NETWORK GEOGRAPHY AND ACCESSIBILITY

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1. INTRODUCTION

In “Network, network, network: pedestrian movement analysis and activities”, Wedderburn and Chiaradia (2013) reviewed key aspects of pedestrian behaviour, pedestrian route choice, pedestrian network types and characteristics, and the identification of an array of pedestrians and activities models used at different spatial scale. It was proposed that pedestrian movement analysis can be organised in three different levels, from strategic to tactical that are complementary (See Table 1).

Table 1: Three levels of pedestrian movement analysis

	Multivariate analysis	**Assignment modelling**	**Micro-simulation**
Purpose	Establish a statistical link between network configuration and movement	Incorporate pedestrian movement into a traditional transport modelling and evaluation framework	Understand pedestrian comfort and safety at a detailed level
Role in the design process	Option generation and testing	Planning, feasibility, appraisal	Detailed planning and design
Spatial Scale	Large urban area or neighbourhood wide	Large urban area or neighbourhood wide	Junction, individual station (interchange node), individual place
Method	Calculation of the statistical relationship between activity density distribution and network Calculation of potential movement	Calculation of change in trip production / attraction Pedestrian route assignment model	Simulation of pedestrian movement and interaction Calculation of density measurements
Cost	Low	Medium	High
Information cost	Low	Medium	High
Level of operation	Strategic	Strategic to tactical	Tactical

The following diagrams present the approximate nesting of the spatial scales of the above table.

Figure 1. The nested spatial scales of pedestrian movement analysis.

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Node and/or Place in wider context walking trip

Access to and from Node and/or Place

Junction, Node and/or Place interchange

While assignment and micro-simulation modelling are well charted in the literature and better known by the transport practitioner community, the use of multivariate analysis using spatial network design analysis for modelling pedestrian movement and its grounding in the transport discipline remains to be made explicit. The following sections aim to revisit a study using space syntax, which is idiosyncratic in both its use of non-standard network codification using axial lines and ‘accessibility on network’ measures. This previous approach does not explicitly acknowledge prior definitions of ‘accessibility on network’ in transport studies, and thus, was not grounded in transport studies. This article re-analysis a previous space syntax study and ground such analysis in the transport and geography disciplines.

2. CIRCULAR CAUSATION BETWEEN LAND USE, TRANSPORT AND ACCESSIBILITY

It is generally recognized that land use patterns and transportation patterns are closely related to each other through change in accessibility. The spatial organization of human activities creates a patterns of personal travel and goods transport, and thus influences the mobility behaviour of actors such as households and firms. Conversely the availability of infrastructure makes certain locations more or less accessible. The impact of transport on land use is well recognized (Hansen, 1959; Banister, 1995; Wegener & Furst, 1999; Giuliano, 2004; Geurs & van Wee, 2004; Borzachiello, et al., 2010; Banister, 2012).

While new transport infrastructure can change accessibility instantaneously, land uses inertia, information costs, long investment cycles, land use redistribution produces a lag in the exploitation of these accessibility changes. Exactly how developments in the transport system influence the locational behaviour of landowners, investors, firms, and households is less clearly understood. In addition to market forces, this influence is also mediated by planning regulation.

The idea of the “land use transport feedback cycle” (Giuliano, 2004; Meyer & Miller, 2001; Wegener & Furst, 1999) is often used to illustrate the complex relationship between land use, transport and change in accessibility. In this cycle, land use and accessibility patterns both influence each other. Land use patterns are partly conditional upon accessibility advantage, the locational sorting of human activities such as living, working, shopping, education, and leisure, etc. The distribution of human activities reflects the different requirements and competition for accessibility advantage. By overcoming the distance between the locations where these activities take place, the transport system changes the pattern of accessibility, by enabling different level of ease of movement. Conversely, the increase and clustering of activities can create new travel demand and, consequently, a need for transportation services, whether in the form of new infrastructure or more efficient operation of existing facilities which in turn change accessibility. The resulting increase in accessibility would then co-determine the location decisions of landowners, investors, households and firms, and so result in changes of the land use. This starts the cycle again. This process continues until a (provisional) equilibrium is reached or until some external factor intervenes (Meyer & Miller, 2001). Key to understanding the cycle is understanding change in accessibility and the co-variation of land use in a process akin to circular causation between accessibility level, urban form and travel.

