Towards a walkability model for strategic evaluation of policy action and urban active transport interventions

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Abstract
This article presents a recently developed walkability modelling tool that draws on a number of UK national datasets to construct a statistical picture of the potential of streets to be used for walking. Using components common to standard North American models, but adapted for the UK context, the model is novel in its integration of space syntax analysis as a measure of network accessibility as well as in its use of large data surfaces that are not constrained by geographical administrative units. The study area of Greater London is used to validate the model against actual pedestrian activity measurements from across the city. A range of results from the analysis are presented. This approach enables the integration of the model with numerous other datasets and spatial data structures used in transport applications, expanding its capabilities from research into the realm of active travel infrastructure planning and evaluation.

1. Introduction

Measuring the walkability of urban environments by analysing and evaluating physical environmental characteristics has gained wide acceptance as a method for assessing a street network's potential for everyday walking - or active transport. Walkability models are used widely both in transport and health research domains. In the former research domain, the focus tends to be on the potential and suitability for a street system to be used for walking (Moudon and Lee, 2003), whilst for the latter, walkability models are used to assess dose–response relationships between the built environment and physical activity (Van Dyck et al, 2012). In some cases walkability is used as a variable for studies of health outcomes across neighbourhoods with differing geographical attributes (Buman et al, 2010).

Whilst there have been a multitude of studies carried out that show how certain features of the built environment are associated with differentials in the level of physical activity that occurs in a population living in the modelled location, these analyses do not provide ways of evaluating the intensity of active transport taking place in a specific location, or methods of transferring this research into tools that can be used by those engaged in transport planning - for example, in order to identify areas that lack adequate pedestrian facilities on the ground to match the potential of the area for walking, or how to maximise the potential for active transport to occur by improving the design of walking and cycling network infrastructure.

This article presents an approach to modelling walkability within urban environments that allows the consideration of a range of variables across a range of statistical unit scales. The model functions both as an exploratory research tool as well as an application to be used in urban design and planning – whether to identify potential community severance, or to assess town centre viability. The approach diverges from other walkability analysis in that the model is not constrained by geographic or administrative boundaries; instead the components of the index are constructed as continually varying surfaces across the entire urban area being studied. This not only enables a broad range of statistical comparisons, but better visualisation – and so communication of the model to key stakeholders. By using national, or city boundary datasets, it is not constrained by local administrative boundaries, which can distort geographic statistical analysis.

2. Background

2.1 Walkability

Walkability can be defined in several different ways (Lo, 2009), and therefore attempts to measure it do not necessarily coincide well with its theoretical or conceptual underpinnings. In the realm of public health studies, the focus is on an area's suitability for walking. Previous research has found that people walk more in neighbourhoods with multiple destinations and where the environment enables more opportunities for walking, including many street intersections as well as good connections to motorised transport. Such studies also take account of reasons for walking, such as accessibility to shops and businesses (Frank et al., 2005 ; Giles-Corti et al., 2005; Song 2005; Moudon et al., 2006). Their findings form the basis for a vast array of health studies which audit neighbourhood walkability based on such parameters, where a neighbourhood's walkability is considered to be a proxy for the levels of activity within a population within a specific area, rather than an inherent quality of an area or location. Such walkability frameworks will examine its component variables in order to ascertain which aspects of the environment or socio-cultural make-up correlate most significantly, and then these features are considered to be determinants of walkability.
Walking activity is often subdivided within walkability studies into different domains of in order to enable the extraction of the environmental attributes that contribute to different types of walking activity, since different variables will affect each of them differently (Sallis et al., 2006). The most common subdivision of walking activities is between walking for transport and walking for recreation. Walking for transport includes walking to places of work, visiting shops and other services as part of daily routines. Walking for recreation is walking as a pastime or as part of an exercise routine. This article focuses upon walking for transport, broadly referred to as active travel or active transportation.

