	4.4	3.1	−0.2
Characteristics of street connectivity			
Average metric reach (1 mile)	44.7	39.5	30.4
Average metric reach (0.5 mile)	12.7	12.0	8.2
Average metric reach (0.25 mile)	3.5	3.2	2.1
Average two-directional reach (10°)	9.6	30.6	8.3
Average metric reach (1 mile)/directional reach (1 mile, 10°)	15.7	17.2	10.2
Average block area (hectares)	1.7	3.0	7.5
Land use characteristics at the road segment scale (in millions)			
Residential sq ft per 100 m	0.0	0.009	0.01
Non-residential sq ft per 100 m	0.09	0.02	0.004
Total sq ft per 100 m	0.09	0.03	0.02
Land use characteristics at the metric reach scale (in millions)			
Average residential sq ft (1 mile)	0.6	4.5	6.9
Average residential sq ft (0.5 mile)	0.09	1.5	1.9
Average residential sq ft (0.25 mile)	0.02	0.4	0.5
Average non-residential sq ft (1 mile)	15.2	8	0.5
Average non-residential sq ft (0.5 mile)	8.6	2.1	0.07
Average non-residential sq ft (0.25 mile)	2.6	0.5	0.01
Average total sq ft (1 mile)	15.8	12.5	7.4
Average total sq ft (0.5 mile)	8.7	3.6	1.9
Average total sq ft (0.25 mile)	2.6	0.9	0.5
Land use characteristics at the buffer scale (in millions)			
Average residential sq ft (1 mile)	1.6	6.8	10.8
Average residential sq ft (0.5 mile)	0.1	2.3	3.5
Average residential sq ft (0.25 mile)	0.04	0.7	0.9
Average non-residential sq ft (1 mile)	17.7	12.2	1.2
Average non-residential sq ft (0.5 mile)	10.7	3.7	0.1
Average non-residential sq ft (0.25 mile)	4.2	0.9	0.02
Average total sq ft (1 mile)	19.3	19	12
Average total sq ft (0.5 mile)	10.8	6	3.6
Average total sq ft (0.25 mile)	4.3	1.6	0.9

in determining the distribution of pedestrian density within areas.

Analysis of the three areas as a single set

After benchmarking, the selected areas were merged into a single set. On the basis of this data set, 'connectivity' and 'urban form' models were produced to investigate the extent to which street connectivity and land use density explain the distribution of movement per street segment. The 'connectivity' model originally included standard connectivity measures, as well as metric reach computed at 0.25-, 0.5- and 1-mile ranges and two-directional reach. The 'urban form' model includes land use variables (residential, non-residential and total), in addition to connectivity measures. Aggregate (sum of residential and non-residential) and disaggregate land use densities (separated residential and non-residential) – measured at the street segment, metric reach and buffer scales – were added to the 'urban form' model separately. When multivariate and bivariate regression equations were estimated for metric reach computed at 1, 0.5, and 0.25 miles separately, the highest coefficient of determination (R^2) was obtained for metric reach computed

