Transportation Research Part A

Effects of built environment on walking at the neighbourhood scale. A new role for street networks by modelling their configurational accessibility?

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ABSTRACT

The hypothesis of this paper is that some features of the built environment, particularly those concerned with the accessibility of the street network, could be associated with the proportion of pedestrians on all trips (modal split) found in different parts of a city. Quantitative analysis (bi-variate correlation and a multiple regression model) was used to establish the association between variables. The study area covered a substantial part of the metropolitan area in Madrid, Spain. Results showed a consistent influence of five particular indexes in the multi-variate model. Not surprisingly for this kind of research, four of them described density and mix of land uses. But perhaps more interestingly, the first one was a measure of the accessibility of the public space network, a less prominent variable in literature to date. This variable is called herein configurational accessibility, calculated using Space Syntax, an urban morphology theory. The relevance of configurational accessibility is probably related to its surprising ability to synthesize global and perceived properties of street networks at the same time. The findings introduce the idea that the configuration of the urban grid can influence the proportion of pedestrians (as a part of total trips in any transport mode) who choose to walk on single-journey trips. The discussion links with the current debate about walkability indexes and the need of empirical support for the chosen variables and also with transport planning. Because the relevance of the street network's role is not so easy to grasp, inputs from configurational theory and the pedestrian potential underlying this fact are also discussed at the end of the paper.

1. Introduction

In the last two decades, walking has attracted increasing attention in urban mobility studies and policies due to its potential as a complementary strategy to deal with urban non-sustainability. Not by chance, transport policies are gradually shifting to include new objectives where walking can definitely play a role. Targets such as enhancing access to public transport, reducing the burden of transport costs on the family budget, preventing health problems by promoting active transportation or recovering the urban quality of cities, are now quite common.

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Regarding the last aspect, the relationship between pedestrian traffic and urban space, this is a crossroad for two disciplines, transport planning and urban design, a field where more empirical evidence is needed. Although it is clear that walking has surprising impacts on the city itself in the form of a series of positive “by-products”, these are yet to be properly understood. They seem to be partially due to some of the specificities of walking as a form of mobility; for example, the fact that pedestrians can easily take decisions on the fly or that, in addition, not being in a vehicle makes them freer to interact with other people or activities. As a result, pedestrians seem to activate or promote other phenomena in their surroundings. For example, they can enter a shop and buy something, and even prevent crime with their mere presence. A person on the move could therefore be assimilated to a small energy field that can produce positive changes to the environment he/she passes “through”. It is interesting to note that these effects increase exponentially when many of these “energy fields” merge on the main city streets or squares.

Again, as a peculiar form of mobility, walking does not only rely on dedicated infrastructure (e.g. pavements and crossings) or a vehicle, but is also highly dependent on the built environment (Krizek et al., 2009). In fact, built environment characteristics such as density or land use mix are more relevant for walking than for any other transport modes such as cars or even bicycles (Niemeier and Rutherford, 1994). Of course, it is not a simple relationship. Not in vain, even since early quantitative studies in the field such as LUTRAQ (1993), it has been clear that the pedestrian “friendliness” of urban environment is better described using no single but composite indices. Many have been proposed, probably the most pervasive being the “walkability” type (see for example, Frank et al., 2005, 2007). Most of them aim to be operative tools to evaluate and design walkable communities, even cities, in order to improve the chances of walking in modal choice (Southworth, 2005; Pozueta et al., 2009). However, as Maghelal and Capp (2011) conclude after analysing 25 of these indices most are yet to be validated for their measurement or aggregated effect on walking. Furthermore, it is not clear which variables should be included.

To date, transportation studies have scarcely considered the “Space Syntax” (SS) approach to accessibility, but it has been widely used in urban design. SS was conceived as a descriptive theory of spatial forms, starting from the configurational idea, but then applied to a number of disciplines. According to Hillier (1996), “configuration” is the degree of relationships that a spatial system allows amongst and through its elements. Thus, this is a particular form of accessibility, the accessibility provided by the network itself (i.e. how a street is connected to the rest of the network), before considering activities or opportunities. SS research has found that the configuration of the street network alone is closely related to the amount of pedestrian movement –traffic volumes– on streets. Evidence shows that configuration statistically determines how pedestrian flows are distributed within street networks, even without considering land uses (Penn and Turner, 2004, 83):

“Up to 80% of the variance in pedestrian and vehicular movement from space to space in urban areas can be explained by simple measures of the degree of ‘integration’ of the street segment”.

On the other hand, no references have been found in mobility or Space Syntax literature to whether configuration relates to the fact that people choose to walk instead of taking public transport or cars (i.e., specifically to modal split) and, therefore, to the walkability concept. This paper analyses this new factor, the “configurational accessibility” of Madrid in order further knowledge about the requirements of walkability.

According to this initial definition of the scope, the requirements of a walkable city, the main question addressed in the paper is an empirical one: is configurational accessibility statistically associated to the percentage of walking in all trips (i.e. modal split) in urban areas? Additionally, two more tentative questions are targeted: (i) if the previous one is true: why could this be so in relation to pedestrian needs? and finally (ii) what could be the implications of configuration accessibility for walkability, urban design and transport planning? In order to do this, the paper will proceed as follows: immediately, in Section 2, the background of the specific topic of the paper is briefly reviewed; in Section 3 the case study, data, spatial and statistical methods are described; after this, the results are presented (Section 4), while in Section 5, they are discussed at four levels; finally, the conclusions are established in Section 6.

2. Background

By controlling built environment factors, urban mobility and land use policies can be focused on reducing distances between home and other activities such as shops and work, or on managing particular design features relevant to pedestrians. However, these kinds of factors explain only partially trip generation in cities. They are what Ma and Banister (2006) call the physical dimension of the job-housing imbalance but, also according to these authors, the imbalance also has a major personal component, namely the characteristics of the individual or family (age, gender, race, income, motorisation rate, etc.), which are determinant for mobility. Moreover, Manaugh and El-Geneidy (2013) highlights the importance of a particular subset of these personal characteristics, what they call personal values, preferences and motivations of the individual. They show how values, preferences and motivations mediate amongst the object and subject characteristics and provide powerful arguments to understand how individuals take modal choices. This kind of approach is also related to a long-standing problem in the field, “self-selection” i.e., it is not the built environment that changes travel behaviour, but values and attitudes of the people living in them. However, recent studies such as Aditjandra et al. (2012) add evidence to discard self-selection, confirming the influence of the built environment on mobility, particularly neighbourhood mobility.

How has the particular influence of built environment in mobility itself been analysed up to now? Initially, built environment variables were confronted with mobility in an independent way. This proved to be a useful way to explore the major

relationships at the metropolitan scale, for example between density and energy consumption (e.g., the popular “Cities and automobile dependence” by Kenworthy and Newman), or even related specifically to the number of pedestrians trips per person (Niemeier and Rutherford, 1994). But increasingly, as the spatial scale diminished and detail grew, mobility studies have tended to include them in composite models aimed at describing pedestrian-friendly designs: i.e., already mentioned LUTRAQ model (1993), or Less Auto-Dependent Urban Form – LADUF model (Krizek, 2000) or, more recently, the Walkability indices also described in the introduction.

