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Article *in* Environment and Planning B Urban Analytics and City Science · June 2019

DOI: 10.1177/2399808319857726

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Article

Urban Analytics and City Science

EPB: Urban Analytics and City Science
0(0) 1–17

DOI: 10.1177/2399808319857726
journals.sagepub.com/home/epb
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The morphology and circuity of walkable, bikeable, and drivable street networks in Phnom Penh, Cambodia

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Abstract

Street network analysis is a growing area in sustainable transportation research. Most academic papers on the topic have, so far, been concentrated in Europe and America, with less attention paid to rapidly growing cities in low income nations. This is problematic because transportation networks are rapidly evolving in developing countries and the impacts of misguided transportation policies (including air pollution and road traffic casualties) are particularly acute. Metrics on the performance of street networks could help inform policy. This paper uses the Python package OSMnx to analyze and evaluate street networks in 12 districts of Phnom Penh from OpenStreetMap. Results suggest that topological and geometric characteristics of street networks are more conducive to walking and biking in the central districts than in the peripheral districts. The central districts are also better connected to core network corridors. To promote sustainable urban mobility, new developments and street renewals should be incorporated facilities, services, and safety of walking and biking. Some policy implications are suggested for future designs of the Phnom Penh's street networks to increase livability and sustainability.

Keywords

Street network, circuity analysis, urban morphology, OpenStreetMap, OSMnx

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Introduction

Making transportation systems more efficient and sustainable has become the main focus of urban researchers and planners in recent years (Sharifi, 2019). Sustainable transport has particularly positive effects on the promotion of active travel and living (Mahmoudi et al., 2015; Wey and Huang, 2018). A street that is designed for different modes of travel has a range of mobility choices to reach the shortest destinations and provides safe and comfortable experiences for pedestrians, cyclists, and transit riders (NACTO, 2016). However, such a design is mostly neglected in the process of urban planning practice and research for the majority of world cities (Lee, 2016). Streets that are optimized only for vehicular traffic will impose dangers on all road users, mainly pedestrians and cyclists. For instance, World Health Organization reported that pedestrians were the primary victims (between 55 and 70%) of road traffic deaths in the developing world (WHO, 2015). A lack of proper urban design has therefore been tagged as a key contributing factor for major public health and traffic accidents (Singh, 2016).

Numerous studies have been conducted to measure street networks (SNs) in Europe and America, with less attention paid to rapidly growing cities in low income nations (Cao et al., 2017). For example, Boeing (2018c) measured 27,000 urban SNs in the US cities, towns, and urbanized areas. Likely, Karduni et al. (2016) analyzed SNs of 80 populated cities around the world but did not include emerging cities in low income countries. Remarkably, some researchers measure only SNs of car (Giacomin and Levinson, 2015), bike (Godwin and Price, 2016), transit (Huang and Levinson, 2015), train (Caset et al., 2018), and travel time (Cao et al., 2017), but the relative drivable street networks (DSNs) versus walkable street networks (WSNs) have not been much explored (Boeing, 2018b). In this regard, Boeing examined DSNs and WSNs in 40 US cities. Still, his study did not analyze bikeable street networks (BSNs) together with DSNs and WSNs (Boeing, 2018b). Of course, BSNs are also likely accessible for walking, but not all WNSs are bikeable, because some may include mid-block cut-throughs, passageways between buildings, paths across parks, and other shortcuts that are not bikeable or not allowed for biking. More importantly, different cities have different street patterns. Some cities have irregular street patterns with short or crooked streets while others have a hierarchical structure with regular, curvilinear, and orthogonal patterns (Lee and Jung, 2018). Moreover, research highlights the lack of available datasets for DSNs, WSNs, and BSNs in many cities, specifically in Cambodia. Some researchers also admit to difficulties when doing research on SNs, such as (1) data limit and processing constraints, (2) coding and programming skills required for data reproducibility (Karduni et al., 2016), (3) excessive network simplification and inconsistency of definitions (Marshall et al., 2018), and (4) the shortage of free and easy-to-use tools (Boeing, 2017).

Consequently, the extant paper examines the characteristics and accessibility of SNs in Phnom Penh, a typical city with its distinctive properties. The study produced a network dataset of the city and then used multiple metrics and the OSMnx toolkit to analyze spatial features of DSNs, BSNs, and WSNs. The interpretation of various effects among the metrics of the street configuration produced specific concepts for urban policy and design that could re-adjust traffic issues and plans for better SNs.