In a recent meta-analysis of more than 200 studies on the built environment-travel behaviour relationship, Ewing and Cervero (2010) found that of all of the built environment variables considered, no individual variable has a significant impact on that relationship. Still, the combined effect of several such variables on travel could be quite large. Consistent with prior work, it was found that vehicle distance travelled is most strongly related to the measures of accessibility to destinations and secondarily to the street network design variables; walking is most strongly related to the measures of land use diversity, intersection density, an implicit measure of urban block size and shape, and the number of destinations within walking distance; bus and metro-train use are equally related to proximity to public transport access point and street network design variables, with land use diversity being a secondary factor. The study does not make an attempt to assess the accessibility evaluation methods used. Surprisingly, population and job densities were found to be only weakly associated with travel behaviour once these other variables are controlled for.

For pedestrians, we can identify a set of key indicators relating urban form and travel: urban block size (design), non-residential land use location and clustering (diversity, destination) and accessibility to opportunities (opportunities as destination and public transport service point locations). .

The remainder of the paper is organised as follows:

- Section 3 gives a brief outline of the various definitions of accessibility and the problems associated with deploying area-based spatial unit of accessibility analysis in relation to active mode of transport and urban design requirements.
- Section 4 describes the relationship between network density, population and job density. It describes an empirical testing of the relationship between accessibility index on network and pedestrian and vehicular traffic in four areas in London.
- Finally, Section 5 discusses the results.

3. ACCESSIBILITY AND SPATIAL UNIT OF ACCESSIBILITY ANALYSIS

The history of transport network layout analysis is very old. Euler in 1736 solved analytically the “first traveling salesman problem” for Konigsberg, inventing at once network codification, graph theory and transport network analysis (Coupy, 1851) and showing that network layout can make certain travel pattern impossible. In this section we briefly review accessibility analysis and the spatial unit used. Accessibility is grounded in transport analysis, we trace briefly the genealogy of accessibility indices and to what extent they relate to Social Network Analysis centrality indices.

In the past decades, various definitions of accessibility as well as indicators have been developed and used to describe spatial accessibility (Reggiani, 1998; Geurs & van Eck, 2001; Geurs & van Wee, 2004; Vega, 2012) which, according to Pooler (1995), are mostly derived from the seminal work of Hansen (1959) and other early pioneers of “mean shortest path length” as in Christaller (1933-1966) and Reilly (1931). Over time, the concept and indicators of ‘accessibility’ have been redefined with increasing sophistication to match the endless complexities of human spatial behaviour in places and time (Hagerstrand, 1970; Kwan, 1998; Kwan & Weber, 2003).

Hansen defined ‘accessibility’ as “the potential of opportunities for interaction”. More precisely, Hansen defined that “the accessibility at area A to a particular type of activity at area 1 (say employment) is directly proportional to the size of the activity at area 1 (number of jobs) and inversely proportional to some function of the distance separating area A from area 1. The total accessibility to employment at Area A is the summation of the accessibility to each of the individual areas (1 to n) around area A.” The accessibility at location A varies directly with the sizes of the other locations (1 to n), and inversely with the spatial separation between A and (1 to n).

Size is measured with respect to quantities such as employment, retail floor area, population, retail sales, etc., while spatial separation is measured with respect to distance, travel cost, travel time and other similar spatial metrics variables. The alternative to Hansen’s weighted version of accessibility (type 1) is an unweighted accessibility measure (type 2) which omits the size variable (Ingram, 1971). This focuses on the spatial separation variable (Pooler, 1995). Spatial separation is easy to understand and calculate. This is of particular interest in intra-urban situation to disentangle the role of accessibility in the potential for interaction between land use diversity and intensity which are thickly and continuously intertwined with transport service access points.