Many of those initial environment-mobility analysis found that land use factors have a pervasive influence on mobility, basically density and the mix of land uses. Frequently, these studies also considered a third quite broad factor, including “street network” (Handy et al., 1998), “urban design” or simply “design” (Cervero and Kockelman, 1997). However, several of them (Krizek, 2000; Greenwald and Boarnet, 2001; Schlossberg et al., 2006) showed that land use factors were more relevant than urban design in determining people’s modal choice and trip characteristics. Others (Cervero and Duncan, 2003; Frank et al., 2007) even found that what they call “micro-design variables” such as block size or intersection configuration exert an inconsistent influence on walking. In this paper it is argued that the underperformance of many of these third design factors is probably related to the fact that it still lacks a precise definition, often amalgamating several rather heterogeneous elements, from the perceived landscape (Cervero and Duncan, 2003) to the size of metropolitan areas (Banister et al., 1997; Giuliano et al., 2002).

More recently, the description of the design factors that affect mobility has been considerably enhanced by the use of Geographic Information Systems (GIS). This technology permits the measurement of geometric grid, block and street properties such as street density, intersection type, connectivity, etc., even at the scale of metropolitan areas. Two subsets of design descriptors can be identified within these studies: spatial structure descriptors, and perceived local descriptors. Since the latter are more difficult to quantify, the former are normally used as their proxies, although some are of debatable value.

Spatial structure factors can be based on area measurements (e.g. street network density) or can be more elaborated, using graph theory measurements, in fact an approach with a long tradition in transport studies. A planning-oriented example is the use of centrality to qualify nodes in urban transportation networks. Gonçalves et al. (2009) have applied this not only to transport network nodes but also to describe access to the surrounding urban area facilities, in order to compare the suitability of the area of influence of different train stations for new developments. A policy-planning oriented example is the use of parameters such as street connectivity by several North American administrations in new urban development review processes. A formulation of this factor is included in “LEED for Neighbourhood Development Rating System”, which is increasingly used to test the ability of the network of roads and pedestrian paths to support urban sustainability. However, in this case Stangl and Guinn (2011), has questioned its reliability by proving that its results could be easily skewed by using key “obstructions” in the network. They argue that more complex parameters are needed, and propose a new one based on route directness. Both examples suggest the convenience of re-testing and developing measurements from the graph theory to urban networks.

In fact, the above-mentioned Space Syntax approach is a particular type of graph theory measurement. Why can this type of approach be now more useful in transport studies than before? Broadly speaking, SS proposes fairly simple measurements of accessibility, but includes some refinements that could make the difference. In principle, SS accessibility descriptors are based on accessibility measures familiar to anyone working in transport modelling. Probably the most prominent one, “integration”, is basically the proximity of a visual line (similar to a street axis) to the rest of the lines of the network. Some sophistication is added in another similar SS measurement, “local integration”, the same idea of mean distance but calculating only to a specific local radius. Another one, “choice”, is a measure of betweenness, basically the number of shortest itineraries that pass through a particular line. So, what else? The tricky bit is to include “straightness” (i.e. minimising the number of turns) to calculate distances or itineraries. In other words, geometric distance/time is not the only impedance factor to be considered when selecting routes in urban grids, but also the number of turns. Why could this be so relevant? Studies have found that straightness seems to be related to the amount of information we use to navigate urban grids or, when pedestrians, to our perception of personal security in cities.² How does it work in term of cognition? One of the related SS measurements is called “Intelligibility” (Hillier, 1999). Can (2012), and stresses the relevance of this factor:

“Intelligibility is the relationship between global and local analysis. Therefore the whole can be deduced through composing the parts in the system. With intelligibility the concept of cognition is on the agenda. Lynch (1960) provides visual cognition by urban images; however Space Syntax does this by movement. Additionally, cognition of space through local and global information is important for complex urban areas. In order to perceive our environment and to find our way around, intelligibility of an area is *sine qua non*”.

While the cognition and perceptive factors lie beyond the scope of this paper, movement, also mentioned, is a central factor in our approach. Its use within Space Syntax helps to explain some of the strengths of walking as a transport mode and its effects in the urban environment such as the ability to resolve multipurpose destinations or the creation of urban vitality. This is also because SS theory is able to propose a different way of understanding the relationship between land uses and movement in cities.

² Several articles about SS can be found in the reference section. Especially informative texts for the interested reader are Hillier et al. (1993) and Penn et al. (1998) <http://discovery.ucl.ac.uk/14001/penn-hillier-banister-xu-1998.pdf> [Last accessed: 4 June 2014].

The consideration of multipurpose trips can help to understand this different relationship of land uses and street network accessibility. It is argued that to be useful and competitive, walking has to be able to resolve multipurpose destinations. In fact, many of the walking trips in the traditional city were not only about getting from A to B, but also about fulfilling other purposes “along the way”, and even for encountering and resolving unforeseen events.

On the other hand, it is clear that finding a sufficient set of possibilities on a route has to be an allowance of one of the requirements of a walkable city: proximity to an adequate mix of land uses. Yet this is not sufficient, the precise location of destinations also matters since walking has a very limited range: most trips are less than one mile. Therefore, it requires not only destination activities in close proximity but a highly “customised” – optimised pattern of places (Ho and Mulley, 2013).³

Curiously, there has been an “invisible hand” solution to solve this “sudoku” of fitting the (changing) needs of the routes of many citizens. Historically, cities “have done” this by adapting some land uses such as traditional retail and services to the patterns of pedestrian movement. In other words, retail and other activities which need passers-by have located themselves where pedestrians flows are bigger. This seems obvious but it is contrary to the gravitational idea after W. Alonso (i.e., activities attract trips), a major paradigm in transport planning. Hillier et al. (1993), Hillier (1999) have argued that a major part of these patterns of pedestrian movement, what they called “Natural Movement” is determined by the properties of the street network such as its connectivity or more precisely, to its configurational accessibility.

This means that configuration accessibility modulates movement through urban grids. And thus, it could influence the location of activities that would seek their best location according to their global or local hinterland. In this sense, it can be argued that itineraries with best configurational properties gather several important features for walkability, a promising but polyhedral concept (Frank et al., 2006).

Amongst walkability indices, a few have now become even popular in the U.S., e.g. Walkscore®.⁴ They are based on opportunity variables (e.g. access to basic services), a quite straightforward approach. However they are evolving and even permits the customised estimation of accessibility levels based on a suite of socio-economic and demographic attributes of the traveller (Páez et al., 2013). At the same time, other type of indexes and variables are being proposed, focusing more on connectivity. Manaugh and El-Geneidy (2011) compare the performance of four walkability indices, concluding that each of them suits different trip purposes, depending on the variables used. For example, those based on accessibility to basic services provide better results for retail trips, while those relying more on connectivity items perform the best for school trips. Regarding this issue, the question in this paper is whether configurational accessibility could be a relevant component for walkability indices or not.