Table 2: Multivariate regression for all areas considered as a single set

Log of pedestrians/100 m	*Connectivity model*			*Urban form model*					
	Connectivity			*+Land use (aggregate)*			*+Land use (disaggregate)*		
	B	*t*	*std β*	*B*	*t*	*std β*	*B*	*t*	*std β*
Land use measured at street segment scale									
Constant	—	−20.57	—	—	**−20.59**	—	—	−16.81	—
Metric reach (1 mile)	**0.30**	**25.36**	**0.89**	**0.30**	**24.90**	**0.86**	**0.30**	**20.99**	**0.87**
two-directional reach	*0.02*	*2.51*	*0.09*	**0.02**	**2.79**	**0.09**	**0.02**	**2.64**	**0.09**
Non-residential sq ft/100 m	—	—	—	—	—	—	**0.00**	**3.41**	**0.12**
Residential sq ft/100 m	—	—	—	—	—	—	0.00	0.59	0.02
Total sq ft/100 m	—	—	—	**0.00**	**3.44**	**0.12**	—	—	—
$N=157$									
R^2		**0.82**			**0.83**			**0.83**	
R^2 adjusted		**0.81**			**0.83**			**0.83**	
Land use measured at metric reach scale									
Constant	—	−20.57	—	—	−12.70	—	—	−5.52	—
Metric reach (1 mile)	**0.30**	**25.36**	**0.89**	**0.28**	**7.76**	**0.81**	**0.25**	**6.74**	**0.72**
two-directional reach	*0.02*	*2.51*	*0.09*	**0.02**	**2.57**	**0.09**	**0.03**	**3.53**	**0.14**
Non-residential sq ft (1 mile)	—	—	—	—	—	—	0.00	−0.30	−0.06
Residential sq ft (1 mile)	—	—	—	—	—	—	0.00	−1.71	−0.24
Total sq ft (1 mile)	—	—	—	0.00	0.82	0.09	—	—	—
$N=157$									
R^2		**0.82**			**0.82**			**0.83**	
R^2 adjusted		**0.81**			**0.81**			**0.82**	
Land use measured at 1-mile buffer scale									
Constant	—	−20.57	—	—	−20.58	—	—	−1.48	—
Metric reach (1 mile)	**0.30**	**25.36**	**0.89**	**0.33**	**14.19**	**0.97**	**0.21**	**5.22**	**0.61**
two-directional reach	*0.02*	*2.51*	*0.09*	**0.02**	**2.89**	**0.11**	**0.04**	**4.68**	**0.21**
Non-residential sq ft (1 mile)	—	—	—	—	—	—	0.00	−2.58	−0.37
Residential sq ft (1 mile)	—	—	—	—	—	—	**0.00**	**−4.11**	**−0.65**
Total sq ft (1 mile)	—	—	—	0.00	1.49	−0.11	—	—	—
$N=157$									
R^2		**0.82**			**0.82**			**0.84**	
R^2 adjusted		**0.81**			**0.82**			**0.83**	

Note: Numbers in bold = $P<0.01$; numbers in italics = $P<0.05$.

at the 1-mile range. Thus, linear models with metric reach computed at the 1-mile range, as well as at two-directional reach, are reported from now onward. Standard connectivity measures associated with less strong correlation coefficients are omitted from the models presented below.

Table 2 summarizes the results for multivariate regressions estimating the natural logarithm of pedestrians relativized by 100 m. The results of analysis at the three scales of land use measures suggest that the impact of street connectivity on the distribution of movement is quite consistent across models. Metric and directional reach together explain 82 per cent of the variation in movement (at a 99 per cent level of confidence). In all models, the coefficients for metric and two-directional reach are positive and statistically significant. However, comparisons of standardized coefficients (in terms of variances of 1, that is, *std β*) between the two variables show that metric reach has the highest explanatory power. In fact, metric reach has the highest relative effect size both at the street segment and metric reach scales, and shares similarly high standardized coefficients with residential density at the buffer scale.

Consistent with theory, pedestrian movement levels are also sensitive to land use densities. The positive coefficients of total and non-residential building square feet at the street segment scale suggest that movement levels increase with higher development densities. However, land use variables add an inconsequential explanatory power of one to two per cent point to the 'connectivity' model.

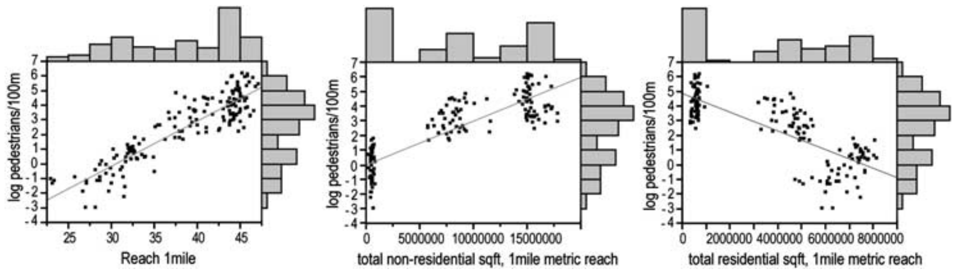

Figure 4: Scatter plots showing the natural log of pedestrians relativized by 100 m against metric reach (1-mile range) and total non-residential and residential building square feet at the metric reach scale.