In the literature, most accessibility measures use an area-based spatial unit, like the Transport Area Zone (TAZ) or other area-based spatial unit of analysis, which are all afflicted with the well-known Multiple Area Unit Problem (MAUP) (Viegas, et al., 2009; Openshaw & Taylor, 1979; Miller, 1999; Kukadia & Zhang, 2005). MAUP is a major problem in itself, which is compounded by the use of the very abstract ‘as-the-crow-flies’ network link codification. This combination cannot be used for pedestrian modelling nor urban design place making, as any zonal area definition is far too coarse to be meaningful. While smaller regular area-based grids have been proposed, they are still too coarse to account for the continuous experience of active mode of transport (Iacono, et al., 2010) and the necessity of both qualitative and/or quantitative primary or secondary attributes that will needed to be related to active mode of transport. (Handy, 1996; Lin & Moudon , 2010; Parks & Schofer, 2006; Lee & Moudon , 2006; Handy & Saelens, 2008). The only realistic alternative to area-based spatial unit is to use accessibility analysis of detailed transport network using standard link-node codification.

Standard detailed transport network codification such as Ordnance Survey (OS) Integrated Transport Network (ITN) or OS Open Data Meridian^{TM} 2 already exist. As the modelling of active modes of travel become mainstream (e.g. Wales Active Travel Act, 2013), standard codification of pedestrian networks will be required for quality control at the different stages of decision making and design processes. Accessibility indices on physical network have existed since the 1950s. Shimbel (1953) defined accessibility *on* network (via link-node codification), defining the concept of “dispersion” as farness or eccentricity, based on the measure of ‘unweighted mean shortest path length’. Since accessibility is the inverse of dispersion, Shimbel’s accessibility corresponds to closeness centrality found in Social Network Analysis (Bavelas, 1950).

Shimbel also defined ‘stress’ as ‘the resulting flow potential on the link’ which measures the number of shortest paths that pass through a link. In the contemporary vocabulary ‘stress’ is also called “path overlap level” or “betweenness centrality” also used in Social Network Analysis (Freeman, 1977). Shimbel’s network accessibility indices were cited and elaborated in Kanski’s work (1963). In the 1970s, Haggett and Chorley (1969) provided an extensive review of applications of ‘on network’ measures of accessibility. Pooler (1993) defined motorised trip distribution associated with the minimum value of the mean shortest path as the “structural spatial interaction”. More recently a number of transport research studies have demonstrated the fruitfulness of such a network-based accessibility approach (Cutini, 2001; Newman, et al., 2006; Porta, et al., 2006; Levinson & Bhanu, 2005; Levinson & Xie, 2009; Levinson & Xie, 2009; Levinson, et al., 2007; Xie & Levinson, 2007).

Bovy and Stern (1990) reported on a single minimum path model study (1981) for motorised trips where mean shortest path calculation were performed for the entire city road network without any restriction or omission. The predicted routes were then compared with the observed routes choice. On average the overlap between observed and predicted routes was 60%: that is nearly 60% of the length of observed routes was predicted correctly. Bovy and Stern remarked that despite its simplicity, this model gives useful results. These results should not be misunderstood that mean shortest path of a particular metric is thus a major choice criterion: the shortest path can also be the safe path, or otherwise the shortest path may be identical to other optimal paths according to other criteria.

Figure 1: Example of path between the same origin (top) and destination (bottom) according to four different shortest path metrics.