On the other hand, there have been some applications of configurational accessibility to mobility studies, especially those by Dr. Peponis and colleagues, who implement new measurements that add more detail (down to the plot level) and look for a closer integration with land uses. For example, Ozbil et al. (2009) find that one of these new configurational indices is decisive for enhancing the description of the built environment and understanding its influence on the catchment areas of transit stations, Scoppa et al. (2009) successfully associate them with the way local automobile flows are distributed within local urban roads, and Ozbil et al. (2011), propose that the configurational approach could facilitate a link between urban planning (master plans) and traffic engineers (subdivision guidelines).

Returning to recent approaches and wider implications of walking, the distinction between “object requisites” and “personal needs” could be a useful one. A bold example can help to make the point: density is a “requirement” of a pedestrian friendly environment, but not a “need” of the pedestrians themselves, i.e. density is not a relevant argument in a person’s modal choice. In other words, most people do not choose to walk because a place is dense, but probably make that choice because dense places satisfy some of their needs as a pedestrian: density promotes proximity between origin and destination and could foster variety or introduce amusement.⁵

Hitherto in this paper, only the issues of the built environment (land uses, street network) and their requisites have been discussed. So, what about pedestrian needs?, what about personal motivations for walking?. These have been defined since Maslov’s work, and recently analysed further for pedestrians in a specific European RTD project, “Pedestrian Quality Needs-PQN”.⁶ In order to analyse them, a less comprehensive but perhaps more practical definition of pedestrian needs is used herein. According to Pozueta et al. (2009), contributing factors in the pedestrian decision can be classified into five groups: proximity, comfort, safety, security and attractiveness (Pozueta et al., 2009, 39–55).

The distinction between requisites and needs helps to refine some of the statements in Section 1.1, such as why walking relies not only on infrastructure but also on the built environment. Thus, it can be better understood that pedestrian infrastructure is important to fulfil certain pedestrian needs (for example, safety or comfort), while others (for example proximity, security or attractiveness) depend not so much on pavements, but on the environment, on how pedestrian-friendly buildings are or which land uses they house.

It is also suggested that this second group of needs, those depending not on pavements but on buildings, are key issues for promoting walking as a transportation alternative, both in its “stand alone” mode or as the last mile step.

³ Although the data in this paper only use single-purpose pedestrian trips, the characteristics of places were people found to chain multi purposes at a single destinations, remain a very interesting field for future research.

⁴ <http://www.walkscore.com/> [Last accessed: 25 March 2014] has become popular in the U.S. due to its blending with real estate market websites, in order to show walkable neighbourhoods, walkable urban places, etc.

⁵ For example, needs/requirement distinction can be useful for revisiting a well-known definition of pedestrian requirements: the 5Cs (convivial, convenient, connected, conspicuous and comfortable). Attending to this distinction, it can be argued that convivial and convenient cannot be defined as objective requirements, since they are subjective factors, needs. And this is why it is so difficult to use them as sound design criteria.

⁶ http://www.walkeurope.org/final_report/default.asp [Last accessed: 14 October 2013].

3. Case study and methodology

The case study was Madrid metropolitan area in Spain up to the M-50 ring road, an area of approximately 34×31 km ($106,313$ Ha) including the capital city and ten metropolitan municipalities, with a total of $4,132,820$ inhabitants (2004).⁷ This is roughly speaking 80% of the metropolitan area's population, living in quite a dense, mixed use spatial development (see Fig. 1). In order to test the hypothesis, the modal split and built environment characteristics were analysed at the level of transport zones and neighbourhoods.

Although a single geographic location, Madrid provides a wide range of urban environments encompassed in its evolution from an 11th century Moorish village to its present role as the capital city of Spain. Similarly, from the point of view of pedestrian mobility, Madrid can be regarded as a suitable case study. For several decades, walking rates have been decreasing gradually in the city. Still, Madrid and Spain as a whole have one of the economically developed world's highest proportions of pedestrians in the modal split, with the second highest walking rate amongst twelve OECD countries (OECD, 2012).⁸ For example, of all trips in Madrid's central core, 33.6% are on foot, rising to 42% in the other metropolitan municipalities (OMM, 2008). This remarkable proportion of walking trips evidences the maintenance of a considerable walking culture while there is also a solid transit culture (García and Gutierrez, 2007). It is suggested that this walking culture is not due to low motorisation or income levels,⁹ but to a denser, more pedestrian and transit-oriented built environment than similar cities in other countries.

3.1. Data sources, methods and spatial unit

Two main data sources were used to describe selected area mobility and land uses. The first one was the Regional Mobility Home-Based Survey 2004, the latest one available in Madrid, providing data on mobility habits, population, jobs and students. It was commissioned by the regional transit authority, and included more than 35,000 homes and 96,000 trip diaries. As usual in this type of data sets, trips refer to transport zones, and they are classified into internal and external trips, also stating if the trip was generated or attracted by the transport zone. The key mobility descriptor chosen for the study was the modal split, i.e., the percentage of walking trips in all modes. A second data source was the Regional Census of Economic Units, which describes the micro-location (i.e. x,y coordinates) and characteristics of retail and other economic activities in the Madrid region (i.e., activity type and number of jobs).

Basic spatial analysis was done using a Geographical Information System (GIS), while configurational accessibility calculations (Space Syntax methodology) were done using, "Depthmap" software.¹⁰

The data available from Regional Mobility Home-Based Survey did not include trip length, a shortage that posed a major methodological challenge in the analysis. Bearing in mind that the aim of the study was to analyse the influence of the built environment on the decision to walk, it was obvious that only trips in which the former could exert at least some influence on the choice had to be considered. In other words, for a 15 km trip nobody would even consider walking as an option, simply because is too time consuming, regardless of whether the environment was walkable or not. We therefore chose to only select trips within transport areas, requiring such areas whose size would not exceed a given "walkable" distance. Available size references were (i) mean trip length in several Spanish cities which, according to the OMM (2008), was 22.5 min or, approximately, 1000 m; (ii), up to a maximum of 8000 m (around 5 miles), used in a similar studies in the U.S. (Cervero and Duncan, 2003). Two basic kinds of spatial areas were eligible for the survey: transport zones and neighbourhoods. Transport zones have a relatively homogeneous population (around 7500 inhabitants), but vary greatly in size through the different metropolitan areas, larger in the periphery than in the city center, where development is denser. Thus, each Neighbourhood contains several transport zones in the metropolitan core but not in the periphery. In fact, Transport Zones in the periphery are similar in size to Neighbourhoods in the Central and 1st metropolitan ring (481 vs. 472 Ha), and both have a nearly identical hypothetical radius (1238 vs. 1226 m), slightly above the mean walking distance in Madrid (22.5 min or 1000 m) (see Tables 1 and 2).

Thus, in order to limit trip lengths similarly, the spatial unit had to differ according to its location in the metropolitan area: for those areas in the central core and the first metropolitan ring, neighbourhood was the selected reference unit, while the transport zone was used for those for the second metropolitan ring. This was considered to be a reliable way of removing longer trips for which walking would not be an option, although it meant overlooking a certain number of trips in the sample. Nevertheless, the number selected trips is considered representative: 76% of total pedestrian trips and 36.9% of trips in any transport mode were within the selected units, and could therefore be analysed. On the contrary, if transport zones were considered, only 40.3% of pedestrian trips would be within the reference area. A similar problem, that of avoiding short distances for which the car was an unlikely option (distances < 500 m), was addressed by removing neighbourhoods and transport zones smaller than 3.6 Ha. According to these criteria, finally 150 areas of these two different types, transport zones and neighbourhoods, were analysed.

