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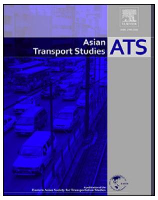

Comparing accessibility and connectivity metrics derived from dedicated pedestrian networks and street networks in the context of Asian cities

Daniel Martin Pearce [a,*], Ryoji Matsunaka [a], Tetsuharu Oba [b]

[a] *Graduate School of Engineering, Kyoto University, Kyoto, 615-8540, Japan*
[b] *Graduate School of Management, Kyoto University, Kyoto, 606-8501, Japan*

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ABSTRACT

Studies that compare accessibility and connectivity metrics derived from pedestrian and street networks have been conducted in urban environments outside of Asia. This creates uncertainty concerning the performance of measures calculated on pedestrian networks globally. The purpose of this research is to: (1) develop a dedicated pedestrian network approach suitable for Asian cities; and (2) further develop understanding of pedestrian accessibility and connectivity by including centrality metrics rarely applied to dedicated pedestrian networks before comparing results across network representations. In total, eight networks were created – one dedicated pedestrian and street network each centred on metro stations in Bangkok, Manila, Osaka, and Taipei chosen to represent different urban typologies. Results indicate substantial differences between values calculated on both networks. Measures that have no distance component are particularly susceptible to how the pedestrian network is represented, while distance-based and centrality measures are less affected and more stable across urban forms.

1. Introduction

The pedestrian network is arguably the most complex transportation network found in urban environments globally. It ties together all transportation modes, making it central to network-based analyses, including those that relate to pedestrian accessibility, connectivity, and walkability (Zhang and Zhang, 2019). Nevertheless, most studies to date have relied on street centreline network representations when calculating accessibility and connectivity in pedestrian studies (Cruise et al., 2017; Ellis et al., 2016; Tal and Handy, 2012; Chin et al., 2008).

While street networks have been found to work well as a proxy for pedestrian networks in some cases, they fail to account for finer-grained paths available to pedestrians, including those found on different levels, across open spaces, and that serve as pedestrian crossings. Therefore, relying on them is a questionable endeavour if a city's pedestrian network is substantially different. Recent studies have argued that this reliance leads to distortions in reality, particularly regarding distance and potential route choices, potentially affecting our understanding of connectivity, accessibility, and consequently the walkability of an area (Cruise et al., 2017; Ellis et al., 2016; Tal and Handy, 2012; Chin et al., 2008). These studies suggest that pedestrian networks better represent how pedestrians traverse the built environment and provide a more robust network for analysis.

This paper builds on existing studies by exploring how dedicated pedestrian networks (DPNs), which include formal and informal pedestrian paths, as well as shared paths, compare to street network proxies when measuring accessibility and connectivity in Asian cities. We argue that similar studies have been conducted in different urban contexts outside of Asia that have distinct urban morphologies and walking cultures. For example, some approaches only include pedestrian links where there are formal sidewalks or crossings (Zhang and Zhang, 2019). While this may work well in places like the USA that has strict jaywalking laws, it is not applicable to cities in Asia where pedestrians will typically walk along or cross a street whether a sidewalk or formal crossing is present or not. Indeed, countries such as Japan maintain very walkable environments without the presence of raised sidewalks, while those in developing parts of the region may have limited pedestrian facilities or lack them altogether. Furthermore, in some parts of Southeast Asia crossing opportunities may be restricted largely to pedestrian bridges, as opposed to at-grade signalised crossings found in other parts of the world, prioritising traffic flow over pedestrian accessibility. This is likely to not only negatively impact distance-based measures by lengthening routes, but also non-distanced-based measures that rely on the ratio of links to nodes, if more nodes are added than links.

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* Corresponding author.
E-mail addresses: dpearce@urban.kuciv.kyoto-u.ac.jp (D.M. Pearce), matsunaka.ryoji.3v@kyoto-u.ac.jp (R. Matsunaka), oba.tetsuharu.5n@kyoto-u.ac.jp (T. Oba).

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These differences do not even touch on the variations in urban form found in regions across the world. Consequently, there is still some uncertainty with regard to how well accessibility and connectivity metrics will perform on DPNs in Asian cities. Thus, the specific objectives of this research are to: (1) develop a DPN tailored for cities in Southeast and East Asia; and (2) further develop understanding of how accessibility and connectivity metrics perform when derived from DPNs and street networks by including network centrality measures that specify the importance of network elements not typically applied to pedestrian networks in pedestrian studies.

2. Literature review

Pedestrian accessibility, connectivity, and walkability are three closely interrelated concepts that play an important role in solving many of the environmental, economic, and social challenges facing large cities throughout the world (Speck, 2012). In simple terms, walkability is an all-encompassing term containing many aspects used to describe how conducive the built environment is to physical activity (Ellis et al., 2016). Some of these aspects include the quality of the built environment, its level of safety and comfort, and the ability of pedestrians to access destinations (Tal and Handy, 2012). Accessibility is concerned with the fit between transportation and land use patterns. It considers an individual's ability to reach relevant activities, individuals or opportunities that require travel to where those opportunities are located (Handy, 2005). Therefore, accessibility is a function of proximity – where things are located and how close they are to each other, and connectivity – the directness and multiplicity of routes through a network, or in simple terms, how easy it is to get from A to B (Tal and Handy, 2012). This interconnectedness has contributed to connectivity calculated on street networks often serving as a proxy for pedestrian accessibility to local destinations.

2.1. Measuring accessibility and connectivity

Table 1 provides an overview of common objective metrics referenced in the literature. For the purpose of this study, accessibility and connectivity metrics have been classified into three groups – conventional connectivity, conventional accessibility, and configurational or spatial accessibility measures. Definitions of metrics utilised in this study and their calculation methods are provided in the methodology section.

Table 1
Common connectivity and accessibility metrics.

Classification	Metric	Reference Literature
Conventional Connectivity	Block – Length, Size, Density	Song (2003); Hess et al. (1999); Cervero and Kockelman (1997)
	Connected Node Ratio	Song (2003)
	Intersection/Node Density	Cervero and Kockelman (1997); Cervero and Radisch (1996)
	Link-Node Ratio	Ellis et al. (2016); Tal and Handy (2012); Ewing (1996)
	Percent Grid	Greenwald and Boarnet (2001)
	Percent 4-way Intersections	Cervero and Kockelman (1997)
Conventional Accessibility	Gravity Index	Hansen (1959)
	Pedshed	Ellis et al. (2016); Porta and Renne (2005)
	Pedestrian Route Directness	Ellis et al. (2016); Randall and Baetz (2001); Hess (1997)
	Metric Reach	Ellis et al. (2016); Peponis et al. (2008)
Configurational / Spatial Accessibility	Directional Reach	Ellis et al. (2016); Peponis et al. (2008)
	Betweenness Centrality	Freeman (1977)
	Closeness Centrality	Freeman (1979)

Source: Adapted from Zhang and Zhang (2019) and Tal and Handy (2012).