Literature review

Definitions and measures of SNs

SNs are a backbone of urban transportation structures that organize human dynamics and traffic flow. SNs also provide useful information that shapes commutes, travel behaviors, and location decisions of households and firms (Kang, 2017; Shatu and Yigitcanlar, 2018). Theoretically, an analysis of SNs requires measuring both topological and geometric characteristics (Spadon et al., 2018). The topological character explains the SNs' connectivity, centrality, and clustering, whereas the geometric character describes SNs' distances, areas, and densities (Boeing, 2018a).

Many studies used different tools and models to measure SNs. For example, some used historical development patterns to measure SNs for bicycling and walking (Godwin and Price, 2016), others employed circuity analysis to measure the travel time and distance (Cao et al., 2017), and some others applied SPOT imagery to assess the morphology of SNs (Mohd Nor et al., 2018). However, these studies used only some measures to analyze SNs' connectivity, centrality, circuity, traversal, topography, and evolution (Marshall et al., 2018). Our study applied multiple metrics, such as closeness centrality, betweenness centrality, average circuity, densities, nodes and edges, and street lengths, to measure SNs. Using these approaches, the study more precisely captures multi-dimensional spatial features of SNs.

SNs metrics are defined in some studies (Boeing, 2017; Ibnoulouafi and El Haziti, 2018; Kirkley et al., 2018). Some definitions of the metrics associated with SNs are herewith presented. *Closeness centrality* is a reciprocal of the sum of the distance from a node (origin) to all reachable nodes (destinations) in SNs (He et al., 2018). It is necessary to know the maximum closeness centrality values of the network in order to decide where to place emergency service facilities that could enhance accessibility in case of disaster (Sharifi, 2019). *Betweenness centrality* is a prediction of how each SN link is populated as all possible shortest paths pass through the node (Boeing, 2017). *Edges* are the interfaces between streets and the adjoining buildings and plots. Whereas, the *average street length* is a linear proxy for block size and specifies the network's grain. *Street density* is a measurement of the total street length divided by the areas in square kilometers (Boeing, 2018c). Additionally, *circuity*, a ratio of shortest network distances to straight-line distances between origin and destination, is a crucial element of network structure and transport efficiency that affects how humans utilize urban space for settlement and travel (Ballou et al., 2002; Giacomin and Levinson, 2015). Cities whose SNs have a low average circuity have more efficient transport systems (Giacomin and Levinson, 2015).

The significance of SNs

The prominent roles of SNs in facilitating socioeconomic activities and environmental sustainability have attracted much research efforts in this area (Marshall et al., 2018; Wang et al., 2018). Specifically, each SNs' metric interprets important information that has implications on urban morphology design and planning. For instance, different street attributes promote higher walking and biking volumes (Sarkar et al., 2015). Also, a longer convex hull with a maximum radius that covers a broader area and edges tends to boost social interactions and cohesion in neighborhoods (Cooper et al., 2014). Furthermore, a higher density of nodes could reduce traffic congestion (Gundlegård et al., 2016), promote connectivity within neighborhood communities (He et al., 2018), and increase property value (Bielik et al., 2018). Likewise, a vibrant edge that has active frontages and sidewalks, vegetation, mixed land use, and traffic calming can turn streets into active boundaries and ensure active living. Moreover, people tend to choose residential areas that offer less circuitous commutes (Giacomin and Levinson, 2015) because the least average circuity is closer to the shortest travel distance/time and indicates travel efficiency as well as the promotion of nonvehicular dependency (Cao et al., 2017). Although mounting scientific evidence proves the importance of SNs, there has been scant information from such studies in Cambodia.

Method and materials

Study area

With a growth rate of 4.4% per year, Phnom Penh is the fastest growing city in Southeast Asia. The city encapsulates 12 districts with a total area of 678.47 square kilometers and 1.8 million people in 2015 (Yen et al., 2017). The four central districts, Daun Penh, Chamkar Mon, Tuol Kork, and Prampi Makara were jointly designed by French colonial urban planners in the 1950s (Sub-Decree, 2015) and the peripheral districts were subsequently integrated from neighboring provinces in 2000s (Figure 1).