The fastest path (time)	The shortest path (length)
	

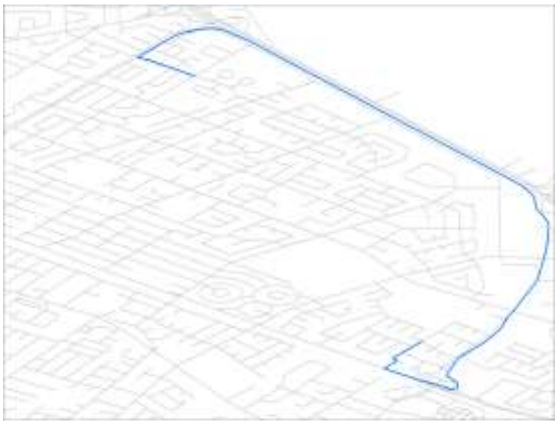
The path with fewest turns	The path with fewest intersections (via motorway and merging)
	

Figure 3. Illustration of stress, path overlap or betweenness centrality between shortest metrics

Different shortest path overlap on different part of the network: path overlap is a flow measure


‘Betweenness centrality’ can be interpreted in traffic assignment as the flow resulting from all trips between origin-destination (O-D) pairs assigned to a single optimal route: the shortest path. The shortest path can have different metrics related to route choice preferences and labelled as such: fastest route (time), shortest route (length), fewest turn (least angular) or fewest intersections (junction density) (See Figures 4 – 6 above). These different accessibility metrics can be calculated for all O-D pairs to establish the accessibility geography of the network and the betweenness centrality, the flow potential on a network link resulting from shortest path interactions (Figure 7).

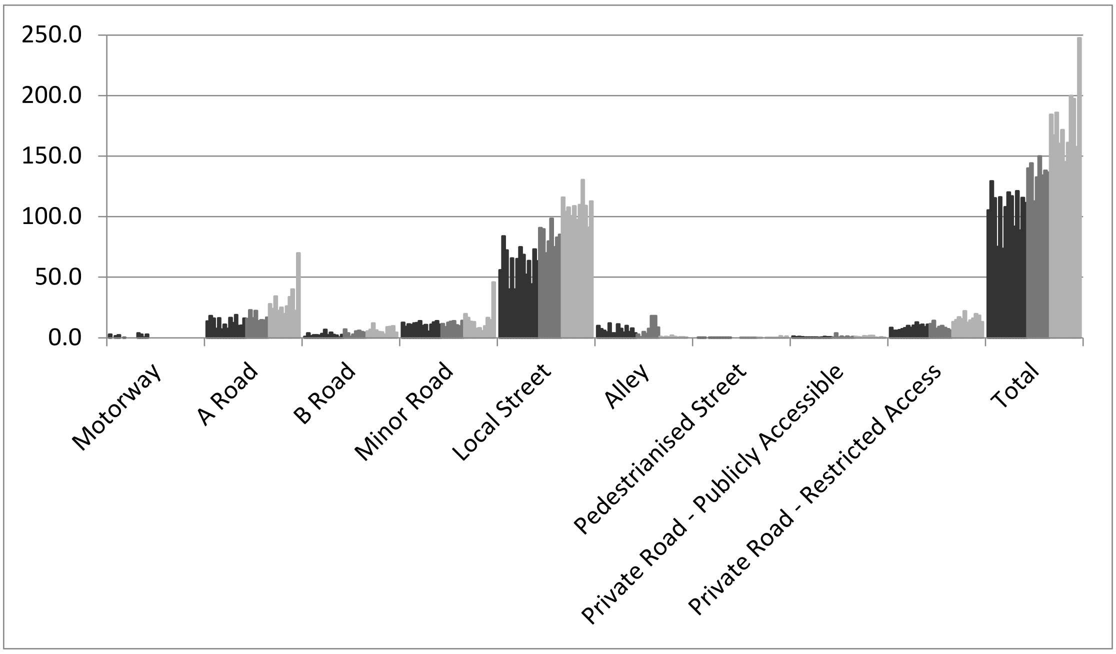
In the next section we analyse the network density geography of London in relationship to population and workplace density. We also analyse the accessibility measure of four areas in London with accessibility on network indices updated from Shimbel (1953) and empirically test their relationship with pedestrian and car cordon counts in those four areas.