Conventional measures of connectivity are concerned with countable features to calculate the density, dimensions, or ratio of one feature to another within a defined area. As such, they are non-distance-based measures that provide a broad account of connectivity across a general area. Common examples include intersection density – the number of intersections per unit area (Zhang and Zhang, 2019) and link-node ratio (LNR) – the ratio of the number of links to nodes in a network (Song, 2003; Ewing, 1996).

Conventional accessibility metrics are measured with respect to the time or distance cost of reaching potential destinations or opportunities. Therefore, they are location specific distance-based measures that characterise a particular location on a network (Tal and Handy, 2012). Common examples include pedsheds – a measure of accessible area that can be reached from a specific location via a network for a specified distance, expressed as a percentage of the corresponding Euclidean area (Ellis et al., 2016; Porta and Renne, 2005); and pedestrian route directness (PRD) – the ratio of actual travel distance to straight-line distance between specific origins and destinations within a network (Randall and Baetz, 2001; Hess, 1997).

Configurational or spatial accessibility metrics are concerned with the configuration and shaping of networks and draws from Space Syntax research and graph theory (Hillier and Hansen, 1984). This group includes centrality metrics, such as betweenness centrality – a measure of the importance of an element in a network in terms of how many shortest paths pass through it (Freeman, 1977); and closeness centrality – a measure of how close an element is to all other elements in a network calculated as the mean of the shortest path lengths (Freeman, 1979).

2.2. Pedestrian network representations

In pedestrian studies addressing accessibility and connectivity, the street network has frequently been used as a proxy for pedestrian networks. The most common approach is based on street centrelines where intersections are represented as nodes and street segments as edges (Kang, 2018; Mansouri and Ujang, 2016; Hajrasouliha and Yin, 2015; Ozbil et al., 2011). This has proved popular due to the wide availability of standardised street centreline datasets that are easily employed in geographic information systems (Zhang and Zhang, 2019). A variation on this approach is found in Space Syntax axial maps, which consist of the fewest set of longest lines that cover all spaces in an urban system (Hillier and Hanson, 1984). These lines differ in their ability to represent several street segments and are more akin to lines of sight. Axial maps represent pedestrian networks in a simplified manner and have been used to represent pedestrian only paths, including in studies conducted in Asia (Fang et al., 2019; Mansouri and Ujang, 2016). However, a generalised street network still comprises the vast majority of these networks and rarely do they incorporate pedestrian infrastructure.

Whereas standardised street centreline data exists, pedestrian network data has remained relatively underdeveloped. Here we discuss four specific approaches to representing missing pedestrian network data. Firstly, Chin et al. (2008) created their pedestrian network by adding in missing pedestrian data, namely paths connecting dead ends and crossing parks to the existing street network in Perth, Australia. This is the simplest approach encountered in the literature, where despite the presence of sidewalks, the pedestrian network is only ever represented by a single link running down the centre of a street right-of-way. Tal and Handy (2012) refined this approach by firstly removing streets deemed inaccessible to pedestrians and then adding the network of multi-use paths to the existing street network of Davis, California. Paths through shopping centres and redundant paths designed primarily for leisure in open spaces were also included. Interestingly, the authors modelled their network to minimise the number of nodes at intersections, representing arterial streets as single links. Both of these approaches emphasise simplicity when constructing a network in GIS resulting in significant time savings, but do not reflect the actual locations where pedestrians walk, impacting metrics that rely on distance and angle.

A third approach by Ellis et al. (2016) created a standalone pedestrian network in Belfast, Northern Ireland termed the *"Real Walkable Network"* (RWN). This approach included both sidewalks and informal facilities such as paths through open spaces, and modelled crossings at all instances where links intersected at streets. Thus, crossings were assumed whether they were formally designated or not. However, formal or marked crossings were not modelled due to missing data. Finally, a different approach to representing the pedestrian network was undertaken by Zhang and Zhang (2019). Like Ellis et al. (2016), the authors constructed standalone pedestrian networks in a variety of cities in the USA described as *"Formal Pedestrian Facilities Networks"* (FPFN). The FPFN consists solely of formal pedestrian facilities, namely sidewalks and designated crossings. Both the RWN and FPFN approaches differ from previous studies by preserving distance, angle and node count by being geographically accurate.

These four approaches all require some form of manual digitisation, which is a time-consuming task requiring extensive verification to ensure data accuracy (Zhang and Zhang, 2019). Fortunately, developments in machine learning, image processing, and collaborative mapping have increased the availability of more detailed pedestrian networks allowing for more comprehensive analyses (Zhang and Zhang, 2019; Gil 2015; Karimi and Kasemsuppakorn, 2012). Recent studies have also begun exploring the application of 3D pedestrian networks that utilise CAD and GIS data in high density environments, such as central Hong Kong with moderate success (Zhang and Chiaradia, 2019). Among these, the collaborative OpenStreetMap (OSM) project is increasingly being used as a source of pedestrian data that represents pedestrian specific paths, including sidewalks, trails, and pedestrian bridges into its network dataset. OSM data is not without issues (Gil, 2015). Some cities have more complete data than others and the integration of open spaces, typically represented as enclosed areas, has been the focus of research to provide more realistic pedestrian routes (Graser, 2016). Nevertheless, it has been successfully applied in all manner of studies, including in multimodal network accessibility analyses (Gil, 2014). In these applications, however, a true pedestrian network is typically not the sole analytical focus and missing pedestrian data such as sidewalks are not always accounted for.

2.3. Pedestrian network performance

While street networks have substituted well for pedestrian networks in many cases, a chief concern of this study is how they compare alongside more accurate pedestrian networks (Fang et al., 2019; Kang, 2018; Mansouri and Ujang, 2016; Hajrasouliha and Yin, 2015; Ozbil et al., 2011).

In studies that directly compare metrics calculated on both pedestrian and street networks, substantial differences are reported with generally higher values observed in pedestrian networks across neighbourhood typologies. For example, in Perth, Australia, link-node ratio, pedshed, and pedestrian route directness values derived from pedestrian networks increased connectivity in all study areas, including by as much as 120% in suburban areas (Chin et al., 2008). Tal and Handy (2012) calculated the same metrics in addition to the number of households accessible within 5-min pedsheds for several retail and educational sites throughout nine neighbourhoods in Davis, California. They found that pedestrian networks increased pedshed distances by an average of 12.2%, and that the street network underestimated housing accessibility by as much as 40%. This is attributed to the increase in routes that arise from using pedestrian networks allowing a greater area to be covered. Counterintuitively, their research found that connectivity measured with the link-node ratio suggested that suburban areas were better connected than more traditionally dense and grid-like downtown areas when using their pedestrian network.