It should be noted that, surprisingly, once the surroundings rather than the segment itself are considered, the signs of residential and non-residential land use variables are negative, which is contrary to *a priori* expectations. This is due to the negative effect size of residential square feet, which, when included in the same model with the non-residential land use variable, inverses the sign of the latter. When analyzed separately, the coefficient of non-residential density produces the expected positive sign.

When the scatter plots shown in Figure 4 are examined closely, a more precise picture emerges regarding the distribution of pedestrian density by street segment. Whereas street density (metric reach) is evenly distributed across areas, land use densities are strongly polarized. This finding implies that there are two distinct forces at play. Whereas street density varies proportionately with movement density at the street segment scale, the variation in land use density does not correspond to the variation in flow rates. In short, it can be concluded that when three areas are considered as a single set, the distribution of pedestrian movement is explained to a large extent by street density; yet this correlation is underpinned by the polarization of areas in terms of land use densities.

Analysis of individual areas

In order to better understand the distribution of pedestrians in each area, previous models were rerun by considering each area separately. The best-fitting regression equations were obtained for metric reach computed at the range of 1 mile, which is consistent with the results reported in section 'Analysis of the three areas as a single set'.

Table 3 presents the individual impacts of connectivity and land use variables on the distribution of movement in Downtown. Connectivity measures explain 28 per cent of the variation in pedestrian movement across all scales of land use measures. When the 'urban form' model is examined, land use variables add a marginal explanatory power of four–six per cent to the 'connectivity' model. However, land use variables did not enter as significant measures. Only the residential density coefficient is marginally significant at the metric reach scale (at a 95 per cent level of confidence).

More surprisingly, given the findings reported in section 'Analysis of the three areas as a single set', the coefficient of metric reach is statistically insignificant in all models. By contrast, the composite variable metric reach over directional distance at the 1-mile range is the most significant correlate of movement. Put simply, this is equivalent to saying that road segments that give more direct access to more surrounding streets draw greater volumes of pedestrians. In other words, the effect of street connectivity is based not on the mere density of connections, but also on the straightness of street alignment.

In Midtown, however, spatial variables *fail to correlate with pedestrian movement*, as shown in Table 4. Although the coefficient of the composite variable metric reach over directional distance is statistically significant (at a 95 per cent level of confidence) both at the road segment and buffer scales of land use measures, the coefficient for metric reach is significant (at a 99 per cent level of confidence) only at the buffer scale (in the case of total land use considered as a single variable). Land use variables, on the other hand, are the strongest correlates of movement across all models with consistently high significance levels (at a 99 per cent level of confidence). It would seem that the pedestrians observed in Midtown do not orient their movement according to the spatial structure of the area. This is surprising