The literature on walkability tends to focus on walking as being beneficial to health. However another important aspect is the role of walking as a function of the vitality and the liveability of cities. In the transport literature, seminal work by Jones et al (2007) points to the tension that can arise between routes being heavy trafficked by both pedestrians and motorised traffic, whilst in the urban design literature there is an increasingly large body of work on how well-connected and spatially patterned town centres can benefit from increased footfall as well as dwell time. (Carmona, 2015; Karimi, 2012). Qualities of the walking environment such as lighting, pavements and street blocks have also been found to correspond to higher rates of walking (Forsyth et al., 2008; Frank et al., 2010).

With the vast majority of studies looking at the home environment and the levels of walking activity associated with those environments, a consideration of the way the urban system functions as a whole and how it can be adapted to enable the greatest level of physical active for transport purposes is lost. The model presented in this article aims to overcome some of these limitations, by analysing the city as a single system, to enable considerations of how the environment can be adapted, enhanced and targeted for system-wide interventions.

Physical activity can also be considered in relation to the informational environment, for example, by signposting alternative routes or communicating where a walking route is faster than a route taken by public transport. Such policy interventions aim to bring about positive physical activity behavioural change by communicating their benefits and the methods to achieve recommended activity goals, this itself relates to the idea of self-efficacy and the barriers that people may perceive to living a more active lifestyle. This is particularly important for assessing policies aimed at behaviour change through media campaigns. By changing the informational environment, psychological barriers to physical activity can be reduced.

Since becoming familiar to the general public over the past decade, walkability has become increasingly scrutinised across the public health, transportation and urban planning domains and has spawned several commercial walkability enterprises that provide city, neighbourhood and localised rankings and rating of walkability. This has occurred mainly in North America, but European based companies are also starting to emerge. The companies are principally orientated around consultancy and the commercial and residential property markets. The key message that many deliver is that property prices are higher and will rise more rapidly in walkable areas as cities pivot away from reliance on the car as the principal form of personal mobility. Furthermore in relation to the commercial property markets much of the focus is on the creative cities agenda put forward by Florida (2005) that suggests that areas that are more walkable and where there is a greater level of street based activity are more likely to become ‘creative’ hubs due to the type of individuals that will be attracted to work there. More prosaic analysis focuses on land and property values, demonstrating that walkable areas are more liveable and hence, more desirable when measured by property values (see e.g. Chiaradia and Koch, 2013), whilst work at UCL points to the importance of walkability in the long-term viability of smaller town centres (Vaughan and Griffiths, 2013).

2.2 Street networks and space syntax

An important part of this research is the application of space syntax network analysis methodologies to enable a more nuanced evaluation of the relationship between intensity of walking activity and the built environment. Network science is an interdisciplinary academic field studying the complex relationships between components related by a common variable, using methods from graph theory and mathematics. It studies centrality, community and the dynamics of complex networks such as social, biological and transportation networks (Freeman, 1977 and Barabasi, 2009). Space syntax was at the forefront of applying such methods to study the configuration of spatial networks in architecture, urban design and transport planning in the 1970s, (Hillier and Hanson, 1984). An important aspect of space syntax is theorising the relationship between space, society and human flows of movement (Hillier, 2007). The theory of natural movement (Hillier et al., 1993) proposes that a significant proportion of movement through urban streets is determined by the structure of the grid rather than by specific attractors or generators itself. The emergent pattern of busier and quieter streets shapes the opportunities for people to come together. This coming together is referred to as co-presence, and relates to the social and cultural potentials for exchange that arise through the co-location in space of individuals (Urry, 2002 and 2008). It is also a central component of the theory of cities as movement economies (Hillier, 1997), which suggests that the function and evolution of urban systems is bound-up in the structuring of flows of people through the urban system, generating certain locations with high potential for encounter and the clustering of high intensity land uses. Importantly for walkability applications outside of the North American and other areas where urbanisation took place at a later stage, the highly complex non-rectilinear grids that occur in cities where the cities have developed over hundreds, if not thousands of years create nuances of the street structure that necessitate the application of methods such as space syntax that can capture the structural properties of these highly complex street network systems.