Ellis et al. (2016) expanded these measures to include intersection density, metric reach, and directional reach calculated on their standalone RWN. Metric reach measures the total length of network that can be covered from a specific origin for a specified distance. Directional reach differs by placing restrictions on the number of permitted direction changes. These metrics were compared at 5-min (500m) and 10-min (1000m) walking distances, and their correlations with actual levels of physical activity were verified. Intersection density and metric reach recorded the highest correlations with physical activity, while the lowest correlations were recorded for pedestrian route directness and directional reach. According to the authors, the small area covered by directional reach was due to the dense and winding nature of their Belfast study area. They state that directional reach may be more applicable by applying a higher threshold angle for signifying direction changes, or increasing the number of directional changes permitted in the analysis.

Zhang and Zhang (2019) compared nine accessibility and connectivity metrics calculated on their FPFN and existing street networks in four US neighbourhoods selected to represent different network typologies. The authors included five novel measures relating to crossings to highlight the potential of developing new metrics that can only be measured on pedestrian networks. These measures capture pedestrian exposure to vehicles when crossing streets. Thus, they aid in measuring a pedestrian network's potential impact on pedestrian perceptions of safety, comfort, and convenience. Their results indicated substantial differences between metrics calculated on both networks. However, pedestrian route directness values calculated on the FPFN conflicted findings in comparable studies (Tal and Handy, 2012; Chin et al., 2008). This is due to the difference in network representations, where missing sidewalk links resulted in more broken and less connected networks in their study. Additionally, they found that their FPFN could better distinguish gridded networks that appear very similar with respect to conventional metrics but differ drastically in terms of crossing width and distance to crossings.

2.4. Literature summary

The literature is clear that accessibility and connectivity differs substantially when calculated on pedestrian networks or existing street network proxies. In general, switching to pedestrian networks results in higher values indicating improved measurement of accessibility and connectivity. How the pedestrian network is represented also clearly affects the performance of metrics questioning their applicability in pedestrian network-based studies. This comparative research comparing network representations has been conducted primarily outside of Asia, where street networks have largely substituted for true pedestrian networks (Fang et al., 2019; Kang, 2018; Mansouri and Ujang, 2016). We address this gap and contribute further by incorporating centrality metrics. With the exception of studies that extend these metrics to open spaces, or include them as part of the street network, this paper presents an early case of applying these metrics to dedicated pedestrian networks and street networks in different Asian cities (Gil, 2014; Fukuyama and Hato, 2012; Porta et al., 2008).

3. Methodology

A total of eight analysis networks were created for study areas located in Bangkok, Manila, Osaka, and Taipei. These cities were chosen from a larger list of candidate cities to represent a variety of urban forms at various levels of urban development for comparative purposes. The UN Human Development Index (HDI) score that ranks countries based on per capita income, education and life expectancy (UNDP, 2018) was used to select two lower and higher developed cities. Bangkok and Manila were selected owing to lower HDI scores of 0.755 and 0.699, while Osaka and Taipei were selected owing to higher scores of 0.909 and 0.907, respectively.

In each study area, Euclidean dedicated pedestrian networks and street networks were created centred on a major metro station, drawn

Table 2
Study site network characteristics (400m).

Study Site	Street Network			Dedicated Pedestrian Network		
	Length (m)	Links	Nodes	Length (m)	Links	Nodes
Bangkok – Sukhumvit	8,346	91	60	11,257	189	117
Manila – Carriedo	13,894	207	115	18,948	464	255
Osaka – Namba	14,676	246	125	28,053	960	557
Taipei – Songjiang Nanjing	14,947	255	120	21,236	674	409

from the centroid of each station building. The analytical focus is the first 400m network area corresponding to a 5-min walking catchment. However, networks were extended to 800m in order to minimise the ‘edge effect’ when calculating centrality metrics. This refers to analytical bias that results from the partial analysis of networks due to the exclusion of network elements when imposing an artificial boundary (Gil, 2017).

The selected stations represent dense urban retail centres and were selected due to their high levels of ridership and pedestrian amenities within their network areas. Each area represents different network forms and pedestrian path typologies (Tables 2 and 3 and Fig. 1). For example, Bangkok is dominated by long blocks and dead ends, while study sites in Manila, Osaka and Taipei are far more gridded with shorter blocks. Finally, stations were chosen as the focus of this study due to the large number of Asian cities that are investing in rapid transport systems to alleviate issues related to rapid growth and motorisation, and for the role that pedestrian environments play in supporting these investments.

3.1. Data preparation

OpenStreetMap network data was used for the reference street network and as the base for constructing geographically accurate dedicated pedestrian networks (DPNs). The street network comprises all network links open to vehicular traffic. As such, network links that are designed for other modes, such as sidewalks and cycleways were removed. Streets inaccessible to pedestrians were also omitted from the study to limit possible bias. Conversely, the DPN comprises all network links designed exclusively for pedestrians or that pedestrians have legal access to. The DPN is detailed in the following section and will be hereon referred to as the pedestrian network.

The integrity of each network link was verified by cross-referencing the network with a combination of aerial and satellite imagery provided by either national agencies, Google Earth, or Google Maps services. All reference imagery dated from 2018 to 2019. Missing links identified during this process were digitised in ArcGIS 10.7 according to the pedestrian network principles detailed in the following section to minimise errors. Further verification of the pedestrian network took place during field visits conducted during October to December 2019. Errors were further minimised by quality assurance checks and running network connectivity tools within ArcGIS. These methods overcome errors in spatial data digitisation and are reported to guarantee accurate networks for spatial analyses (Ellis et al., 2016). Finally, each network was used to create a Network Dataset using the ArcGIS Network Analyst extension to conduct network analyses.

3.2. Dedicated pedestrian network definition

This study employs the standard approach to pedestrian networks in which pedestrian paths are represented as links and intersections as nodes (Fig. 2). Pedestrian paths are modelled even in the absence of delineating kerbs or painted lines that are typically not found in many Asian cities. All formal and informal pedestrian facilities are included in the network regardless of whether they exist below or above ground, as long as they accessible throughout the day. This is important due to the high number multi-level paths observed during field visits to the region.

One of the biggest questions that arises when constructing a pedestrian network is whether one or two paths should be modelled along a street. Single pedestrian links are modelled for all formal pedestrian facilities such as sidewalks and crossings (Fig. 2 – A). In the absence of pedestrian infrastructure, a judgment is required on how wide a paved roadway ought to be to merit two separate pedestrian paths. This study employs a simple design rule for instances when no physical pedestrian infrastructure is present. Single pedestrian links are modelled when street widths are less than 7m (Fig. 2 – B). Pedestrian exclusive paths such as pedestrian zones are always modelled as a single line (Fig. 2 – C). Pedestrian paths in large open spaces, including perimeter and redundant paths are modelled if they are observable in aerial imagery, appear in Google or OpenStreetMap basemaps, or were observed during field visits. If paths are not observable using these methods, paths are created connecting entries and exits to the public space accounting for deviations around obstacles (Fig. 2 – D).