4. NETWORK GEOGRAPHY AND ACCESSIBILITY

4.1. The relationship between network density and population and workplace density in London

The London borough boundaries have been used to cut out the corresponding part of the ITN, and each link length has been recalculated. For each borough, the length of the network for each category of road has been displayed and related to the borough area. Network length and area allow determination of the network density, the metres of network per population (number of residents, census 2011), the jobs (workplaces, GLA 2011) and the ‘population plus jobs’ (Figures 4–6). To retain a sense of the London geography, the graph bars of Figures 4–6 have been organised spatially progressing from the outer London boroughs to central London. The left of the graph starts bar in black with the outer London borough of Enfield to the north, the graph progress with Borough going clockwise, east, with Waltham Forest, Redbridge, Havering, Bexley, then south, west and returning north to Barnet. Next, the graph displays in dark grey boroughs that are between the outer boroughs and the central borough: starting with Haringey, Newham, Barking, Greenwich, Lewisham, Merton, Ealing and Brent, moving to the central boroughs displaying in light grey Islington, Hackney, Tower Hamlets, Southwark, Lambeth, Wandsworth, Hammersmith, Kensington, Westminster and Camden and ending with the City of London. The outer ring is coloured in black, the middle ring in dark grey and the central ring in light grey. These heuristics are not exact, but they summarise much of the spatial information, permit spatial consistency and enable consistent investigation. Figure 4 shows for all of the London boroughs the link length category per hectare.

Figure 4: London boroughs (33) – link length (m) according to categories per hectare (10 000 m2). Dark grey outer ring, mid-grey middle ring, light grey inner London



The trend is very clear for most categories in relative terms: the total link length increases from the outer to the central boroughs. The inner ring boroughs have more network than elsewhere. As a category, the local streets, or the residential streets, dominate. Figure 5 shows the jobs available for all London boroughs while controlling for population.

Figure 5: London boroughs (33) – link length ratios. Black outer ring, dark grey middle ring, light grey inner London

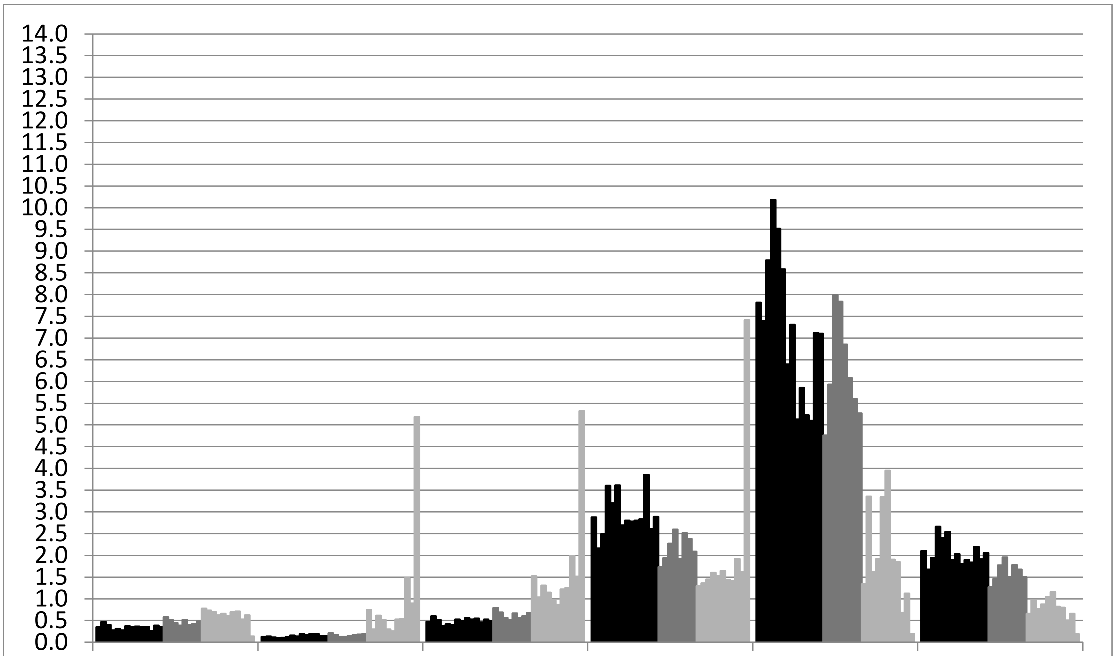


Figure 6: London boroughs (33) – link length ratios. Black outer ring, dark grey middle ring, light grey inner London