⁷ Source: Instituto Estadístico de la Comunidad de Madrid.

⁸ In decreasing order, Switzerland, Spain, Austria, Germany, Sweden, France, Finland, Norway, Belgium, The Netherlands, New Zealand and United States, according to figures from different sources and years.

⁹ According to Eurostat, in 2007 the Madrid Region had a GDP per inhabitant of 136.8, compared to the EU-27 mean (100). http://epp.eurostat.ec.europa.eu/portal/page/portal/publications/regional_yearbook [Last accessed: 14 October 2013]. Madrid has a motorisation rate of 0.54 veh./inhabitant, well above the EU27 mean (0.46). http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/search_database [Last accessed: 14 October 2013].

¹⁰ www.spacesyntax.net/software/ucl-depthmap/ [Last accessed: 14 October 2013].

Fig. 1. Land use map of Madrid metropolitan area. Source: Visor Planea, Comunidad de Madrid <http://www.madrid.org/cartografia/visorCartografia/html/visor.htm>.

Table 1
Transport zone characteristics. Source: Regional Mobility Home-Based Survey, 2004.

Metropolitan location ^a		Inhabitants	Transport zones (#)	Mean values for transport zones		
				Inh./Area	Size (Ha)	Radius. (m)
1	Central Madrid	1,002,868	121	8288	30	310
2	1st Metropolitan ring	2,048,609	326	6284	122	624
3	2nd Metropolitan ring	2,210,402	298	7417	481	1238

^a (1) + (2) = Madrid municipality. (3) Other metropolitan municipalities.

Table 2
Neighbourhood characteristics (Madrid municipality). Source: Regional Mobility Home-Based Survey, 2004.

Metropolitan location	Inhabitants	Neighbourhood (#)	Mean values for neighbourhood		
			Inh./area	Size (Ha)	Radius (m)
Madrid municipality	3,051,477	128	23,840	472	1226

3.2. Statistical analysis

Bivariate correlation and multivariate analysis were used to test the hypothesis. Indices were selected according to literature and availability in the data. The dependent variable was the percentage of walking trips for each neighbourhood or transport zone (i.e., proportion of single journey pedestrian trips within the neighbourhood). Following the literature review, independent or predictor variables were arranged in three groups:

- (1) **Street Network**, including its *geometry* (line length, segment length, etc.) and its *configurational accessibility* (connectivity, integration, etc.).
- (2) **Land Use**, including *density* and *mix*.
- (3) **Other, non-built environment, variables**, i.e., socio-economic issues, which have a proven influence on the modal choice (age, car ownership) (see Table 3).

While most of these predictor variables are easy-to-grasp and come from transportation literature, a more careful description of Configurational accessibility variables (SN-A1 to SN-A5) could be useful, as they are less common in mobility studies. The starting point of the analysis for the Space Syntax method is the “axial map”, which basically draws the visual lines connecting all the streets and public spaces of the spatial system, in this case the metropolitan area of Madrid (Fig. 2).

Table 3
Candidate predictors.

		Predictor variables	Code
Street network	Geometry	Mean line length	SN-G1
		Mean line density	SN-G2
		Mean segment length	SN-G3
		% “cul de sac”	SN-G4
	Accessibility (config.)	Connectivity	SN-A1
		Radius N integration	SN-A2
		Radius 5 integration	SN-A3
		Radius 3 integration	SN-A4
		Intelligibility	SN-A5
	Land Use	Density	
		Residents/Ha	LU-D1
		Resid. + jobs + students at schools/Ha	LU-D2
		Retail food units/Ha	LU-D3
		Retail units/Ha	LU-D4
		Retail jobs/Ha	LU-D5
		Mix	
		Jobs/residents	LU-M1
		Retail units/residents	LU-M2
		Retail jobs/residents	LU-M3
		Retail food units/residents	LU-M4
Other			
	Distance to city centre (m)		OT-P1
	% Residents > 65		OT-S1
	% Residents 45–65		OT-S2
		Car ownership per dwelling	OT-S3

Table 4
Correlation study with dependent variable (% pedestrian trips).

	Predictor variables	<i>r</i>	<i>p</i>		Predictor variables	<i>r</i>	<i>p</i>
SN-G1	Mean line length	0.249781	0.0798	Sqr(LU-D3)	Retail food units/Ha	0.623918	0.0325
SN-G2	Mean line density	0.544974	0.2961	LU-D4	Retail units/Ha	0.449573	0.3208
SN-G3	Mean segment length	−0.24487	0.0021	LU-D5	Retail jobs/Ha	0.354163	0.0000
SN-G4	% “cul de sac”	−0.52549	0.3998	LU-M1 T	Jobs/residents	0.121267	0.0032
SN-A1	Connectivity	0.496847	0.0000	LU-M2 T	Retail units/residents	0.163694	0.0600
SN-A2	Radius N integration	0.562826	0.0000	LU-M3 T	Retail jobs/residents	0.089998	0.2654
1/SN-A3	Radius 5 integration	−0.69982	0.0000	LU-M4 T	Retail food units/Residents	0.489099	0.0064
SN-A4	Radius 3 integration	0.596969	0.0000	OT-P1	Distance to city centre (m)	−0.50882	0.0931
SN-A5	Intelligibility	0.310763	0.0818	OT-S1	% residents > 65	0.37557	0.2624
LU-D1	Residents/Ha	0.600306		OT-S2	% residents 45–65	0.27776	0.0000
Log (L-D2)	Resid. + jobs + students at schools/Ha	0.748079	0.0248	OT-S3	Car ownership per dwelling	−0.66017	0.2813

Thus, the axial map is a network graph containing visual lines and their relations, but having no information about, for example, land uses, rents or population.

A first simple measurement of these network relationships is the number of connections for each line, called “Connectivity” (SN-A1). Integration measures are a bit more elaborated and offer a range from measures of centrality for the whole system, such as “Radius-N integration” (SN-A2), to local centralities or sub centres, as in the case of “Radius-3 integration” (SN-A4).¹¹ They respond to the following general formulation:

$$\text{Radius N Integration} = 1/A_j \text{ with } A_j = \frac{\sum_{d=1}^N n_{dj} \cdot d}{\sum_{d=1}^N n_{dj}}$$

where

N = radius, from 2 to *n*.

A = asymmetry, or mean distance from *j*.

d = depth or distance measured as the number of changes of direction needed to travel between two street axis and *n_{dj}* the number of axis at a distance *d* from axis *j*.

Radius-3 integration is generally associated with smaller scale phenomena such as retail convenience stores (local activity), while Radius-N correlates with broader scale phenomena (global activity and long distance), such as CBD locations. An

¹¹ They are basically mean distance values. Radius-N integration is defined as the mean distance from visual line “j” to the rest of the lines in the axial map. Radius-3 integration is the mean distance from visual line “j” to the lines around it, up to “depth” 3. “Depth” is the particular way of measuring distances in the axial analysis of Space Syntax. It is defined as the least number of changes of direction when travelling from visual line “x” to visual line “y”.