Formal crossings are modelled at all marked locations and locations connecting two pedestrian paths at street corners. Informal crossing opportunities are modelled where all pedestrian paths intersect at streets (Fig. 2 – E). This is similar to the RWN approach (Ellis et al., 2016) but adds a restriction that informal crossings cannot span more than four lanes of traffic without a crossing aid, such as a pedestrian refuge island (Fig. 2 – F). This additional caveat better reflects pedestrian crossing patterns observed during field visits to each study area where high traffic volumes make it difficult to cross wide streets. Fences, barriers and signage prohibiting crossings were taken into account in determining if crossing opportunities were possible. This approach strives to be geographically accurate and representative of crossing behaviour. As such, it is important to note that it can significantly impact non-distance-based measures like the link-node ratio and connected node ratio. For example, adding pedestrian paths that are not represented in street networks can result in more 3-way nodes, especially at large intersections (Fig. 2 – A) and at informal crossings (Fig. 2 – E). All DPNs and street networks are shown in Fig. 3.

3.3. Accessibility and connectivity metrics

Seven metrics were calculated on eight networks utilising ArcGIS Network Analyst and Urban Network Analyst (UNA), an open-source toolbox used to compute centrality measures (Sevtsuk and Mekonnen, 2012). These metrics comprise two conventional connectivity measures, two conventional accessibility measures, and three configurational or spatial accessibility measures described above. All metrics are calculated on 400m networks unless otherwise stated and are described below.

We hypothesise that conventional distance-based accessibility measures will perform better on dedicated pedestrian networks, while non-

Table 3
Percentage of pedestrian facilities by path level (400m).

Path Level	Bangkok – Sukhumvit	Manila – Carriedo	Osaka – Namba	Taipei – Songjiang Nanjing
Sub-Surface	02	02	13	02
Surface	90	97	86	98
Elevated	09	01	01	00

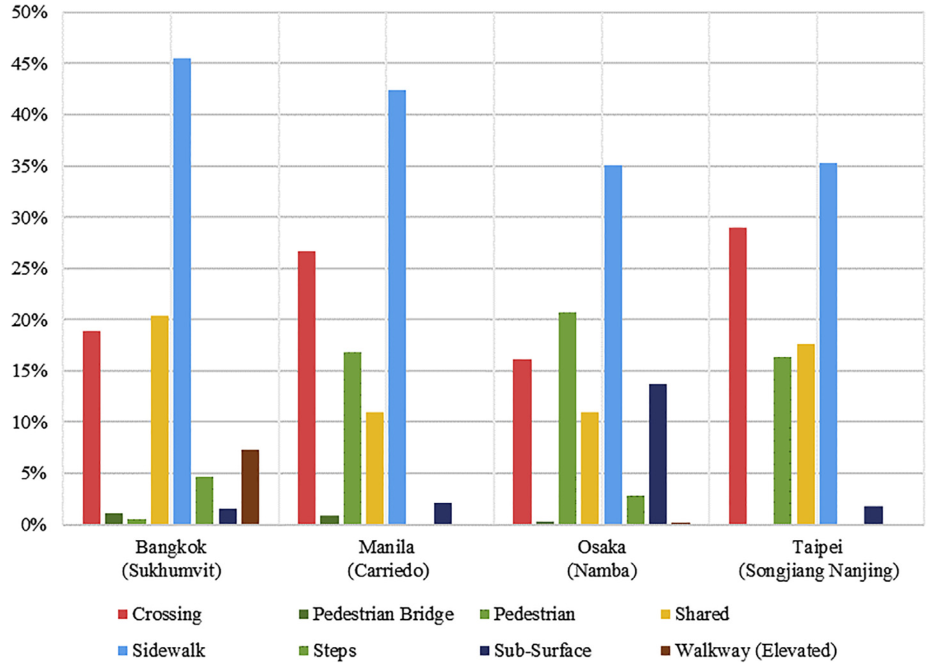
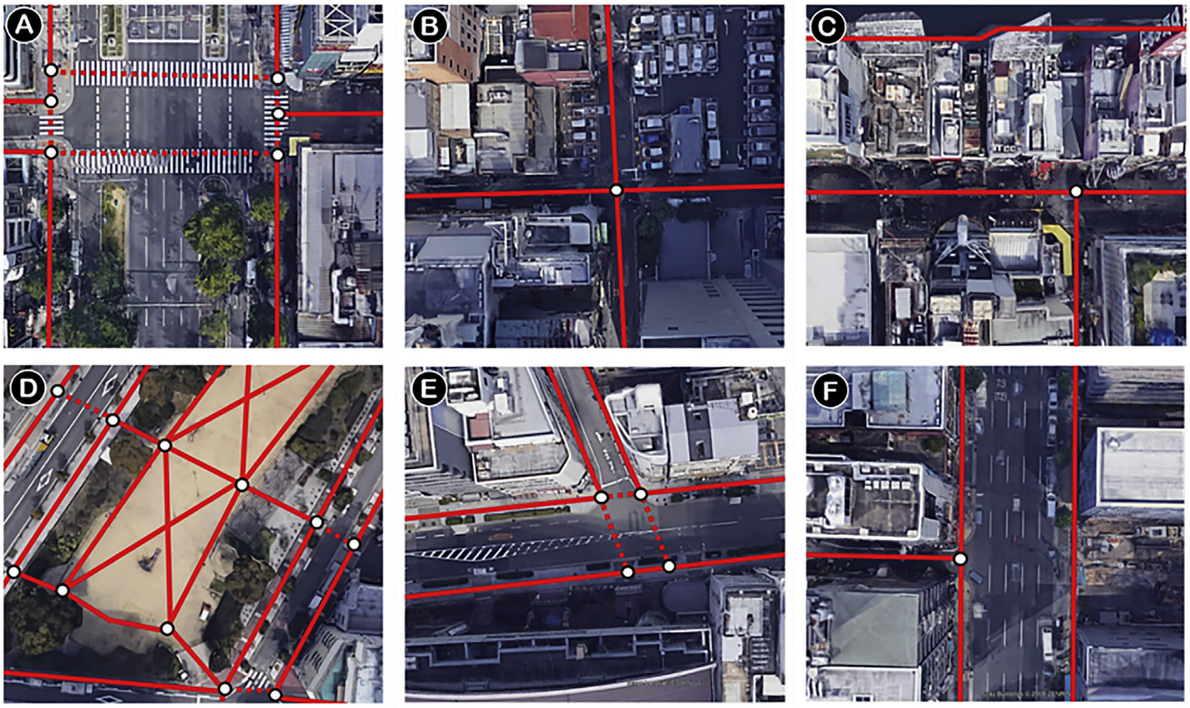


Fig. 1. Composition of pedestrian path types (400m network).



A. Sidewalks and formal crossings; B. Single pedestrian link on shared narrow streets; C. Pedestrian exclusive zone; D. Paths located in open spaces; E. Informal crossing opportunities; F. Informal crossing not possible.