Empirically space syntax has found a strong relationship between configuration measures and pedestrian flows (Hillier and Iida, 2005) bicycle flows, (McCahill and Garrick, 2008) and public transport passenger flows. (Law, Chiaradia & Schwander, 2012) These relationships have helped shape and influence design of real projects (Karimi, 2012). The angular nature of space syntax measures capture the straightness of the street network configuration, relating to directness, that is considered an important aspect of the walkability of certain routes in the walkability and health literature (Duncan et al., 2011). Although it goes further than this and capture the local totality of access to geometrically simple routes, thus enabling area based evaluation.

There is a growing number of studies which explicitly use space syntax analysis to model walkability. (Geddes and Vaughan, 2014) have confirmed Joseph and Zimring’s 2007 finding that after accounting for accessibility, people are more likely to walk along routes with ‘active’ land uses and to avoid barriers to walking routes, such as railway lines. Space syntax analysis has also been used in studies of healthy built environments, such as the work of Sarkar, et al. (2013); Koohsari et al. (2013); Sarkar et al. (2015); Lamiquiz and Dominguez, (2015).

2.3 Space syntax, Cognition, Wayfinding and Walkability

The way in which the spatial structure of urban environments relates to movement patterns and behaviours is a complex subject, but past research has indicated that it is likely to be a result of how we make route choices based on mental representations of the structure of space. Wayfinding has been shown to be a cognitive process involving sequential and recursive planning and execution of conscious movement. These decisions are affected by the environment, familiarity and presence of people. Lynch’s (1960) *The Image of The City* is considered the foundational publication on how information about the structure of urban environments is encoded in the mind. The primary components of the mental representation of the city that Lynch identified were: paths, edges, nodes, districts and landmarks, which he said formed the 'imageability' of the urban environment. Lynch's notion of imageability has been shown to be refined by using space syntax principles of intelligibility (Dalton and Bafna, 2003), which take account of the relationship between how much an individual's location provides information on where they can go. Similarly, a seminal study from Weisman (1981) identified various environmental variables, which influence wayfinding ability in space. These include visual access, architectural differentiation, configuration and signage.

Space syntax is centrally concerned with configuration, whilst the relationship between configuration, cognitive representations of space and wayfinding form the linkages between space syntax and walkability. These synergies are investigated in an article by Peponis et al (1990), which explored the relationship between configurational properties and observed pedestrian behaviour. The authors found that signage and architectural differentiation alone were not sufficient to explain wayfinding behaviours, and that configuration had to be taken into account. Different aspects of wayfinding have been successfully examined using space syntax analysis including modelling movement flows in multi-level complexes (Chang and Penn, 1998), decision point in junctions (Conroy-Dalton, 2001), multi-level buildings (Holscher and Brosamle, 2012) agent simulation (Turner and Penn, 2001) and the use of virtual environments (Conroy-Dalton, 2001). Further methodological development expands on the theory in stating that using angular distance (Hillier and Lida, 2005) to measure accessibility provides a more accurate representation than metric distance and topological distance. This is due to the similarities between the way in which route geometry is simplified in the mind (demonstrated in research on mental maps). The explanation of this relationship is that the cognitive maps that are constructed in the brain, using cues as we move and position our body (O'Keefe, 1978), are non-random, distorted and incomplete (Tversky and Gati, 1982). These distortions and simplifications in mental representations have been shown to relate to the angular centrality that is evaluated in networks with space syntax analysis (Dara-Abrams, 2006). By basing space syntax analysis on the angular properties of networks it more closely approximates the geometric simplification that spatial relationships are subject to in the mind, and therefore the analysis reveals a structure of the city that is closer to mental representations than other network analysis methodologies.

The relationships that exist between network configuration and cognition highlight the interrelationship between mental representation and navigation in environments. Taken together with the evidence of a strong correlation between space syntax measures of centrality and pedestrian flows, the implications for understanding the inherent walkability of street networks, brought about by the configuration of urban networks, the incorporation of space syntax measures into walkability indexes has the potential to greatly increase their effectiveness. This is likely to be especially the case for models of urban walkability relating to walking for transport, given that active walking is more likely to follow the spatial logic of the network than walking for leisure.