Table 3: Multivariate regression for Downtown

Log of pedestrians/100 m	*Connectivity model*			*Urban form model*					
	Connectivity			*+Land use (aggregate)*			*+Land use (disaggregate)*		
	B	*t*	*std β*	*B*	*t*	*std β*	*B*	*t*	*std β*
Land use measured at street segment scale									
Metric reach (1 mile)	0.19	1.58	0.18	0.12	0.07	0.21	0.12	0.07	0.21
Metric reach (1 mile)/directional reach (1 mile, 10°)	**0.18**	**3.97**	**0.45**	**0.05**	**0.00**	**0.40**	**0.05**	**0.00**	**0.40**
Non-residential sq ft/100 m	—	—	—	—	—	—	0.00	0.07	0.21
Residential sq ft/100 m	—	—	—	—	—	—	—	—	—
Total sq ft/100 m	—	—	—	0.00	0.07	0.21	—	—	—
$N=61$									
R^2		**0.28**			**0.32**			**0.32**	
R^2 adjusted		**0.25**			**0.28**			**0.28**	
Land use measured at metric reach scale									
Constant	—	−1.33	—	—	0.23	—	5.70	0.04	0.00
Metric reach (1 mile)	0.19	1.52	0.18	0.12	0.11	0.19	*0.13*	*0.02*	*0.30*
Metric reach (1 mile)/directional reach (1 mile, 10°)	**0.18**	**3.97**	**0.45**	**0.05**	**0.00**	**0.45**	**0.05**	**0.00**	**0.36**
Non-residential sq ft (1 mile)	—	—	—	—	—	—	0.00	0.31	−0.11
Residential sq ft (1 mile)	—	—	—	—	—	—	*0.00*	*0.05*	*0.25*
Total sq ft (1 mile)	—	—	—	0.00	0.45	−0.09	—	—	—
$N=61$									
R^2		**0.28**			**0.28**			**0.34**	
R^2 adjusted		**0.25**			**0.24**			**0.29**	
Land use measured at 1-mile buffer scale									
Constant	—	−1.33	—	—	0.78	—	5.88	0.77	0.00
Metric reach (1 mile)	0.19	1.58	0.18	0.12	0.24	0.14	0.12	0.25	0.14
Metric reach (1 mile)/directional reach (1 mile, 10°)	**0.18**	**3.97**	**0.45**	**0.05**	**0.00**	**0.40**	**0.06**	**0.01**	**0.39**
Non-residential sq ft (1 mile)	—	—	—	—	—	—	0.00	0.11	−0.22
Residential sq ft (1 mile)	—	—	—	—	—	—	0.00	0.88	−0.02
Total sq ft (1 mile)	—	—	—	0.00	0.06	−0.22	—	—	—
$N=61$									
R^2		**0.28**			**0.32**			**0.32**	
R^2 adjusted		**0.25**			**0.28**			**0.27**	

Note: Numbers in bold = $P<0.01$; numbers in italics = $P<0.05$.

given the deliberate policies to create a pedestrian-friendly mixed-use environment. We interpret these results to imply that pedestrian movement is oriented to local attractors, whether they be high-rise residential buildings or various restaurants and bars, and has not yet become tuned to the larger surrounding fabric. Another factor that may help explain the results is the very uneven distribution of land uses and the still uneven development of the area, with extensive surface parking between new major construction projects.

In Virginia Highland, which has a relatively uniform and even pattern of land use dominated by residences, the relationship between movement and spatial variables is strong. Table 5 reveals that the 'connectivity' model explains 56 per cent of the variation in movement. Effect levels and significance levels indicate that metric reach over directional distance is the main factor associated with the distribution of movement. The coefficients for the composite connectivity variable are positive and statistically significant (at a 99 per cent level of confidence) across all scales of measuring land use. In fact, metric reach over directional distance has the highest relative effect size in all models. Land use density is statistically significant only at the buffer scale. The 'urban form' model adds a moderate explanatory power of five–seven per cent to the 'connectivity' model.

In conclusion, although metric reach is most strongly associated with movement when all data are merged into one set, a different picture emerges when areas are analyzed separately. In Downtown and in Virginia Highland, the distribution of movement is associated with the