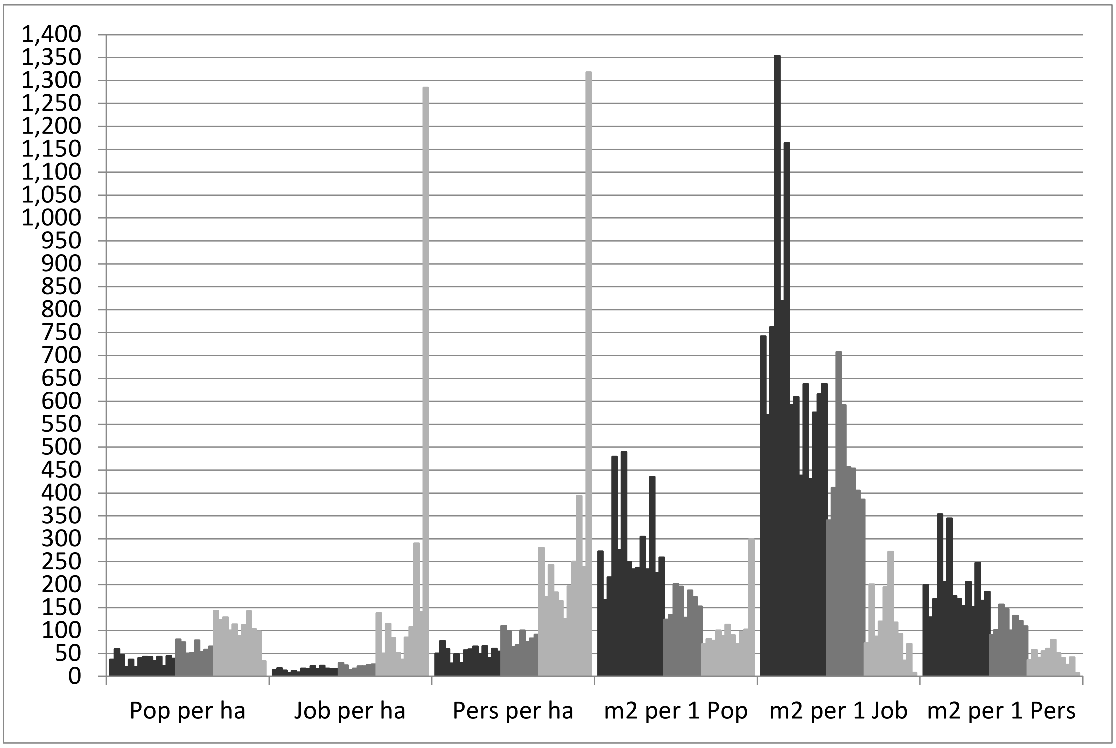


Figure 5 also shows the ‘population plus jobs’, the relationship to the 1 m of network; the pattern found in Figure 4 is reversed. The network is most ‘efficient’, or intensively put to use, by serving the combined highest population and jobs, at locations closest to the centre of London. The same calculation in relation to 1 ha (Figure 6) reveals that the pattern is very similar.