The majority of the walkability literature accounts for configuration by applying simple connectivity measures. Block size, used as a proxy for street connectivity - whereby smaller blocks suggest greater connectivity - captured as a block level measure (Oakes et al., 2007). The other, more common measure of connectivity is the number of true intersections (3 or more street segment end points coinciding) per unit area of analysis e.g. block, block grouping or statistical unit area. This is often called intersection density (Leslie et al., 2005; Frank et al., 2010; Grasser et al., 2013).

In contrast with measures of connectivity, space syntax analysis measures angular closeness and angular betweenness centrality, also referred to as integration and choice respectively, are the two principal measures that are used. Closeness is a measure of the proximity of one street segment to all other street segments within a specified search radius. The way that proximity is measured in the street network using space syntax techniques is by measuring the angular change when moving from one street segment to another. For a given street segment the closeness centrality will be higher if angular change is minimized between it and all other street segments in the network within a specified radius. It will have low closeness centrality if many large angular changes are required to access all other street segments in the network within a specified radius. Betweenness accounts for the centrality of a street segment on routes between any two street segments within a specified search radius. A street segment will have a higher betweenness if it is traversed many times on the shortest angular path between a pair of origins and destinations.

Closeness centrality (equation below), also known as angular segment integration in space syntax literature, measures the reciprocal of the sum of the shortest path between every origin (i) to every destination (k), i.e. the potential of movement to a street segment, due to the angular proximity to all other segments within a specified radius (Freeman, 1977 and Hillier and Iida, 2005).

$$C_c(P_i) = (\sum_k d_{ik})^{-1}$$

Betweenness centrality (equations below), also known as angular segment choice in space syntax literature, measures how many times paths overlap between all pairs of origins (j) and destinations (k), i.e. the potential of moving through a street segment, due to falling on the shortest angular path between all other segments within a specified radius (Freeman, 1977 and Hillier and Iida, 2005).

$$C_B(P_i) = \sum_j \sum_k g_{jk}(p_i)/g_{jk}(j < k)$$

In space syntax, contrasting to other urban network analysis approaches, the street segment itself is the urban unit rather than the points of connection between street spaces that more realistically approximates the experience on the ground and how urban environments are cognised. The use of angular change between street segments has been shown to explain aggregate pedestrian intensity better than topological or metric distances (Hillier and Iida, 2005).

A fuller account of configuration provided by space syntax modelling and analysis has the potential to improve walkability metrics by providing a greater quantitative account of the relationship between spatial cognition, wayfinding and walkability. This is especially in the case of understanding the overall walkability of city systems that is addressed here.

3. Methods

The walkability model that is presented here is made up of four components: Land use intensity and diversity, residential density, public transport accessibility and street network configuration as measured through space syntax analysis methods. These measures were chosen both due to their statistically significant associations with walking levels in the walkability literature (public transport accessibility, land use diversity and residential density) and statistically significant association with walking levels and flows outside of the walkability literature domain (space syntax street network configuration), which expands on the widely used measure of junction density. Furthermore these four measures can be constructed from data that is available for the whole of the UK, and similar datasets are found worldwide. Enabling the application to many different contexts is important for carrying out comparative studies both nationally and globally.

For all the components the values are normalised through z-scoring, and then re-scaled between 0 and 1. The values are re-scaled for all the components of the walkability index so that they can be added together to create the composite index whilst maintaining equal weighting, and maintaining the ability to adjust the weighting as desired. Once this is complete the values are transformed into surfaces of continuous values with a cell size of 25m for each component. Surfaces of continually varying values are used rather than discrete areas being assigned a walkability index value as this can be weighted and selectively combined to explore different compositions of the walkability index. The reason for adopting this method of generating continuous surfaces of values is to capture the constantly varying qualities of urban space as perceived by people who inhabit it, therefore creating a more accurate representation of environmental perception, which is continuous rather than discrete. Furthermore it enable interoperability across a wide range of other datasets so that it can be used for analysis against as many other data sources as possible, such as socio-economic indicators, traffic levels, greenness and pollution.