Table 4: Multivariate regression for Midtown

Log of pedestrians/100 m	*Connectivity model*			*Urban form model*					
	Connectivity			*+Land use (aggregate)*			*+Land use (disaggregate)*		
	B	*t*	*std β*	*B*	*t*	*std β*	*B*	*t*	*std β*
Land use measured at street segment scale									
Constant	—	0.75	—	—	0.80	—	—	1.14	
Metric reach (1 mile)	0.11	1.68	0.27	*0.12*	*2.22*	*0.31*	0.10	1.74	0.26
Metric reach (1 mile)/directional reach (1 mile, 10°)	−0.17	−1.73	−0.28	*−0.21*	*−2.44*	*−0.34*	*−0.21*	*−2.47*	*−0.35*
Non-residential sq ft/100 m	—	—	—	—	—	—	**0.00**	**3.89**	**0.52**
Residential sq ft/100 m	—	—	—	—	—	—	0.00	−0.19	−0.03
Total sq ft/100 m	—	—	—	**0.00**	**3.78**	**0.50**	—	—	—
$N = 42$									
R^2		0.10			**0.35**			**0.37**	
R^2 adjusted		0.05			**0.29**			**0.30**	
Land use measured at metric reach scale									
Constant	—	0.75	—	2.60	1.01	0.00	13.30	3.39	0.00
Metric reach (1 mile)	0.11	1.68	0.27	0.13	1.94	0.34	−0.10	−1.11	−0.26
Metric reach (1 mile)/directional reach (1 mile, 10°)	−0.17	−1.73	−0.28	−0.16	−1.58	−0.26	−0.05	−0.51	−0.08
Non-residential sq ft (1 mile)	—	—	—	—	—	—	0.00	−0.39	−0.07
Residential sq ft (1 mile)	—	—	—	—	—	—	**0.00**	**−3.54**	**−0.73**
Total sq ft (1 mile)	—	—	—	0.00	−1.05	−0.18	—	—	—
$N = 42$									
R^2		0.10			0.12			**0.33**	
R^2 adjusted		0.05			0.06			**0.26**	
Land use measured at 1-mile buffer scale									
Constant	—	0.75	—	1.54	0.65	0.00	24.74	3.67	0.00
Metric reach (1 mile)	0.11	1.68	0.27	**0.23**	**2.76**	**0.59**	−0.25	−1.65	−0.64
Metric reach (1 mile)/directional reach (1 mile, 10°)	−0.17	−1.73	−0.28	*−0.22*	*−2.20*	*−0.35*	−0.11	−1.27	−0.18
Non-residential sq ft (1 mile)	—	—	—	—	—	—	0.00	−0.55	−0.13
Residential sq ft (1 mile)	—	—	—	—	—	—	**0.00**	**−4.10**	**−1.12**
Total sq ft (1 mile)	—	—	—	*0.00*	*−2.16*	*−0.43*	—	—	—
$N = 42$									
R^2		0.10			*0.20*			0.41	
R^2 adjusted		0.05			*0.13*			0.34	

Note: Numbers in bold = $P < 0.01$; numbers in italics = $P < 0.05$.

composite connectivity variable, which takes into account both street density and the shape and alignment of streets as indexed by the direction changes needed to navigate the system. Thus, in addition to street density, the manner in which streets are aligned and the direction changes needed to navigate the network also affect movement. This is consistent with findings reported in section 'Analytical framework'. In Midtown, the network plays a secondary role in explaining the distribution of pedestrians.

In terms of land use density, findings indicate that at the micro-scale (analysis of individual areas) land use variables become more significant once the surroundings rather than the segment itself are considered. The relative significance levels of non-residential, residential and total building square feet are higher at the metric reach and buffer scales in comparison with the road segment scale.

Discussion

The findings presented in this article confirm that the spatial structure of urban areas plays a significant role in the distribution of pedestrian movement on a street-by-street basis. The measures of metric and directional reach not only help compare one area with another, on average, but they also help discriminate between proximate road segments within the same area. Figure 5 shows the street networks of the three areas under consideration embedded within the surrounding