Fig. 2. Dedicated pedestrian network modelling approach (Source: Google Earth).

distance-based conventional measures will produce mixed results dependent upon the complexity inherent in each study area's pedestrian network. Regarding centrality, we expect lower values for betweenness measured on pedestrian networks due to the increase in route options that accompany these networks. Conversely, we predict higher values for closeness measured on pedestrian networks owing to the increase in density of network elements bringing network elements closer to each other.

3.3.1. *Conventional connectivity metrics*

Link-Node Ratio (LNR) is the ratio of the number of links divided by nodes in each network. Higher values denote more route options and more direct connections to destinations (Song, 2003; Ewing, 1996). *Connected Node Ratio (CNR)* measures the number of four-way nodes divided by the total number of nodes (Song, 2003). Higher values indicate fewer dead ends and more nodes where pedestrians have greater direction choices.

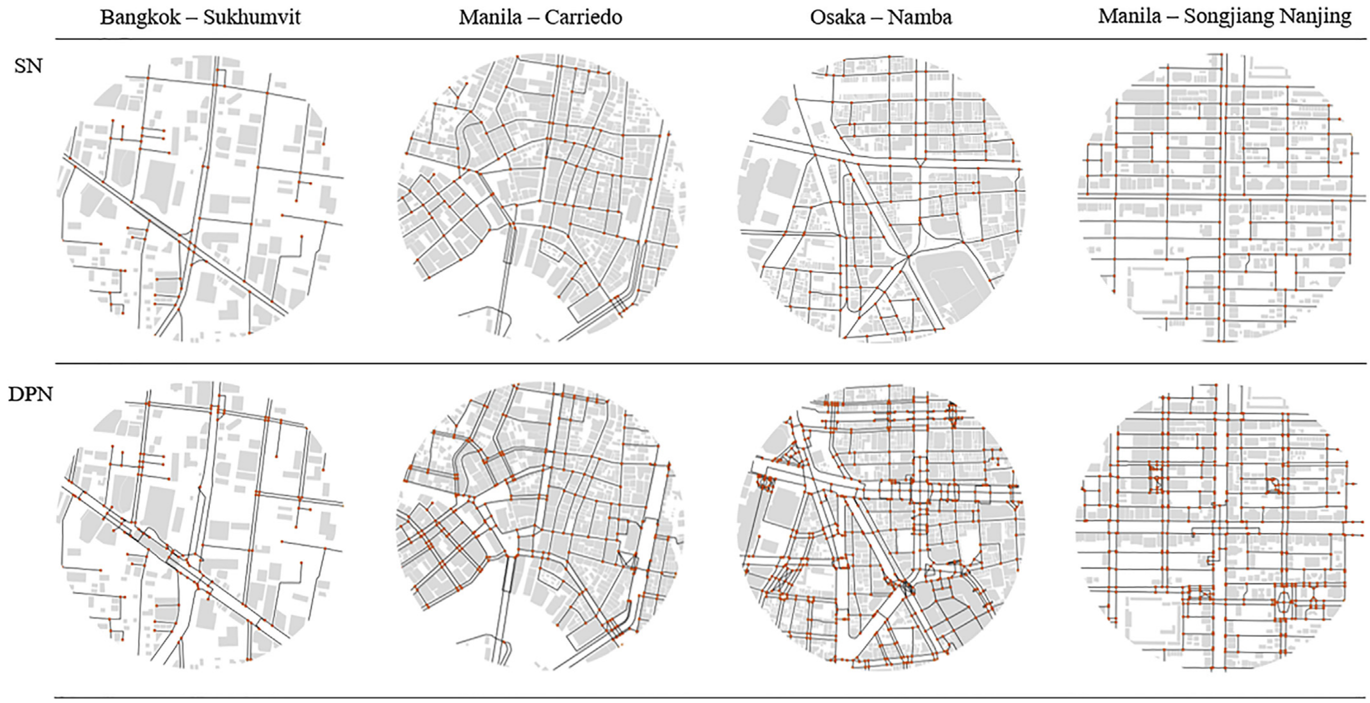


Fig. 3. 400m study street networks (SN) and dedicated pedestrian networks (DPN).

3.3.2. *Conventional accessibility metrics*

Pedsheds measure the accessible area that can be reached from a specific location via a network for a specified distance, expressed as a percentage of the corresponding Euclidean area (Porta and Renne, 2005). Higher percentages denote greater accessibility. Pedsheds are calculated for 400m distances from the centre of each study area. *Pedestrian Route Directness (PRD)* is the ratio of actual travel distance to straight-line distance between specific origins and destinations within a network (Randall and Baetz, 2001). This study reverses PRD by dividing network distance by Euclidian distance, similar to approaches taken in other studies. This ensures the measure is in line with others with higher values indicating more direct routes and hence better connectivity as assessed by permeability to destinations. PRD is calculated as the mean of all routes from the midpoints of network links to the centre of each 400m study area.

3.3.3. *Configurational and spatial accessibility metrics*

Directional Reach measures the total network length that can be covered when walking in all directions from a specific origin up to a specified distance with conditions placed on the number of direction changes allowed (Ellis et al., 2017). Consequently, it considers directional accessibility taking into account the cognitive impedance of going from path to another, which is important in navigation (Ozbil et al., 2011). Directional reach is defined by equation (1):

$$R_u(P_i,\ \delta,\ \alpha,\ r) \tag{1}$$

where the directional reach $R_u(P_i,\ \delta,\ \alpha,\ r)$ of a point P_i is measured according to a directional threshold δ as the aggregate length of path links that are no more than δ directional changes away subject to a direction change threshold of α and a very small line segment threshold set to a fraction r of the average path link (Peponis et al., 2008). This study employs a directional threshold of two turns and a degree threshold of 30° to constitute a turn each time it is exceeded. These parameters ensure that the distance covered is sufficient for analysis in denser pedestrian environments (Ellis et al., 2016). Directional reach is calculated from the midpoints of network links that are within each 400m study area and measured up to a 400m distance. Finally, the results are dissolved and the mean value is computed for each study area.

Betweenness Centrality measures the importance of an element in a network in terms of how many shortest paths pass through it (Freeman, 1977). Normalised betweenness centrality used in this study is formally defined by equation (2):

$$BC(i)^r = \frac{2}{(N-1)(N-2)} \sum_{j,k\in G-\{i\},\ d[j,k]\le r} \frac{n_{jk}[i]}{n_{jk}} \tag{2}$$

where $BC(i)^r$ is the betweenness of node i within search radius r; $n_{jk}[i]$ is the number of network shortest paths between nodes j and k that pass through node i; and n_{jk} is the total number of shortest paths between nodes j and k (Sevtsuk and Mekonnen, 2012). Normalised betweenness is calculated for network links within 400m of the centre of each study area and is calculated locally up to a 400m radius on a larger 800m network minimise edge effect. Mean normalised betweenness was then computed for each study area.