3.1 Land Use Intensity and Diversity

Land use diversity is a measure of the degree to which there is a mix of a given set of categorised land uses within a pre-defined area. Land use mix can be characterised in numerous way but a commonly used and accepted approach in walkability studies and other research domains is to use an entropy based measure of diversity, Shannon's Diversity Index, is used to then account for the distribution of values across the land use classes using a second calculation, referred to as Shannon's Equitability (Frank et al. 2010, Van Holle, et al. 2012). This intends to capture the diversity and composition of land uses within a given unit area. An area that is highest scoring would be equal to 1 and would have all possible land uses from the schema contained within it, in equal proportions. Shannon's Diversity Index (H) is produced by applying the following formula:

$$H = -\sum_{i=1}^{s} p_i \ln p_i$$

This formula assesses the diversity in terms of the proportion of a particular land use (i) relative to the total number of land uses (p_i) in a given area. It does not account for the evenness of the mix of different land uses that are present. To incorporate this into the land use diversity index component, Shannon's Equitability (E_H) is then calculated on the H value from the first formula. The formula for Shannon's Equitability is given below.

$$E_H = \frac{H}{H_{max}} = H / \ln S$$

In this instance of calculating land use diversity the block is used as the spatial unit for attribution of land use diversity values. It is defined as any continuous area bounded by roads or other barriers on all sides that has no roads passing completely through it. The land uses that are attributed to each block represent all land uses that occur at the addresses located within the block. In this case the land use is appraised across three dimensions, using volumetric measures of land use that occur within each block based on the number of addresses occurring within a building, incorporating a volumetric value based on footprint and height. The land use schema used is made up of twelve categories: commercial industrial, commercial non-industrial, commercial general, commercial agricultural, retail, food retail, food and drink, tourism and leisure, community and health, transport, residential and education. The second stage of calculating the intensity and diversity is to multiply the equitability value calculated from the composition and diversity of the land uses within a block by the intensity of land use. Intensity here is defined as the cubic metres of building per square metre of land area of a given block. This accounts for the vastly differing utilisation of land area across the city and the likely intensity of pedestrian destinations in a given location. The resulting metric values capture both diversity and intensity of land use as multiplying factors that potentially generate pedestrian activity.

3.2 Public Transport Accessibility

Public transport is a vital component of the way that people move in urban environments where public transport is available. It is also central to multimodal trips of which walking is frequently a component. In the case of London public transport is central to mobility in the city, therefore it has been included as component in the walkability index. In order to do this every bus stop, railway station and London Underground station within London were located. The locations were then used to generate accessibility surfaces for bus stops (radius 500m) and tube/rail stations (radius 1000m). These two surfaces were then added together to create a composite surface of all public transport components. The resulting surface represents the transport accessibility component of the walkability index.

3.3 Residential Density

Residential density represents the number of individual residential addresses per area. The area that can be used to define the density can either be the block that the residential units are situated within aggregated blocks or another statistical areal unit (Frank and Pivo, 1994; Frank et al., 2010; Leslie at al., 2005). This can be defined as the number of residential units as a ratio of the total land area within a block. Here this is calculated using the same block areas as used in the diversity calculation and the location of residential addresses. All the residentially classed addresses were extracted and a count generated for the number of residential addresses that are present in each block area. The number of addresses per block is divided by the block-area to generate a density value of addresses per square metre.

3.4 Space Syntax Street Network Configuration

The model incorporates space syntax methods to evaluate the spatial structure of the street network instead of the standard approach of measuring intersection density. Here, space syntax network analysis methods are used, which examine the spatial relationship between street segments at a range of scales across the street network by looking at the geometric relationships between street spaces. As described earlier this method accounts for spatial cognition and human wayfinding principles in its approach to analysing spatial networks and extends the concept of junction density that is commonly used in walkability studies. In approaching the problem of modelling human walking behaviour this approach should be more fruitful than other approaches that do not use this approach to appraising the street network systems contribution to walking behaviour.