Fig. 2. Axial map of Madrid showing the distribution of Radius-5 integration variable (SN-A3).

additional variable, “Radius-5 integration” (SN-A3), was selected to describe accessibility within a wider area, in this case similar to a district (in Madrid, approximately four times bigger than a neighbourhood). Finally, Intelligibility (SN-A5) the relationship between global and local information (i.e., to what extent local SN information – Connectivity- correlates with the global accessibility of the same street – Radius N integration), how local information available while walking reflects the position of the line in the system, was also included following SS literature. Additionally, a measurement of the geometric accessibility to the city centre found in some initial mobility-land use studies, “Distance from city centre” (OT-P1), was measured “as the crow flies” for this one, in order to compare its performance with that of the measures based on configurational analysis.^{12,13}

4. Results

The first statistical analysis was a correlation study between each of the independent (predictor) variables and the dependent one. Two types of transformations of the predictor variables were considered, aiming (a) to account for possible curvilinear associations and (b), to correct the “malfunctioning” of land use mix indexes. In the first case, mathematical transformations of the predictor variables were used according to the shape of the graph representing the association. The second case is a common problem in land use-mobility studies: how to measure the mix of land uses. Some authors have proposed statistical formulations (e.g., Dissimilarity indexes), while others –and herein– we have chosen simpler indices in the form of ratios relating, for example, jobs and residents or shops and residents. Considering its influence on pedestrians, previous evidence shows that for this second kind of indices, balance (i.e. mixed use developments), is the key rather than its maximum value (i.e. industrial states, retail centres) or the minimum (i.e. residential mono-functional areas). Therefore, the transformation for the mixed use variables used here aims to consider the mean value of each variable as the maximum (#1) and range the rest of the distribution between 0 and 1, regardless of whether they are bigger or smaller than mean value.

When $v \leq \bar{v}$, $v_T = v/\bar{v}$

When $v > \bar{v}$, $v_T = 1 - \frac{v - \bar{v}}{v_{\text{Max}} - \bar{v}}$

¹² One of the constraints of this method is precisely that, as noted before, the distance is measured with the property called “depth”, i.e., the number of changes of direction from “x” to “y”. Thus, neither geometry (m) nor time (min) is considered in the axial analysis. Although this has caused some debate about the method’s limitations (see for example Ratti, 2004), its validity for a far-reaching description of streets networks is firmly established according to the results of Space Syntax literature.

¹³ On the other hand, although some recent techniques for configurational analysis have overcome this limitation, e.g., “Segment and angular analysis” (Hillier, 2009) and similar measures developed by Peponis et al. (Ozbił et al., 2009), they were not applied in this study for practical reasons. Nevertheless, the “traditional” axial lines analysis can be considered perfectly valid for the purpose of this study, which was observe the relevance of the accessibility of the street network in comparison to land uses.

These transformations reflect better the associations of candidate predictors with the dependent variable in the following cases: SN-3, LU-D2, LU-D3 (curvilinear transformation); LU-M1, LU-M2, LU-M3 and LU-M4 (mean value transformation).

The results of the bi-variate correlation study show that Residents + jobs + students at schools/Ha (LU-D2), one of the indexes of the Density of the Land Use variable, was the best individual predictor for the percentage of walking trips. It yielded the best individual association ($R = 0.7481$, $p < 0.0001$) for all 22 indices considered in the study. The second best correlation ($R = 0.6998$, $p < 0.0001$) was the association with Radius 5 integration (SN-A3), which is a Street Network variable. The third one, was motorisation rate's (OT-S3), a Socioeconomic variable. Several other indices (OT-S2, LU-D3, LU-D1, SN-A4, SN-A2, SN-G2) obtained also a high level of association (>0.5).

However, some land use mix indices that had been transformed for the analysis (LU-M1 to LU-M4) got much poorer associations. Even so, still they are statistically significant at the 0.05 level and, moreover, the signs of these associations are now as expected (i.e. more land use mix meaning more pedestrians), something that did not happen with the previous untransformed versions.

Next step was to calculate correlations between predictor variables in order to prevent multi-collinearity (Table 5). Indices describing the same variable (e.g., Geometry, Accessibility, etc.) that showed a correlation higher than 0.5 were removed from the model and p -value was used to decide which one had to go. In this way, Connectivity (SN-A1), Radius N integration (SN-A2) and SN-A4 (Radius 3 integration), Residents/Ha (LU-D1), Retail jobs/Ha (LU-D5) and the percentage of residents aged 45–65 (OT-S2) were removed. Strong correlations were also found between two different variables: Street Network Accessibility and Land Use Density. However, one of the objectives of the paper was precisely to analyse the relationship between them. (cfr. discussion in Section 5).

Additionally, two variables with very high p -values (>0.7) in the multivariate model were also removed: Mean segment length (SN-G3) and Retail jobs/residents (LU-M3).

In this way, a multivariate analysis was fitted using 14 predictor variables, in order to account for the variance of the percentage of walking trips for each neighbourhood or transport zone (see Table 6).

The multivariate model yields an R -squared (adjusted) of 70.63% ($p < 0.0001$). Three of the indices included (SN-A3, LU-M1 and LU-M4) are significant at the 99% confidence interval and two more (LU-D2 and LU-D3) at the 95% level. Another four (SN-G1, SN-A5, LU-M2 and OT-P1) have a 90% statistical significance, and will also deserve some attention. The other five indices are not statistically significant to determine pedestrian modal choice, however they were kept in the model in order to be able to discuss some relevant socio-economics factors according to the literature, such as Age or Motorisation rate, in contrast with built environment factors.

The relative importance of the top indices was confirmed by the Beta coefficients, with Radius 5 integration (SN-A3) attaining both the highest Beta and the lowest p -value. This is the only index in the final model describing the Street Network variable. On the other hand, two out of the five most significant indices ones ($p < 0.05$) correspond to the Land Use Density variable (LU-D2, residents + job + students/Ha and LU-D3, specialised food units/Ha), while the remaining two account for Land Use Mix (LU-M4, specialised food units/Residents and LU-M1, Jobs/Residents). Therefore, these five indices form the core of the model.

The signs of these core indexes in the model are congruous with their urban meaning. All of them are positively associated with the increment in pedestrian modal share as hypothesised. The only negative sign is for Radius 5 integration, but this is only an apparent contradiction. It is due to the mathematical transformation used, the inverse, which means that the higher the value of this variable, the less accessible the neighbourhood is.

With less statistical significance, two of the indices in the 90% interval, are negatively associated with walking (SN-G1, Mean line length and OT-P1, Distance to the city centre), but they seem to have a plausible cause: for the first one, the longer the line, the less walkable the environment and for the second, obviously, there is more walking in the city centre than in peripheries. On the contrary another two indices, Intelligibility (SN-A5) and Retail units/residents (LU-M2), present negative signs, but these two will require a more careful analysis in the next section. The rest of the negative signs seem in some cases coherent and not in others. Notwithstanding they correspond to indices that either have a very low statistical significance, very small Beta coefficient, or both. They include the already mentioned socioeconomic variables (OT-S1, percentage of residents over 65 years old or OT-S3, motorisation rate), one of the Density indices (LU-D4, Retail units/Ha) and two of the Street Network Geometry descriptors (SN-G2, Mean line density and SN-G4, percentage of “cul de sac”).