Table 5: Multivariate regression for Virginia Highland

Log of pedestrians/100 m	*Connectivity model*			*Urban form model*					
	Connectivity			*+Land use (aggregate)*			*+Land use (disaggregate)*		
	B	*t*	*std β*	*B*	*t*	*std β*	*B*	*t*	*std β*
Land use measured at street segment scale									
Constant	—	−4.06	—	—	−4.33	—	—	−3.82	—
Metric reach (1 mile)	0.09	1.68	0.23	*0.11*	*2.04*	*0.28*	0.10	1.83	0.25
Metric reach (1 mile)/directional reach (1 mile, 10°)	**0.23**	**4.21**	**0.57**	**0.19**	**3.14**	**0.47**	**0.18**	**2.96**	**0.44**
Non-residential sq ft/100 m	—	—	—	—	—	—	*0.00*	*2.11*	*0.23*
Residential sq ft/100 m	—	—	—	—	—	—	0.00	0.36	0.04
Total sq ft/100 m	—	—	—	0.00	1.42	0.15	—	—	—
$N=54$									
R^2		**0.56**			**0.58**			**0.60**	
R^2 adjusted		**0.54**			**0.55**			**0.56**	
Land use measured at metric reach scale									
Constant	—	−4.06	—	—	−2.93	—	—	−1.97	—
Metric reach (1 mile)	0.09	1.68	0.23	−0.09	−0.51	−0.22	−0.13	−0.73	−0.32
Metric reach (1 mile)/directional reach (1 mile, 10°)	**0.23**	**4.21**	**0.57**	**0.25**	**4.31**	**0.63**	**0.28**	**4.72**	**0.70**
Non-residential sq ft (1 mile)	—	—	—	—	—	—	0.00	−0.83	−0.09
Residential sq ft (1 mile)	—	—	—	—	—	—	0.00	1.20	0.47
Total sq ft (1 mile)	—	—	—	0.00	1.08	0.42			
$N=54$									
R^2		**0.56**			**0.57**			**0.60**	
R^2 adjusted		**0.54**			**0.54**			**0.56**	
Land use measured at 1-mile buffer scale									
Constant	—	−4.06	—	—	0.86	—	—	−0.40	—
Metric reach (1 mile)	0.09	1.68	0.23	0.04	0.82	0.11	0.05	0.87	0.12
Metric reach (1 mile)/directional reach (1 mile, 10°)	**0.23**	**4.21**	**0.57**	**0.29**	**5.22**	**0.71**	**0.28**	**5.15**	**0.70**
Non-residential sq ft (1 mile)	—	—	—	—	—	—	**0.00**	**−2.79**	**−0.27**
Residential sq ft (1 mile)	—	—	—	—	—	—	0.00	−0.30	−0.03
Total sq ft (1 mile)	—	—	—	**0.00**	**−2.82**	**−0.27**	—	—	—
$N=54$									
R^2		**0.56**			**0.62**			**0.63**	
R^2 adjusted		**0.54**			**0.60**			**0.60**	

Note: Numbers in bold $=P<0.01$; numbers in italics $=P<0.05$.

5 miles by a 5-mile grid, coded according to the composite variable metric reach over directional distance. Even in the absence of any other design information, such as street width, a hierarchy of streets emerges based on the intrinsic relational properties of the networks. Thus, appropriately discriminating measures of street connectivity capture aspects of urban structure that otherwise elude attention, or are treated as effects of other variables (for example, street classification and traffic volume). The analysis suggests that the spatial hierarchy, which is intrinsic to the street networks, is often expressed in functional effects such as the distribution of pedestrian movement. Thus, this article supports standard claims made in the space syntax literature.

The main contribution of this article, however, is the explicit consideration of land use. It has been shown that the structure of space revealed in Figure 5 does not work independently of land use. On the contrary, the preliminary benchmarking of the three areas suggests that development density is the key factor in setting expectations regarding pedestrian volume. The effect of spatial structure is not to determine pedestrian volume, but rather to explain how it is distributed. Intuitively, it seems plausible that even the local distribution of movement should be affected by land use. However, estimated linear models reported in section 'Analysis' suggest that the explanatory power accruing from the consideration of land use variables is limited. This is quite independent from the fact that, over time, land use itself is tuned to spatial structure. In modern city planning, this arises from the combined effects of zoning and subdivision regulations.