The street network that is used for the basis of this analysis is the Ordnance Survey Meridian dataset. This is processed in the Depthmap software (Turner, 2001) to generate centrality values for each street segment a range of radii. This is done for both closeness and betweenness centrality network measures at a range of search radii, before the measure that has the best fit to the pedestrian density data was extracted.

Once the four surfaces have been generated they are then combined together. The output from this is the overall walkability surface that represents the walkability index for the London area.

4. Model performance evaluation

In order to evaluate the model's effectiveness at predicting the location and intensity of pedestrian activity across London a dataset that represents actual measured pedestrian activity is used. The data set is a pedestrian density dataset that was provided by Transport for London (TfL). This data is based on the London Travel Demand Survey (LTDS) over a period of six years, sampling 300,000 trips across the London area from which the origin and destination of any journey or part of journey are completed on foot. The pedestrian trip stages are then geocoded using the origin and destination of each trip. This data are then processed to calculate the intensity of pedestrian activity, measured in metres travelled per square metre within a given area. The areas used are hexagons with a width of 350m. This equates to 15,324 measurement areas across the Greater London area. The measurement given within each hexagon is metres walked per square metre of hexagon area. This equates to a measure of the intensity of pedestrian activity. This data allows the modelled likelihood of the intensity of pedestrian activity to take place in a given location, based on the four model components, to be verified.

Using this data the value of each pedestrian density cell area are analysed in relation to the corresponding area of the walkability model, examining the numerical relationship between the pedestrian density value and the walkability model component's values that fall within each of the pedestrian density cells. The sum value is used since it is not possible to disaggregate the pedestrian density values within each of the hexagons so the walkability model values have to be aggregated up to the hexagon level. The sum of the walkability model components corresponds to the total walking density that the larger hexagon area represents.

5. Results

The first analysis component tested the correspondence between the pedestrian density data and the space syntax centrality variables to determine the measure that produced the best fit. The measure that was found to produce the best fit was angular closeness centrality at a 2500m search radius, with $R = 0.75$ and $R^2 = 0.56$ with a $p < 0.001$. Importantly this matches Marchetti's constant of travel time behaviour (Marchetti, 1994), as it represents a one-hour pedestrian trip from an origin to a destination and back again, if a 5kmph average walking speed is presumed.

The second analysis component tested the performance of the space syntax network analysis method in comparison to the most commonly used junction density measure. For every pedestrian density hexagon the density of junctions where there are coincident endpoints between three or more street network segments was calculated, this was then compared to closeness centrality 2500m that produced the best fit in the first stage of analysis. The comparative analysis in performance of predicting walking volumes demonstrated a significant improvement when using space syntax network analysis methods. The results of the analysis show the following differing correlations between the two network appraisal methods: junction density R = 0.65 and R^2 = 0.42, space syntax Integration 2500m R = 0.75 and R^2 = 0.56. This result confirms the greater utility of space syntax in modelling walkability in comparison to simpler evaluations of the street network, such as junction density

Multiple regression of the combined walkability model and the individual components was then carried out. The results from the multiple regression analysis are presented in the table below.

	Pedestrian Density Correlation		
	R	R Square	Sig.
Combined Model Components	0.813	0.661	<0.001

	Pedestrian Density Correlation		
	R	R Square	Sig.
Transport Accessibility	0.758	0.575	<0.001
Space Syntax Closeness 2500m	0.747	0.558	<0.001
Land Use Diversity	0.662	0.438	<0.001
Residential Density	0.619	0.383	<0.001

The results show that overall the walkability model made up of the four components is both statistically highly significant and highly positively correlated with the occurrence of pedestrian activity, with the combination of the four components resulting in a correlation of R = 0.81, R^2 = 0.66 $p < 0.001$. When the results are disaggregated transport accessibility is the most important (R = 0.758, R^2 = 0.574) followed by street network structure measured using space syntax analysis (R = 0.747, R^2 = 0.558). Land use diversity shows the lowest correlation (R = 0.411, R^2 = 0.168). All the components demonstrated $p < 0.001$