The analysis of the correlations amongst estimates shows some multi-collinearity. It is just above the $r = 0.5$ threshold, and only for two cases: OT-S1 vs. OT-S3 ($r = -0.52$) and LU-D2 vs. SN-A3 ($r = 0.54$). The first one seem to make sense, more aged people, less motorisation rate; moreover, this is not so relevant for the model since both variables get a p -value > 0.05 . On the contrary, due to the importance of the involved variables in the second case (density and configuration), the VIF parameters for the indices in the model are also calculated (LU-D2 = 6.19; SN-A3 = 7.04). According to Hair et al., 2006, values higher than 5 and lower than 10 are acceptable and there is no need to discard any of the variables.

However, the association of both variables proves to be a complex one and, as seen before, it will be at the very centre of the discussion within the next chapter. In order to get more data for the discussion, a spatial association measurement, the Bi-variate Moran Scatter Plot, was used. This type of spatial interaction index based on cross-products, computes to what extent the value at a location for the first variable is correlated with the weighted average of the other variable, computed over the neighbouring locations (full interaction = 1, no interaction = 0) (see Fig. 4)

Table 5
Correlation matrix for predictor variables (*r*).

Row	SN-G1	SN-G2	SN-G3	SN-G4	SN-A1	SN-A2	1/(SN-A3)	SN-A4	SN-A5	LU-D1	Log (LU-D2)	Sqr (LU-D3)	LU-D4	LU-D5	LU-M1 T	LU-M2 T	LU-M3 T	LU-M4 T	OT-P1	OT-S1	OT-S2	OT-S3	
SN-G1	1.00	0.26	0.39	−0.20*	0.80	0.57	−0.60	0.76	0.63	0.38	0.37	0.29	0.64	0.68	0.17**	0.05**	0.32	0.17*	−0.32	0.26	0.25	−0.26	SN-G1
SN-G2		1.00	−0.43	−0.37	0.55	0.46	−0.63	0.63	0.37	0.62	0.67	0.60	0.59	0.48	0.03	0.16*	0.14*	0.29	−0.38	0.27	0.13	−0.39**	SN-G2
SN-G3			1.00	0.13**	0.08**	−0.08**	0.11**	−0.02**	0.18*	−0.21*	−0.28	−0.31	−0.03**	0.07**	0.13**	−0.23	0.03**	−0.31	0.24	−0.21	−0.14	0.25**	SN-G3
SN-G4				1.00	−0.37	−0.43	0.58	−0.48	−0.18*	−0.33	−0.46	−0.38	−0.31	−0.23	−0.07**	−0.14**	−0.09**	−0.28	0.36	−0.17*	−0.14	0.40**	SN-G4
SN-A1					1.00	0.75	−0.87	0.97	0.74	0.58	0.64	0.47	0.74	0.71	0.20*	0.13**	0.36	0.24	−0.52	0.45	0.38	−0.46	SN-A1
SN-A2						1.00	−0.80	0.78	0.60	0.57	0.68	0.57	0.70	0.68	0.27	0.28	0.45	0.41	−0.86	0.70	0.72	−0.68	SN-A2
1/(SN-A3)							1.00	−0.95	−0.62	−0.67	−0.81	−0.60	−0.68	−0.63	−0.12 **	−0.16 **	−0.26	−0.39	0.59	−0.50	−0.42	0.63	1/(SN-A3)
SN-A4								1.00	0.71	0.65	0.75	0.56	0.76	0.72	0.16**	0.14**	0.33	0.31	−0.56	0.48	0.39	−0.54	SN-A4
SN-A5									1.00	0.47	0.54	0.37	0.70	0.70	0.23	0.13**	0.42	0.06**	−0.46	0.35	0.31	−0.37	SN-A5
LU-D1										1.00	0.87	0.83	0.70	0.50	0.11**	0.29	0.14**	0.39	−0.53	0.49	0.36	−0.57	LU-D1
Log(LU-D2)											1.00	0.79	0.70	0.57	0.10**	0.24	0.19*	0.44	−0.62	0.55	0.42	−0.68	Log(LU-D2)
Sqr(LU-D3)												1.00	0.70	0.48	0.05**	0.41	0.18*	0.57	−0.57	0.55	0.39	−0.64	Sqr(LU-D3)
LU-D4													1.00	0.90	0.16**	0.25	0.46	0.28	−0.57	0.48	0.41	−0.47	LU-D4
LU-D5														1.00	0.22	0.17*	0.54	0.20*	−0.52	0.43	0.42	−0.37	LU-D5
LU-M1 T															1.00	0.03	0.43	0.01**	−0.30	0.22 **	0.35**	−0.09	LU-M1 T
LU-M2 T																1.00	0.46	0.30	−0.39	0.30	0.41	−0.18	LU-M2 T
LU-M3 T																	1.00	0.17*	−0.19	0.10	0.26**	0.04	LU-M3 T
LU-M4 T																		1.00	−0.41	0.39	0.31	−0.50	LU-M4 T
OT-P1																			1.00	−0.75	−0.77	0.65	OT-P1
OT-S1																				1.00	0.81	−0.64	OT-S1
OT-S2																					1.00	−0.50	OT-S2
OT-S3																						1.00	OT-S3

All the correlations are significant at the 0.01 level, except (*), significant at the 0.05 level and (**), less significant than 0.05 level.

Table 6

Results of the multiple regression analysis.

Parameter	Index	Estimate	Standard Error	T Statistic	P-Value	Beta	VIF
Dependent variable: R1 – Pedestrian modal choice, as % of trips using all transport modes							
CONSTANT		1.29507	0.276453	4.68459	0.0000		
SN-G1	Mean line length	−0.00010586	0.000059983	−1.76491	0.0798	−0.1339	2.683972
SN-G2	Mean line density	−0.00012054	0.00011494	−1.04877	0.2961	−0.0747	2.364384
SN-G4	% “cul de sac”	−0.00342983	0.00406111	−0.844554	0.3998	−0.0516	1.739547
1/(SN-A3)	Radius 5 integration	−1.501	0.318671	−4.71019	0.0000	−0.5786	7.038387
SN-A5	Intellegibility	−0.168327	0.0960078	−1.75326	0.0818	−0.1336	2.708559
Log (LU-D2)	Resid. + jobs + stud./Ha	0.0588842	0.0259477	2.26934	0.0248	0.2615	6.190915
Sqr (LU-D3)	Retail food units/Ha	0.128431	0.0594522	2.16023	0.0325	0.2148	4.612099
LU-D4	Retail units/Ha	−0.00335559	0.00336745	−0.996477	0.3208	−0.0989	4.593730
LU-M1 T	Jobs/residents	0.126475	0.0421177	3.00289	0.0032	0.1602	1.319106
LU-M2 T	Retail units/residents	−0.0953619	0.0502852	−1.89642	0.0600	−0.1117	1.610477
LU-M4 T	Retail food units/Res.	0.120667	0.0436087	2.76705	0.0064	0.1712	1.782842
OT-P1	Distance to city centre	−0.00000667	0.00000394579	−1.69111	0.0931	−0.1524	3.789156
OT-S1	% Residents > 65	−0.00288795	0.00256627	−1.12535	0.2624	−0.0969	3.457085
OT-S3	% Residents 45–65	−0.00247669	0.0022898	−1.08162	0.2813	−0.0987	3.879863
Source	Sum of squares	Df	Mean square	F-ratio	P-value		
Variance analysis							
Model	4.71983	14	0.337131	26.76	0		
Residual	1.71334	136	0.013603				
Total (Corr.)	6.43317	150					
R-squared = 73.3671%							
R-squared (adjusted for d.f.) = 70.6254%							
Standard Error of Est. =		0.112241					
Mean absolute error =		0.0852905					
Durbin-Watson statistic = 1.91799 (P = 0.3080)							
Lag 1 residual autocorrelation = 0.0368928							