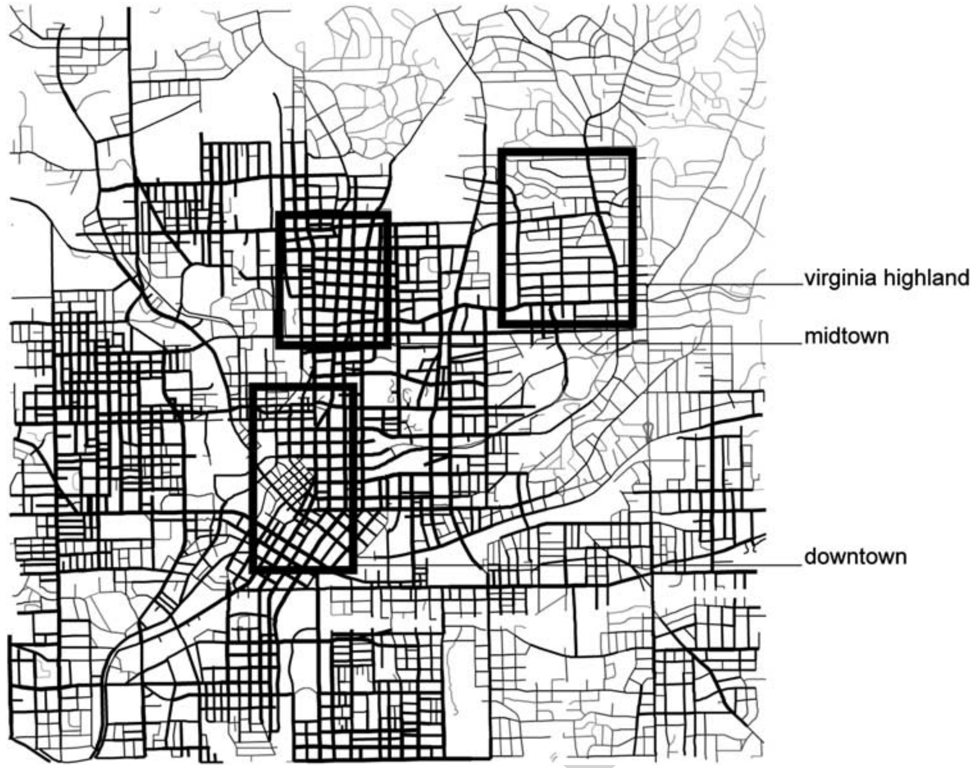

Figure 5: Selected areas embedded within a 5 mile by 5 mile extract of the street centerline map of Atlanta. The thickness of street lines is by 10 per cent percentiles, according to the composite variable metric reach (1-mile range) divided by directional distance (10° threshold).

In the long history of urban evolution, the spatial structure of streets acted as a relatively stable framework within which land uses changed and adjusted in course of time.

The results of this research can inform urban design decisions in creating new streets or realigning existing ones. The notion that street layout can and should serve planning aims has been recognized since the late 1920s and the 1930s. Perry (1929) advocated neighborhood streets that provide internal links but discourage through traffic; Stein (1957) proposed that streets should be specialized according to the spatial scale that they serve; and the Federal Housing Administration (1936) espoused neighborhood planning principles that incorporated these ideas. What have been missing are measures of street connectivity that can support decisions about street layout. The measures used in this research are useful in this context. They mediate between urban planning and urban design. Urban planning is oriented towards principles of general applicability and tends to be concerned with the average or aggregate properties of areas. Urban design must, by definition, address the fine grain of specific contexts. It is concerned with the internal structure of areas and with the way in which street layout impacts the nature, orientation and performance of building developments for which it provides the context. Walking is, after all, a pre-eminently context-dependent activity, one that occurs according to the fine grain of environment, as well as its larger scale structure. This is why we need enriched models of street layout and urban form in order to better design for walkability.

The fact that direction changes are as important as metric distance in describing street connectivity points to the role of cognitive factors. Traditional models of movement patterns are based on the consideration of distance and time, but they do not take into account the intelligibility of urban form. Integrating considerations of intelligibility can lead to enhanced models of urban form and function. Clearly, the key seems to reside in the measures used. The analysis presented in this article suggests that it is possible to incorporate measures of street density and measures of cognitively significant configurational variables in the same model of street connectivity in a manner that resonates with the more familiar techniques of space syntax.

The enhanced model of pedestrian movement has the obvious advantage that it can inform specific urban design and urban master planning decisions, precisely because it can discriminate between alternative street alignments and alternative street shapes in addition to being sensitive to the density of street connections. Furthermore, the model can mediate between urban design or master planning and architectural design. The urban situations of buildings and land uses that can be accommodated at ground level are sensitive to frontage and the character of the associated street. The model presented above can help evaluate the fit between building orientation, intended patterns of use and urban location.

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