6. Discussion

The first finding comes from the analysis comparing space syntax centrality measures to the pedestrian density data. The finding that closeness centrality with a search radius of 2500m corresponds most closely to the pedestrian density data is significant for both theoretical and practical reasons. 2500m correspond to the theories of invariance to travel time behaviour proposed by Cesare Marchetti (1994). The theory is that over the whole of human history the average amount of time in a day that is used from travel purposes is constant, and this constant amount of time is approximately an hour, the variable that changes over time is mobility technology, which from horse based transport onwards, have allowed greater distances to be travelled within the same amount of time. Assuming an average walking speed of 5 km/h, a round trip by foot that corresponds to this theory would be 2500m in each direction. The analysis found that closeness centrality at this search radius corresponded most closely to measured pedestrian activity; implying centres that are structurally central at this scale are where peak pedestrian activity takes place. This suggests that the multiple centres of pedestrian activity across London occur in such a way as to cluster around centres that are accessible on pedestrian round trips of an hour, This clustering of pedestrian activity around centres of this scale is important for planning urban infrastructures and development. If, as these results suggest, centres that operate at this scale are the most important for pedestrian activity, then they should be prioritised so as to enable them to fulfil their potential for use by people on foot, and also be the focus for any active transport network infrastructure developments.. These centres could also be used as the hubs for development outside of the central area of London, where increased density, mixed land uses and greater public transport accessibility could be encouraged. Alongside active travel networks that link these smaller outer centres with one another. Research on the long-term success of many of London's smaller town centres show that there is a demand for local centres which support a combination of short trips on foot and longer range ones by car and public transport (Carmona et al. 2015; Vaughan et al., 2010; Jones et al., 2007). Intensification of network connectivity and non-domestic land uses around these centres would both go with the grain of demand that is evident in the data, but also enhance the city in terms of active travel by developing the areas that are most likely to enable a city-wide active-travel take up (by minimising distance between centres and focussing infrastructural development on developing the links between these centres). We further recommend that this should be tested in other cities where comparable data is available to see if this finding can be replicated. If it is indeed replicated – though it is anticipated that different cities with varying histories of development might operate at different spatial scales,- necessitating adjustments of the model to local conditions - it will have important ramifications for some of the principals of urban planning, design and transport infrastructure planning. Furthermore it would demonstrate the significance of Marchetti's invariance to travel time behaviour theory, extending it to inter-urban behaviour and resultant urban spatial orderings.

The second finding from the analysis is that the space syntax centrality measure improves upon junction density measures in their ability to predict pedestrian activity. The closeness centrality, search radius 2500m measure produced a result that had a 14% greater prediction power than the junction density measure. This indicates that the angular closeness centrality of the street network is a greater determinant of pedestrian activity than solely connectivity as measured with junction density; pedestrian activity can be seen to be a function of connectivity and street network geometry as measured in angular closeness centrality. This finding suggests that walkability analysis should seek to test space syntax based measures of the street network in their appraisal methods to potentially enhance their prediction power for walking levels. Testing this in the context of orthogonal grid systems, such as those found in the majority of North American cities would be important to see if this applies outside of the organic street network system found in London. The majority of walkability studies aim to model the dose-response relationship between an individual and their local environment, therefore space syntax would need to be tested in that context rather than in models such as those presented here that examine the spatial distribution of intensity of pedestrian activity across the whole city-system.

The third key finding is that transport accessibility had the strongest correspondence to levels of pedestrian activity of all four of the walkability model's component. Public transport is more important for predicting and association with pedestrian intensity than any of the other variables. This highlights the paramount importance of public transport to all aspects of city developmental processes that rely on pedestrian activity and accessibility, particularly economic regeneration and development of areas that has historically been deprived and spatially excluded through poor transport accessibility. Another significant aspect of transport accessibility is that it is generally controlled and implemented by a single city-level body, in this case Transport for London. The relevant transport authority will therefore have to take decisions between competing demands of investing in areas where there is proven demand and economic incentive, and investing in areas where there is not a proven case already, but based on forecasting about likely outcomes of the impact of greater transport accessibility on the local area. Using modelling tools such as the one described in this paper the case for that investment might be easier to make through enabling predictive forecasting of the impacts on pedestrian activity brought about by changes to transport accessibility. The implementation of a new train line for example could be modelled and likely levels of pedestrian activity predicted. A natural and highly useful continuation of this would be to link to economic models of the impact of increased pedestrian activity in an area on the local economy. This would enable both the health case for public transport investment (predicting associated increases in active travel levels) and economic case (predicting effects on local economy) to be made.