According to Moran's test, the spatial interaction of variables means that configurational accessibility modifies the location of land use density (Land use as lagged variable, Moran = 0.5943) more than, vice versa, density modifies accessibility (Moran = 0.5764). However, the difference is really small and the test is not conclusive.

5. Discussion

The implications of these findings can be discussed at least at four levels.

5.1. Role of density and the mix of land uses factors

The results confirm the statistical association of density and mix of land uses variables with modal choice, as found in most studies in the literature review. In the fitted model, a substantial part of the indexes describes land uses, both their intensity and mix, with LU-D2, residents + job + students/Ha, being the most influential one. Although the association between density and pedestrian mobility was pervasive in the overall analysis, its behaviour was quite asymmetrical (see Fig. 3). A high pedestrian modal split was not found to be limited by the neighbourhood's low density, and indeed the opposite occurred: whenever the neighbourhood had a minimum density, the proportion of pedestrian trips never fell below a certain threshold. For example, not a single case amongst the neighbourhoods with more than 200 residents + jobs + students/Ha, had less than 60% of internal walking trips within the neighbourhood.

Not only density, but two other indexes representing specialised retail supply got relevance in the model. They are LU-D3, specialised food units/Ha, and LU-M4, specialised food units/Residents. Specialised shops included in both indices are a very precise type of retail trade, taken from the Spanish National Economic Activities Code (“CNAE”). It covers codes starting with #522 in this classification, including specialised shops selling food, fruit and vegetables, meat, fish, bakery, drinks, tobacco, and milk. Counter wise, it can also be said that no small corner or conveniences shops, bazaars, supermarkets or hypermarkets were included in this index nor in the final models (coded under #521), nor were pharmacies and others related to personal care (#523), fashion, home furnishing, electronics, newspapers or stationery (#524).

The fact that the latter types of shops are not represented in the model by a specific variable obviously means they are less important to generate pedestrian trips than specialised shops. But, of course, it does not imply they are not related to pedestrian activity. Their effect is probably represented by one of the other variables that do form part of the model. Initially, we thought that the major importance of specialised food shops was probably due to districts of Madrid where this traditional type of business has been maintained, such as the centre and more traditional peripheral areas. However, two age indices included in the model to test it (OT-S2 and OT-S3), got high p -values and, therefore, this idea is not confirmed by our analysis.

Fig. 3. Correlation of density (V4) and the proportion of walking trips (%).

Next we consider LU-M1 (Jobs/Residents), a long-standing index for job-housing balance used herein as a proxy of the mix of land uses. This ratio was transformed to represent the very idea of mix, so its mean value was converted into the highest one (=1) and any of the extremes of the distribution, into the minimum (=0). This was to represent that in such extremes, corresponding to either industrial states or residential mono-functional areas, walking choice tends to be very low. Although this transformation should deserve further analysis, the fact is that in this way the jobs-housing balance has entered into the model in a statistically significant way. And this was not the case in several previous attempts done with the untransformed version of the index jobs/residents in this kind of micro-scale analysis.

On the other hand, the Retail units/resident index (LU-M2), another proxy for the mix of land uses, has a negative sign in the model, something initially counterintuitive. It is true that its statistical significance is not as high as in the previous cases, but still in the 90% interval. In this case, the mean value for general shops/residents tended to be high because of concentrations at either gentrified city centres or suburban retail centres, and consequently there are no resident's pedestrian trips for shopping. This is something that rarely occurs with specialised food shops (always associated with housing), but could perfectly happen with these other types of retail.

5.2. Using accessibility vs. geometric and global vs. local factor to describe street networks

Most indices representing street networks such as street width, intersection or grid type, connectivity, etc., used to perform poorly in comparison to land uses, according to the literature review.¹⁴

For this reason and following the objectives of this study, particular attention was paid to the performance of two types of street network description, the local, *geometry variable* (commonly used in the past to describe street networks) and the either global or local *accessibility variable* (less common but a focus of this study). Best results were for the last type, in particular for Radius 5 integration index (i.e., mean distance to all the axis-streets up to 5 changes of direction).

Another remarkable result of the study is that the most influential index amongst Street Network descriptors is Radius 5 integration (SN-A3) and not any other of the Space Syntax indices. Unlike Connectivity, Radius 3 integration or Radius N integration, which are more commonly applied and discussed in the Space Syntax literature, this is an infrequent index. However results were clear: these three indexes showed less individual association with the percentage of pedestrian trips (Table 4) and also, in a previous model, they obtained weaker beta coefficients and *p*-values than Radius 5 integration. Connectivity (SN-A1) and Radius 3 (SN-A4) integration are normally associated with local phenomena, so following the previous argument, they do not add relevant information to other variables such as, for example, block length or street density. And, on the other extreme, Radius N integration (SN-A2) represents global configurational centrality in the system, in the metropolitan area. Again, according to our results, this factor is not as descriptive as Radius 5 integration, to explain pedestrian modal choice in each neighbourhood.

Finally, what happens with the other configurational index, Intelligibility (SN-A5)?, why does it get a negative sign? This index represents how perceivable information about the importance of the street (i.e. its number of connections) matches its

¹⁴ These more commonly used urban design indexes are termed "geometric" characteristics of the street network in order to differentiate them from the new "accessibility" sub-type, a focus of this study. In fact, configurational accessibility is a quite singular type since it measures accessibility only within the network, i.e., from one street to another, without considering the activities included in it (e.g. access to public transport or to shops, schools and parks).

Fig. 4. LISA Scatter plot with Moran's test for LU-D2 and SN-A3.

global importance in the street network system, i.e., its Radius N integration. Higher intelligibility makes street networks easier to understand and navigate. Although being relevant for visitors or newcomers, this factor is not so relevant (statistical significance, in the 90% interval) for residents in Madrid, since they have a good knowledge of the surrounding street network, independently whether it offers an accurate picture of the whole system or not.

However, the previous arguments would mean that not just perceived local factors but a mixture of local and global factors, a district-wide description (Radius 5 integration), is relevant in the case of walking. And walking has been traditionally regarded as a purely local issue. Why could this be so?