Closeness Centrality measures how close an element is to all other elements in a network calculated as the mean of the shortest path lengths (Freeman, 1979). Normalised closeness centrality used in this study is formally defined by equation (3):

$$CC(i)^r = \frac{N-1}{\sum_{j\in G-\{i\},d[i,j]\le r} d[i,j]} \tag{3}$$

where $CC(i)^r$ is the closeness of node i within search radius r; $d[i,j]$ is the shortest path distance between nodes i and j (Sevtsuk and Mekonnen, 2012). Normalised closeness is calculated locally up to a400 m radius in the same manner as betweenness centrality to minimise edge effect. Mean normalised closeness was then computed for each study area.

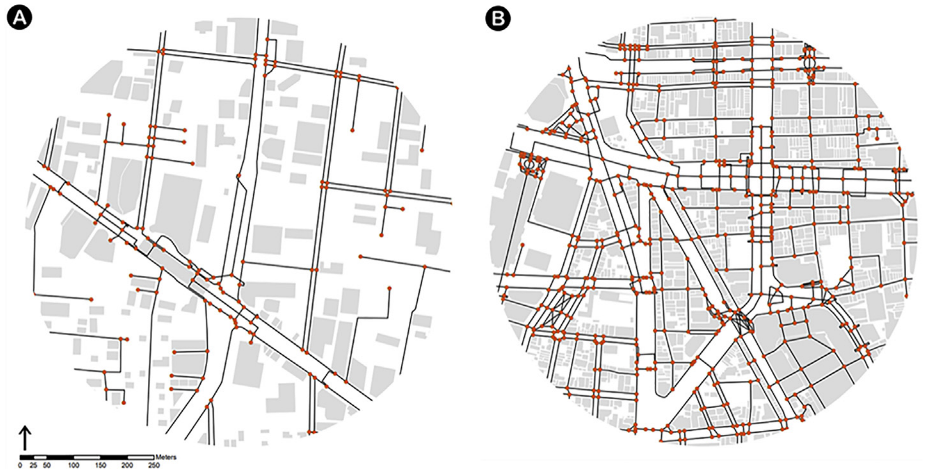
4. Analysis

Table 4 summarises accessibility and connectivity metrics derived from 400m street networks and dedicated pedestrian networks (DPNs) for each study site. It is clear that values calculated on both networks vary considerably across metrics, as shown by the percentage difference when focusing on pedestrian networks.

Table 4
Accessibility and connectivity values for 400m street (SN) and dedicated pedestrian networks (DPN).

Metrics	Bangkok -Sukhumvit		Manila - Carriedo		Osaka - Namba		Taipei - Songjiang Nanjing	
	SN	DPN	SN	DPN	SN	DPN	SN	DPN
Conventional Connectivity								
LNR	1.52	1.62	1.80	1.82	1.97	1.72	1.88	1.65
% change	7%		1%		−12%		−12%	
CNR	0.07	0.20	0.30	0.41	0.33	0.25	0.26	0.31
% change	195%		35%		−23%		19%	
Conventional Accessibility								
Pedshed	43.31	47.31	56.46	61.68	60.05	62.46	63.52	65.96
% change	9%		9%		4%		4%	
PRD	0.63	0.67	0.74	0.80	0.76	0.80	0.80	0.80
% change	6%		7%		5%		0%	
Configurational / Spatial Accessibility								
Directional Reach (m)	17,684	25,080	31,282	47,184	43,656	65,298	39,705	46,264
% change	42%		51%		50%		17%	
BC - Local Mean[a]	607.87	454.44	364.22	231.96	265.45	175.11	305.73	226.74
% change	−25%		−36%		−34%		−26%	
CC - Local Mean[b]	408.90	398.40	388.80	383.90	375.70	375.40	369.10	384.20
% change	−3%		−1%		0%		4%	

[a] Betweenness Centrality values expressed 10 ˆ 4.
[b] Closeness Centrality values expressed 10 ˆ 5.



A. Bangkok – Sukhumvit; B. Osaka – Namba.

Fig. 4. Difference in pedestrian network forms (400m network).

It is important to note that pedestrian networks always result in larger networks with more nodes, and lower mean lengths per link. This further varies by the nature and complexity inherent in each urban network form (Fig. 4). For example, in relatively uncomplex pedestrian environments like Bangkok that is characterised by long blocks with few mid-block crossings, a lack of open public spaces, and few multi-level paths, the pedestrian network is only 35% longer than that of the street network and yields 95% more nodes. This contrasts with the more complex pedestrian environment of Osaka that is characterised by a higher number of sub-surface and pedestrian-only paths not reflected in the street network to result in a pedestrian network that is 98% longer and yields 346% more nodes than its street network. These network differences naturally have a large impact on conventional connectivity metrics that rely on links and nodes as inputs, and conventional accessibility metrics that measure accessibility in terms of area and reachable network.

4.1. *Differences in accessibility and connectivity metrics across network types*

LNR results derived from DPNs yielded mixed results consistent with results reported for urban areas in other studies (Zhang and Zhang, 2019; Tal and Handy, 2012). In Bangkok and Manila, LNR values increased modestly by 7% and 1%, respectively (Fig. 5). This contrasts with much larger differences observed in the more complex and dense pedestrian environments of Osaka and Taipei where LNR values decreased by 12%. This is expected and is attributable to how pedestrian networks in Osaka and Taipei result in fewer 4-way nodes with the addition of paths in public open spaces and large intersections. In other words, the pedestrian network adds more nodes to the network than links. In contrast to Zhang and Zhang (2019) who reported an increase in pedestrian network CNR values in all study sites, this study reports different results. In all but one study site – Osaka, which features many 3-way nodes due to its irregular grid pattern, CNR values improved when calculated on the pedestrian network. Bangkok reported the largest increase in CNR values, where an improvement of 195% was observed when switching to its DPN. The Bangkok street network consists of several divided streets that result in

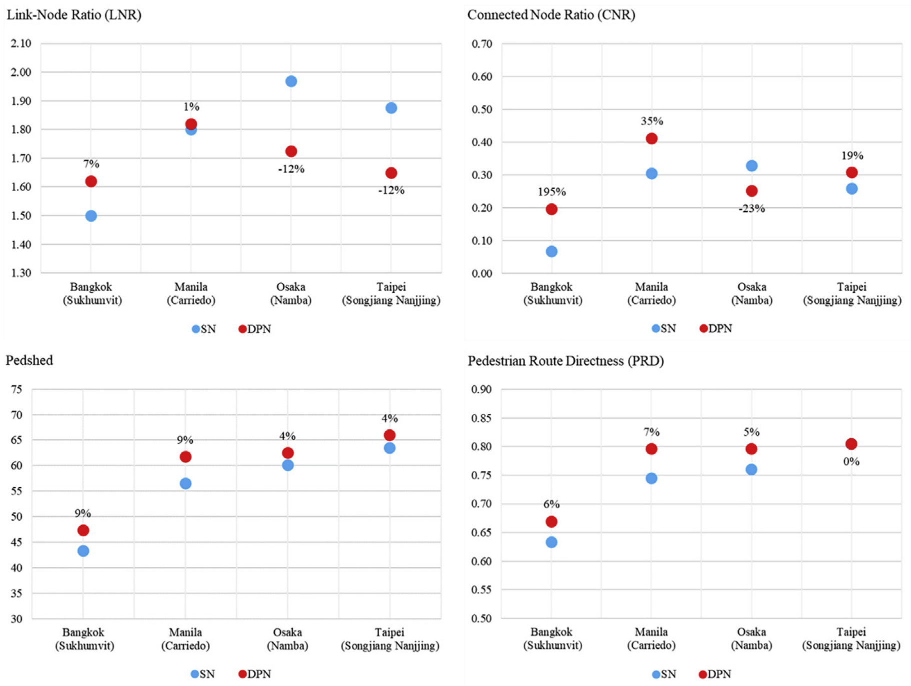


Fig. 5. Differences in connectivity and accessibility values between street (SN) and dedicated pedestrian networks (DPN).