The results of the overall analysis of the combined components of the walkability model and pedestrian activity intensity demonstrate that using a model constructed in this way to predict the likely intensity of pedestrian activity is valid. This is demonstrated by the significant and strong correlations between the built environment model and the measured pedestrian density. Of the model components, transport accessibility and network centrality as measured with space syntax methods, were shown to be the two most important factors. This suggests that the structuring of locations of intensity of pedestrian activity within the city is largely dependant on the accessibility of a location within the broader context of the city, mediated by public transport, and the more local street network structure of the urban space that will affect the pedestrian movement patterns that occur. Whilst residential density and land use diversity were shown to have a significant relationship to the intensity of pedestrian activity they did not demonstrate such high levels of correspondence (R^2=438 and R^2=0.383). This may indicate that transport accessibility and street network centrality are the driving forces behind pedestrian activity with land use and residential density being supplementary factors. None the less higher levels of land use diversity and residential density can be said to contribute positively to levels of pedestrian activity.

7. Conclusions

The method presented here of modelling pedestrian intensity and demand has been demonstrated to be a valid approach, and could augment the current approach to walkability modelling in allowing a city-wide perspective on pedestrian demand and potential. This could enable greater understanding of how to locate and connect active transport infrastructural investments together across the city, increasing the positive impact and decreasing the uncertainty and risk associated with interventions. The space syntax based methods for assessing street network properties holds the potential for improving both walkability studies, and associated health research through more accurate modelling of walkability potentials.

The modelling approaches demonstrated here also enable the functional movement of the whole city to be planned against active transport goals rather than only in smaller areas. Whilst in North America this may be less likely to apply due to the dominant reliance on cars for longer-range trips and lack of public transport, in Europe this approach has the possibility to be more fruitful than approaches used so far in a North America context. This is something that needs to be explored further.

The correspondence between closeness centrality search radius 2500m and intensity of pedestrian activity indicates that, when viewed from a human activity basis, London is polycentric in its nature. This structural ordering corresponds to the theory of multiple centralities (Hillier, 1999) that suggests London is comprised of a network of smaller and larger town centres across the city. Furthermore when thinking of infrastructural development in the city, considering intensification of centres that are prominent at this structural network scale would be an important starting point to enable development that satisfies the demonstrated spatio-temporal structure of pedestrian demand. Even with all the advances in mobility technology it is evident that activity in London is still structured according to pedestrian principles of proximity, centrality and travel time. This highlights the paramount importance of considering pedestrian activity on an equal if not higher footing than other modes of travel and movement. The vital next step for this research field is the ability to link together the walkability modelling tools to economic forecasting tools, which will enable the case to be made from both a health and economic perspective. With both these modelling tool components, the case for urban interventions and regeneration would be extremely powerful, both in public and private commercial contexts.

A unique aspect of this walkability research is the modelling of the levels of walking occurring across the city rather than the levels of walking that an individual may achieve due to the environment around their home location. The validity of the model presented here shows that the approaches used previously can be transferred to this application that can inform city-wide planning. Although improving areas so they promote more active behaviour around home locations is undoubtedly beneficial, enabling planning at the city level is paramount to support walking and other active travel modes between destinations other than home addresses, and moving towards active transport as the de-facto mode of mobility in urban areas.

The application of modelling tools, such as those presented in this article, to urban planning and transport infrastructure development are centred on enabling understandings of the city as a set of interconnected and overlapping places and spaces. Only by understanding how parts of the city join together through their spatial and environmental properties can planning decision be taken that work alongside the pre-existing structure of the city and can maximise the impact of interventions on making cities both better places for walking and active travel more generally, but also more efficient at fulfilling their potential as great urban places.

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