5.3. Configurational accessibility and pedestrian needs

Results herein suggest that in Madrid, configurational accessibility could be a requirement of a pedestrian-oriented environment. In other words, street networks with a high level of configurational accessibility (in this case represented by Radius 5 integration) fulfil one or more of people's needs when they are about to start a trip. Now, how can this type of accessibility relate to pedestrian needs?

It is argued that a high level of the Radius 5 integration index could meet at least three of the five pedestrian needs synthesized in [Pozueta et al. \(2009\)](#): distance, safety and attractiveness.

With regard to the latter two, seminal authors on the pedestrian behaviour such as Jane Jacobs, Holly White and Jan Gehl have argued that increased pedestrian flows improve the safety of sidewalks and the attractiveness of public space; i.e., as [Gehl \(1971\)](#) puts it, "people and human activity are the greatest objects of attention and interest". This is supported by the fact that Radius 5 integration (SN-A3) has got more influence in the model than Intelligibility (SN-A5), other of the configurational indices. It means that the influence of configuration in pedestrian modal choice it is clearly through the "Natural Movement" flows ([Hillier et al., 1993](#)); more precisely, through the attractiveness and safety provided by them.

But, how can configurational accessibility influence distances? Returning to the specificities of walking as a transport mode and the convenience of multipurpose trips, it has been said that literature on Space Syntax suggests that configurational variables may influence the concentration of activities that demand movement. In this study, the Moran test has shown a relevant level of spatial interaction of Radius 5 integration and Density (residents + jobs + student seats), meaning that the first could be influencing at least slightly the distribution of the second. Moreover, since only a very small number of activities (number of jobs, students, specialised shops for food, beverages, tobacco, etc.) were directly included in the final statistical models, the overwhelming importance of Radius 5 integration in the model could be due to its accounting for additional activities: it could bring in the influence of other such as different types of shops, facilities, workshops, consultations, etc., that benefit from the presence of pedestrians. This argument fits the idea of enriching and completing the vision of local centralities, usually too focused on commercial activities, too "retail-centric", as [Vaughan et al., 2010](#) put it. In fact, the description of different kinds of centralities and their benefits for urban sustainability is the core of Space Syntax approach ([Hillier, 2009](#)).

5.4. Improving the description, design and planning of street networks and walkable environments

It has been suggested elsewhere (e.g. Ståhle et al., 2005) and confirmed by the results herein, that the contribution of the configurational variable is to offer a citywide variable (even metropolitan) that, at the same time, can convey relevant local qualities of the built environment. According to this study, cognition–navigation factors are not so relevant in pedestrian modal choice as Natural movement enhancement is. However, some studies (Hillier and Lida, 2005) show that there is a close relationship between the configuration and the pedestrian's perception and movement through urban space. It can be recalled that some mobility studies pointed out the difficulty of integrating this kind of locally perceived qualities in city-wide models (Giuliano et al., 2002; Cervero and Duncan, 2003).

Therefore, in the field of transport planning, the configurational approach can fulfil the need for more precise modelling of local urban environments, at least in the conditions they have to serve pedestrian needs. Studies such as Scoppa et al. (2009) have shown that configurational variables are useful for modelling urban traffic conditions. Others have proposed them as a trip assignment tool for transport models (Baros et al., 2007). The software used to calculate configurational accessibility makes these indexes readily obtainable (cfr. Section 3) and the necessary data are fairly simple and easy to obtain (road centre lines).

This also links with the walkability indexes issue. We think that configurational accessibility would be relevant not only for the connectivity type of walkability indices (Manaugh and El-Geneidy, 2011) but also for the other type, for those indices describing accessibility to basic services. This is because our results point out that for pedestrians the access to opportunities depends not only in geometric distance but to a high degree in the configuration properties of the itinerary.

Finally, at an urban design scale, this new type of measurement facilitates the establishment of operative design parameters and tools, in between the scale of urban planning and urban design (Ståhle et al., 2005).

6. Conclusions

The results support the initial hypothesis: street network and built environment factors are clearly associated with the percentage of walking in urban areas. They also show the relevance of a hitherto infrequent variable in the field of mobility studies based on the Space Syntax theory, the *configurational accessibility of the street network*. In the case of the percentage of walking in all trips in the Madrid metropolitan area, this factor has even higher statistical relevance to much more widely used variables such as density and the mix of land uses.

In fact, Bi-variate study confirmed land use factors as individual predictors for the percentage of walking trips at the level of neighbourhood-transport zone. Then, a multiple regression model also supported it but, overall, showed that the one of the configurational accessibility characteristics (Radius 5 integration) was not only highly significant statistically, but even more influential than density or mix of land use factors. Finally, a spatial interaction index (Moran test), also suggested that configurational accessibility distribution could be modifying the location of activities (i.e. land use) at a small but significant level.

These results are of a different nature but seem coherent with studies which include configurational properties, such as Ozbil et al. (2011), who find that in Atlanta, density best explains the total volume of pedestrians, while configurational accessibility seems to account for their distribution on particular streets. They also concur with recent proposals such as Karimi et al. (2013), who assume a similar type of relationship between both variables in their Origin–Destination Weighted Choice Model for assessing the impact of new urban developments.

In summary, results support the need to continue research into the street network as a distinct component of the built environment. They show that the inclusion of configurational accessibility facilitates a better understanding of the street network, one of the urban design factors that influence pedestrian mobility. Improving the performance of previous local geometric indexes (e.g. # road density, intersection type, connectivity, etc.), they highlight the importance of the global dimension of the spatial system, which is a distinctive characteristic of configurational accessibility; i.e., the relationships amongst elements of the street network.

In a more tentative level, we argue that configurational accessibility is relevant to pedestrian needs because it makes the built environment (i) more attractive, (ii) safer and (iii) closer, by influencing and bringing together the location of shops and services, etc., in most heavily frequented spaces. In other words, the design of an appropriate street network configuration “can act” to insert multiple activities along people's routes, and thus shorten distances. Considering that distance, either real or perceived, is one of the most important barriers for travelling on foot, further study of the configurational aspect would be useful. It is suggested that the very idea of walkability should include not only the proximity of land uses to the residential area, but also how the urban network “arranges” these land uses in the micro scale, either improving or hindering proximity.

The fact that Radius 5 integration (and not Radius N integration nor Radius 3 integration) became the crucial accessibility factor in the analysis means that a sum of local and global accessibilities influences pedestrian modal choice and have to be considered in order to enrich walkable environments.

Finally, with regard to land use density and mix, three results have to be underlined. The best descriptor for density is Residents + job + students/Ha, not Residents/Ha alone. In the case of the mix of land uses, the results highlight the importance in Madrid of a special type of retail for animating walking: specialised shops selling food, fruit and vegetables, meat, fish, bakery, drinks, tobacco, and milk. Also, the jobs/resident ratio was found to be more important for the model than

hypothesised. It is argued that the reason for this could be the applied transformation of the variable, taking the mean value as the maximum and the extremes (industrial estates and mono-functional residential areas) as minimums.

Future research should be conducted to test the inclusion of the configurational variable in traffic models, as a proxy for demand explanatory factors at the local level, as well as in walkability indexes as a synthetic measure of the quality of the itinerary.

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