The 1267 kilometers total road length in the capital is comprised of 718 kilometers municipal, 455 kilometers rural, and 93 kilometers national roads. The capital also has two railways lines—386 kilometers northern line running from Phnom Penh to

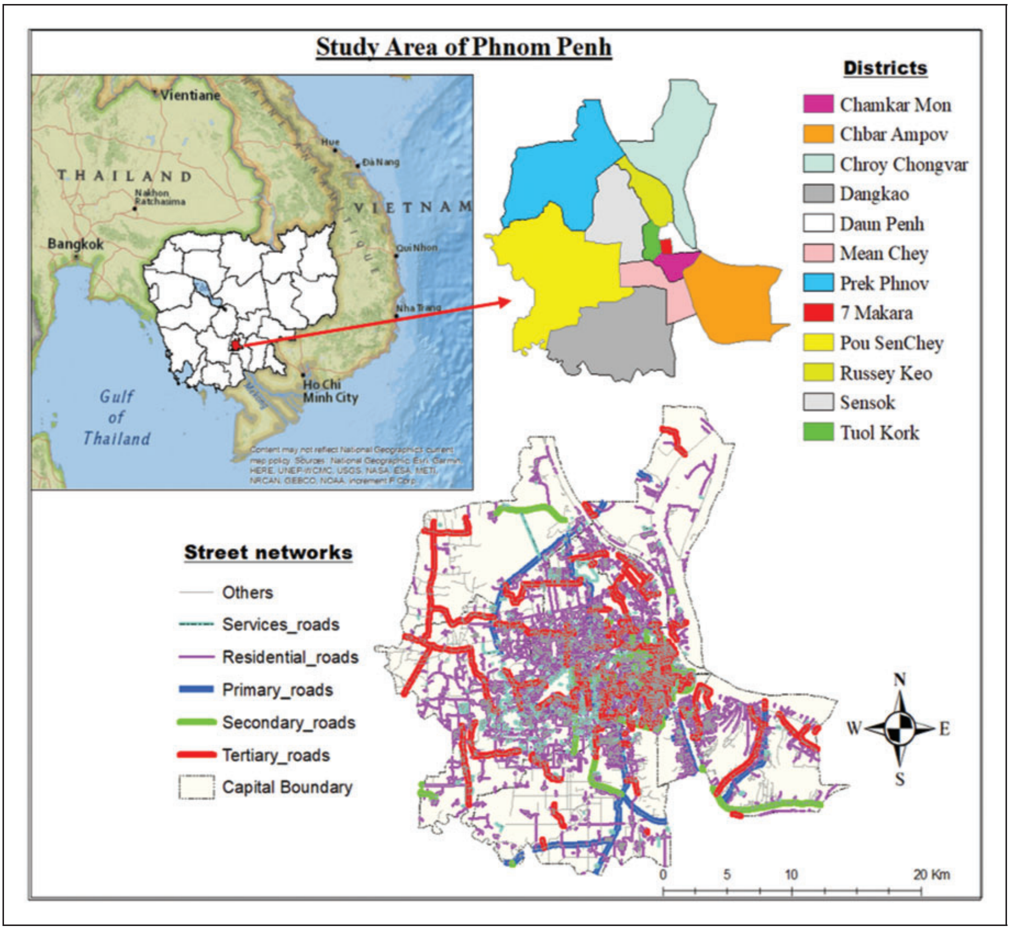

Figure 1. The map of the districts and the location of Phnom Penh.

Figure 2. A section of Phnom Penh's DSNs, showing the shortest path (red line) between two nodes, accounting for one-way streets, and the great-circle path (blue line).

Battambang and Banteay Meanchey provinces, and the 264 kilometers southern line running from Phnom Penh to Sihanouk Ville.

Data acquisition

This study employed the OSMnx toolkit to download and analyze DSNs, BSNs, and WSNs from the 2018 OSM data. OSMnx provides geospatial abilities and interacts directly with OSM's Nominatim and Overpass APIs by running the codes to extract SNs of interest (Boeing, 2017). It can simplify and correct SNs' topology and geometry automatically to ensure that nodes accurately represent intersections and dead-ends. Moreover, it also can calculate the shortest distance between nodes as well as other SN metrics (Figure 2). Users can use OSMnx to query an area of interest by bounding box, address, point, polygon, or by place names. The OSMnx also enables users to save SNs as GIS shapefiles. The researchers could also use other tools, such as R package stplanr (a package for sustainable transportation planning with R) to analyze spatial transportation data, with a focus on origin–destination data (Lovelace and Ellison, 2018), and C++ library sDNA to predict transportation flows (Cooper, 2017). The OSMnx packages and Jupyter Notebook were installed in Anaconda v.4.5.11 (www.anaconda.com) to work with Python 3.7.0. To acquire SN data for this study, first OSMnx buffered each geometry by 0.5 kilometers and then downloaded the "nodes" and "edges" from the OSM within the buffer. Next, it constructed SN graphs from these data, corrected the topology, and calculated metric and topological measures for each SN (Figure 3). Finally, it saved each of SNs as shapefiles.