The two patterns have been regressed and the linkages are very strong (r^2 = 0.99, for population plus jobs, r^2 = 0.92 for population, r^2 = 0.99 for jobs) with a very high significance ($p<0.0001$). This association shows that, whereas the network characteristics differ among outer, middle and central London, at an aggregated level, there is a consistent relationship between the network density and the population and jobs. The network density is a good proxy for the ‘resident plus job’ density. In other words, if we were to calculate weighted accessibility using the London Boroughs as zones weighted by population and job density, it would be almost equivalent to calculate weighted accessibility with network density. If we were to calculate non-weighted network accessibility using the link at the spatial unit, the link density which is also highly correlated to link length (r^2 = 0.96, $p<0.0001$) would be acting as the weighting for population and job density. These relationships have so far been overlooked in most studies using an ‘accessibility on network’ approach, yet could have been the explanatory variable in some of them. This high-level aggregated relationship could disappear at lower spatial scales (MAUP); confirming this would require to be investigated in more detail. However, as shown above, there is no good area-based density measure that would avoid the MAUP for pedestrian modelling. So the question to investigate would instead be how the set of key indicators of urban form and walking relate to ‘accessibility on network’. As a preamble to such study, in the next section, we use accessibility measures on the OS OpenData Meridian to investigate their relationship with vehicular and pedestrian counts in four areas in London.

4.2. The relationship between network accessibility and vehicular and pedestrian counts in four areas in London.

Two of the four areas are in the London Borough of Islington - Barnsbury and Clerkenwell. The South Kensington area is in the Royal Borough of Kensington and Chelsea and the last one, Brompton, is in the City of Westminster. The four areas as well as the observation methodology and data have been previously presented elsewhere (Penn, et al., 1998). The analysis in that study was conducted using space syntax, which is idiosyncratic in both its use of non-standard network codification using axial lines and ‘accessibility on network’ measures. This approach does not explicitly acknowledge prior definitions of ‘accessibility on network’ in transport studies, and thus, was not grounded in transport studies. Indeed, the article dismissed the possibility of using standard network codification in favour of space syntax. The additional and original contribution of the present study is to reanalyse the dataset using standard network codification, thus both demonstrating the possibility of using the standard codification and connecting these findings back to the standard practices in transport studies. This opens up the potential to mainstream the use of multivariate analysis using spatial network design analysis for ‘active mode of transport modelling’ within transport studies at its interface with urban design. The following discussion focuses on the methodology and results of this re-analysis.

The network codification used is the OS OpenData Meridian. This is free to use both commercially and non-commercially under the terms of the OS OpenData license. The spatial units of the accessibility analysis are the links defined as the connection between two adjacent junctions, or between a junction and a dead end. The link is defined by its length, its slope and its curvature: the total angular change along its length. The junction between two links is characterised by the angle of incidence between the links. Another key component of the analysis is to consider specific subset of origin-destination pairs that can be reached from the link analysed within different time budget, expressed in metres. We use the accessibility metric of least angular path analysis. This means that shortest path are chosen based on minimizing the angular change – i.e., the cumulative angle turned on links and at junctions between OD - rather than minimizing the Euclidean distance travelled. Angular analysis is reflecting the cognitive difficulty inherent in navigating (Hill, 1982; Verlander & Heydecker, 1997).

4.2.1. Mean Angular Distance (MAD)

MAD is defined as the mean (averaged per link) of the angular distance from each origin link to each possible destination falling within the network radius of the origin. It is an accessibility measure, in that lower values of MAD indicate straighter paths to destinations within the radius. Thus,

$$\boldsymbol{SAD}(\boldsymbol{x}) = \sum_{y \in \mathbf{Rx}} \mathrm{d}_\theta(\mathrm{x}, \mathrm{y})\, \mathrm{P}(y)$$

Where SAD(x) is the SAD for link x, $\boldsymbol{y} \in \mathbf{Rx}$ is each other link y in Rx the radius surrounding x, $\mathrm{d}_\theta(\mathrm{x}, \mathrm{y})$ is the shortest possible angular distance along a route from x to y, and P(y) is the proportion of y falling within the radius.