many 3-way nodes, while the DPN produces more 4-way nodes. This, in combination with a relatively small increase in pedestrian nodes, produces a large increase in CNR.

DPNs produced higher conventional accessibility values in almost all environments as predicted. Pedshed values increased in all study sites by 4–9%, with the largest increase of 9% observed in both Bangkok and Manila. While direct comparisons are difficult due to methodology, prior studies report much higher levels of improvement in their respective pedestrian networks, primarily due to their focus on mostly suburban areas (Tal and Handy, 2012; Chin et al., 2008). PRD values also increased by 5–7% in all study sites with the exception of Taipei where no change was recorded. Taipei's network within 400m of the centre of the study site consists mainly of sidewalks on both sides of the street and shared narrow streets, largely mirroring the street network. As such the DPN does not really improve route directness. The findings here are similar to Zhang and Zhang (2019) where PRD values calculated on their pedestrian network either stayed the same or increased. However, increases in PRD values in their study were marginally lower than those observed in this study, averaging 2.5%, as opposed to 6% in the present study. This is explained by their decision to include only formal facilities in their pedestrian network that often results in fewer links, and thus a more broken and less direct network (Zhang and Zhang, 2019).

As pedestrian networks are longer than their counterpart street networks, directional reach values increased significantly in most locations. Directional reach improvements ranged from 17 to 51%. The lowest increase of 17% observed in Taipei is most likely explained by the number of small parks and squares that are located within the 800m network that directional reach is calculated on. This can result in more paths that exceed the 30-degree threshold angle reducing how much network can be covered up to the 400m distance threshold. Additionally, several large intersections are "squared off." This also impacts directional reach negatively and further demonstrates the importance of the pedestrian network representation.

A core focus of this study is to understand how centrality metrics would perform on DPNs. Mean normalised local betweenness values decreased substantially when calculated on pedestrian networks across all study sites as hypothesised (Fig. 6). The percentage decrease ranged from 25 to 36%. The decrease in mean betweenness values was expected and can be attributed to the increase of route choices that typically go hand-in-hand with switching to DPNs. Street networks have fewer routes which raises the probability of a link being travelled along between node pairs, raising the overall mean across the study site.

Conversely, closeness centrality yielded mixed results, though the differences in values is far smaller between both network

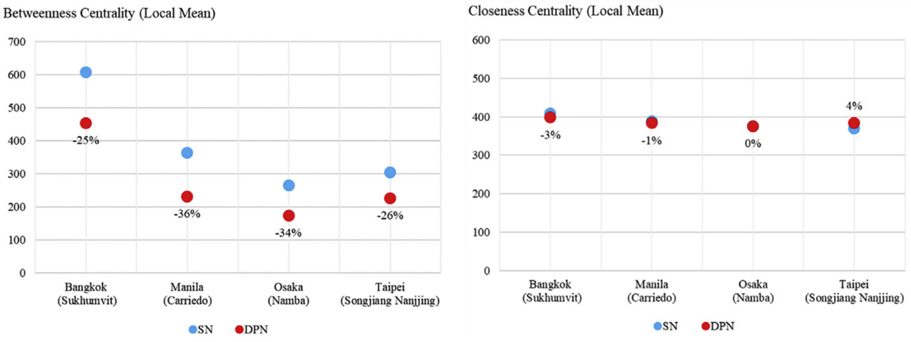


Fig. 6. Differences in centrality values for street (SN) and dedicated pedestrian networks (DPN).

representations. Mean normalised local closeness values either slightly increased, decreased, or stayed the same when switching to the DPN with values ranging from −3% to 4%. Denser pedestrian networks in Osaka and Taipei that have shorter links performed better as hypothesised. Nevertheless, in general it is difficult to discern trends across the different environments in this study. The cause for this could lie in the approach taken in this study to the edge effect and how closeness was measured. This study sought to overcome this effect by doubling the analysis boundary to 800m for centrality metrics. Extending the boundary further and incorporating global measures could yield clearer results. Finally, focusing on the individual closeness values of network links, as opposed to mean values for each study area, may be a better application of closeness when comparing results between DPNs and street networks.

5. Conclusion

This study builds on previous studies by reporting significant differences between dedicated pedestrian networks (DPNs) and street networks when measuring a broad array of accessibility and connectivity metrics in Asian cities.

It is clear that non-distance-based conventional connectivity metrics that rely on countable features are extremely susceptible to how the pedestrian network is represented (Ellis et al., 2016). The complexity inherent in each urban network and how nodes increase with respect to links complicates this matter further. The decreases in LNR and CNR values when calculated on the DPN in Osaka – arguably the most connected in this study – is a cause for concern. These metrics appear better suited to street networks or to provide a simple description of how gridded a network is (Tal and Handy, 2012). Distance-based accessibility metrics on the other hand, performed well and are suitable for DPNs. We found that accessibility measured by pedsheds and PRD is underestimated by as much as 7% and 4%, respectively, across all study sites when calculated on street networks in line with our hypothesis. DPNs as defined in this study, include all manner of shared and exclusive pedestrian paths that are not reflected in street networks. Thus, they account for real distances and actual route options, and should be employed in studies that prioritise these concepts.

The inclusion of centrality metrics networks yielded mixed results. While local betweenness values decreased substantially when measured on DPNs as predicted, local closeness values were far similar between both network types. However, closeness yielded differing results and no discernible trends were observed. This could be attributable to the edge effect of the network boundaries. Centrality metrics are typically applied to larger networks than those used in our study and our findings may be limited by the extent of our networks. Extending the analysis boundary further and focusing on the individual closeness values of network elements, as opposed to the mean value for each study area, may be a better application of closeness when comparing results between DPNs and street networks. Nonetheless, centrality metrics appear suitable for measurement on DPNs and merit further research.

The approach taken in this study to defining and creating a DPN with OpenStreetMap data proved suitable for Asian cities with the vast majority of variables performing as expected. Including study sites in cities in other parts of the world, would further improve our understanding of the applicability of this network representation and the performance of centrality metrics calculated on it. Additionally, it creates an opportunity to develop new metrics specifically suited to this representation that better address pedestrian accessibility, connectivity, safety and comfort, particularly in regard to crossings. Finally, several studies have begun exploring the relationships between accessibility and connectivity metrics measured on pedestrian networks and levels of physical activity (Cruise et al., 2017; Ellis et al., 2016). These studies have reported varying results. A logical step moving forward would be to expand this research by exploring the relationships between pedestrian activity and spatial accessibility measures calculated in this study.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Cervero, R., Kockelman, K., 1997. Travel demand and the 3Ds: density, diversity, and design. Transport. Res. Part D 2 (3), 199–219.

Cervero, R., Radisch, C., 1996. Travel Choices in Pedestrian versus Automobile Oriented Neighborhoods. University of California Transportation Center, p. 281.

Chin, G.K.W., Van Niel, K.P., Giles-Corti, B., Knuiman, M., 2008. Accessibility and connectivity in physical activity studies: the impact of missing pedestrian data. Prev. Med. 46, 41–45.

Cruise, S.M., Hunter, R.F., Kee, F., Donnelly, M., Ellis, G., Tully, M.A., 2017. A comparison of road- and footpath-based walkability indices and their associations with active travel. J. Transport Health 6, 119–127.

Ellis, G., Hunter, R., Tully, M.A., Donnelly, M., Kelleher, L., Kee, F., 2016. Connectivity and physical activity: using footpath networks to measure the walkability of built environments. Environ. Plann. Plann. Des. 43, 130–151.

Ewing, R., 1996. Pedestrian- and Transit-Friendly Design: A Primer for Smart Growth. Smart Growth Network.

Fang, K., Wang, X., Chen, L., Zhang, Z., Furuya, N., 2019. Research on the correlation between pedestrian density and street spatial characteristics of commercial blocks in downtown area: a case study on Shanghai Tianzifang. J. Asian Architect. Build Eng. 18 (3), 233–246.

Freeman, L., 1977. A set of measures of centrality based on betweenness. Sociometry 40, 35–41.

Freeman, L., 1979. Centrality in social networks: conceptual clarification. Soc. Network. 1 (3), 215–239.

Fukuyama, S., Hato, E., 2012. Network analysis of Plaza-street system based on the historical development process of the Old city of Barcelona in considering the range of walking distance. J. Jpn. Soc. Civ. Eng. Ser. D1 (Archit. Infrastruct. Environ.) 68 (1), 13–25 (in Japanese).

Gil, J., 2014. Analyzing the configuration of multi-modal urban networks. Geogr. Anal. 46 (4), 368–391.

Gil, J., 2015. Building a Multimodal Urban Network Model Using OpenStreetMap Data for the Analysis of Sustainable Accessibility. OpenStreetMap in GIScience: Experiences, Research, and Applications. Springer, Cham, pp. 229–251.

Gil, J., 2017. Street network analysis "edge effects": examining the sensitivity of centrality measures to boundary conditions. Environ. Plann. B: Urban Anal. City Sci. 44 (5), 819–836.

Graser, A., 2016. Integrating open spaces into OpenStreetMap routing graphs for realistic crossing behaviour in pedestrian navigation. GI_Forum: J. Geogr. Inf. Syst. 4 (1), 217–230.

Greenwald, M.J., Boarnet, M.G., 2001. Built environment as determinant of walking behavior: analyzing nonwork pedestrian travel in Portland, Oregon. Transport. Res. Rec. J. Transport. Res. Board 1780, 33–42.

Hajrasouliha, A., Yin, L., 2015. The impact of street network connectivity on pedestrian volume. Urban Stud. 52 (13), 2483–2497.

Handy, S., 2005. Planning for accessibility. In: Theory and in Practice. *Access to Destinations*. Elsevier, Oxford, pp. 131–147.

Hansen, W.G., 1959. How accessibility shapes land use. J. Am. Plann. Assoc. 25 (2), 73–76.

Hess, P., 1997. Measures of connectivity. Places 11 (2), 58–65.

Hess, P., Moudon, A., Snyder, M., Stanilov, K., 1999. Site design and pedestrian travel. Transport. Res. Rec. 1674, 9–19.

Hillier, B., Hanson, J., 1984. The Social Logic of Space. Cambridge University Press, Cambridge.

Kang, C.-D., 2018. The S + 5Ds: spatial access to pedestrian environments and walking in Seoul, Korea. Cities 77, 130–141.

Karimi, H.A., Kasemsuppakorn, P., 2013. Pedestrian network map generation approaches and recommendation. Int. J. Geogr. Inf. Sci. 27 (5), 947–962.

Mansouri, M., Ujang, N., 2016. Space Syntax analysis of tourists' movement patterns in the historical district of Kuala Lumpur, Malaysia. J. Urban.: Int. Res. Placemaking Urban Sustain. 1–18.

Ozbil, A., Peponis, J., Stone, B., 2011. Understanding the link between street connectivity, land use and pedestrian flows. Urban Des. Int. 16 (2), 125–141.

Peponis, J., Bafna, S., Zhang, Z., 2008. The connectivity of streets: reach and directional distance. Environ. Plann. Plann. Des. 43, 881–901.

Porta, S., Crucitti, P., Latora, V., 2008. Multiple centrality assessment in parma: a network analysis of paths and open spaces. Urban Des. Int. 13, 41–50.

Porta, S., Renne, J.L., 2005. Linking urban design to sustainability: formal indicators of social urban sustainability field research in Perth, Western Australia. Urban Des. Int. 10, 51–64.

Randall, T.A., Baetz, B.W., 2001. Evaluating pedestrian connectivity for suburban sustainability. J. Urban Plann. Dev. 127 (1), 1–15.

Sevtsuk, A., Mekonnen, M., 2012. Urban network analysis: a new toolbox for ArcGIS. Int. J. Geomat. Spatial Anal. 22 (2), 287–305.

Song, Y., 2003. Impacts of Urban Growth Management on Urban Form: A Comparative Study of Portland, Oregon, Orange County, Florida and Montgomery County, Maryland. *National Center for Smart Growth Research and Education*, University of Maryland.

Speck, J., 2012. Walkable City: How Downtown Can Save America One Step at a Time. Farrar, Straus and Giroux, New York.

Tal, G., Handy, S., 2012. Measuring non-motorized accessibility and connectivity in a robust pedestrian network. Transport. Res. Rec.: J. Transport. Res. Board 2299, 48–56.

United Nations Development Programme, 2018. 2018 Statistical Update: Human Development Indices and Indicators (New York).

Zhang, L., Chiaradia, A., 2019. Three-dimensional spatial network analysis and its application in a high-density city area, Central Hong Kong. Urban Plann. Int. 34 (1), 46–53.

Zhang, H., Zhang, Y., 2019. Pedestrian network analysis using a network consisting of formal pedestrian facilities: sidewalks and crosswalks. Transport. Res. Rec. 2673 (7), 294–307.