4.2.2. Angular Betweenness (BtA)

Angular betweenness measures the frequency with which each link x falls on the shortest angular path between each pair of other links y and z, provided the Euclidean distance from y to z is within the network radius. For BtA, the network radius can be regarded as a kind of maximum trip length. Thus,

$$\boldsymbol{BtA}(\boldsymbol{x}) = \sum_{y \in \mathbf{N}} \sum_{z \in \mathbf{Ry}} \mathrm{P}(z) OD(y, z, x)$$

Where BtA(x) is the angular betweenness of link x, **N** is the set of all links in the network, **Ry** is the set of all links within the defined radius of link y, P(z) is the proportion of y falling within the radius from y, and OD(y,z,x) is defined as

$$\boldsymbol{OD}(\boldsymbol{y}, \boldsymbol{z}, \boldsymbol{x}) = \begin{cases} 1, if\ x\ is\ on\ the\ shortest\ angular\ path\ from\ y\ to\ z \\ 1/2, if\ x \equiv y \not\equiv z \\ 1/2, if\ x \equiv z \not\equiv y \\ 1/3, if\ x \equiv y \equiv z \\ 0, otherwise \end{cases}$$

The ½ and 1/3 contributions to **OD(y,z,x)** handle the cases of routes which terminate on the link of interest, and routes from a link to itself. (1/3 represents the average traffic for each point on a link assuming traffic is generated by the product of origin and destination link proportion, P() in the above formulae). All measure were computer with sDNA software (Chiaradia, et al., 2014; Cooper, et al., 2014).

4.2.3. Observation data points

Correlation studies were conducted using the vehicle and pedestrian flow data. Where vehicle or pedestrian gates fell on links not present on the OS Open Data Meridian map in question, they were discarded (in brackets).

Area	Vehicle points used	Pedestrian points used
Barnsbury	82 (0)	102 (7)
Clerkenwell	42 (1)	51 (5)
South Kensington	46 (2)	62 (7)
Brompton	61 (1)	85 (2)

Figure 8: Map of the pedestrian flow points (vehicle flow points are a subset of these) and the spatial models used to predict flows for each. South Kensington and Brompton share the same spatial model.

4.2.4. Results

As both the flow data itself, and some of the computed measures have a non-normal distribution, all data sets were Box-Cox transformed before testing for correlation using Pearson's r^2. All results are significant. Overall the angular betweenness centrality shows better results for vehicle flows, than pedestrian flows. Relatively large variations are found between the four areas.

Network variable		BtA
r^2 with vehicle flow	Barnsbury	0.69
	Clerkenwell	0.80
	South Kensington	0.61
	Brompton	0.58
	mean	**0.67**
r^2 with pedestrian flow	Barnsbury	0.60
	Clerkenwell	0.73
	South Kensington	0.58
	Brompton	0.41
	mean	**0.58**

5. CONCLUSION AND POLICY IMPLICATIONS

Using the OS OpenData Meridian, the study examined the capability of the accessibility-centrality indices of the street network to predict pedestrian and traffic flow. The spatial distribution of pedestrian and vehicular traffic is recorded using cordon counts.

The study show that non-weighted accessibility-centrality indices of the street network *do* predict pedestrian and traffic flow while using the standard OS OpenData Meridian network codification. Over the four areas significant coefficient of determination (r^2) are achieved with an average of 0.58 for pedestrian and 0.67 for vehicular traffic. This is an original finding.

This study shows, using a standard network representation, that the geographical constraints created by transport network connectivity and accessibility matter. The approach is easy to use and only requires a standard street network and counts at select locations, all of which could be easily be generated for most communities. This approach integrates these data, thereby facilitating the analysis of urban form and pedestrian travel.

In the UK we are witnessing the promotion of active modes of travel such as walking and cycling in urban planning, as evidenced by the Welsh Government's recently legislated Active Travel Bill. The study shows that pedestrian path centreline representation and accessibility measures could provide a set of powerful, simple and affordable modelling tools for pedestrian at strategic stages of the decision making and design processes.

Further work could examine the relationship between accessibility on network, built environment attributes and travel and if different type of weighted accessibility would improve the performance of this type of pedestrian modelling at tactical stage of the decision making and design processes.

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