Data analysis

Data on the 12 districts in Phnom Penh were examined to analyze the differences of SNs. Hypotheses were proposed to compare differences of average circuity of DSNs, BSNs, and WSNs. A paired sample *t-test* was also used to confirm the statistical significance of differences between the three SNs' circuities and to determine if the analysis supports the rejection of the null hypothesis H_0

$$H_0 : \mu_d = \mu_{w,} \quad \text{or} \quad \mu_d = \mu_b, \quad \text{or} \quad \mu_b = \mu_w$$

$$H_1 : \mu_d \neq \mu_w, \quad \text{or} \quad \mu_d \neq \mu_b, \quad \text{or} \quad \mu_b \neq \mu_w$$

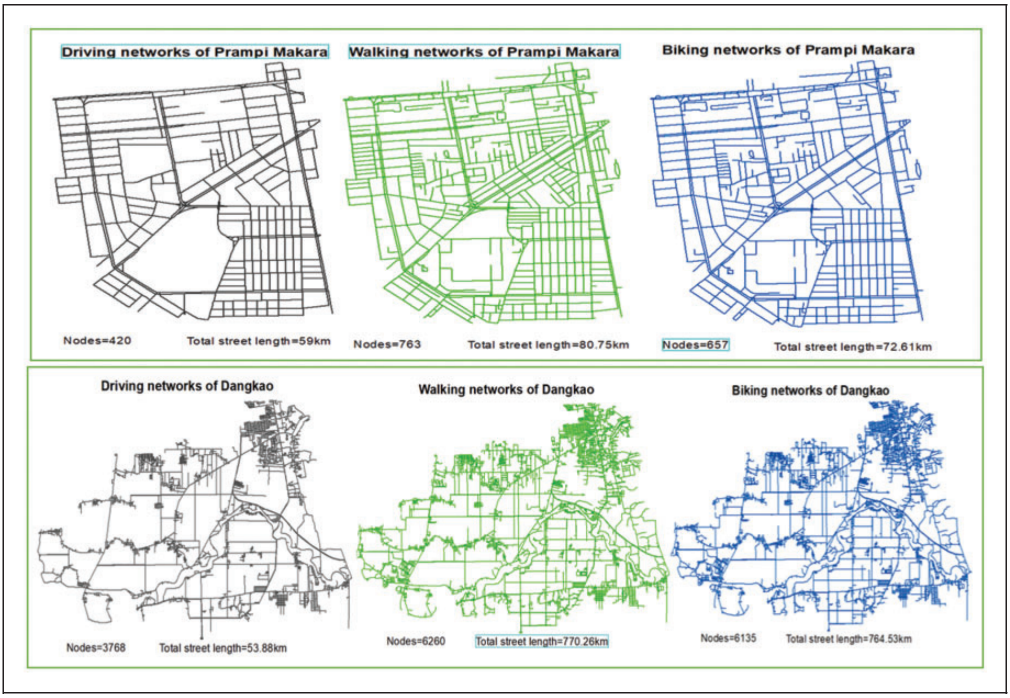

Figure 3. The DSNs (dark gray), WSNs (light green), and BSNs (dark blue) between central district (Prampi Makara) and peripheral district (Dangkao).

where μ_d is average circuity of DSNs, μ_w is average circuity of WSNs, and μ_b is average circuity of BSNs.

The φ ratio of μ_d to μ_w (formula (1)), the ratio of μ_d to μ_b (formula (2)), and the ratio of μ_b to μ_w (formula (3)) were formulated

$$\varphi = \frac{(\mu_d - 1)}{(\mu_b - 1)} \tag{1}$$

$$\varphi = \frac{(\mu_d - 1)}{(\mu_w - 1)} \tag{2}$$

$$\varphi = \frac{(\mu_b - 1)}{(\mu_w - 1)} \tag{3}$$

The φ ratio was subtracted by 1 for each term because the minimum possible circuity is 1 (Boeing, 2018b; Giacomin and Levinson, 2015). Finally, for each district, we calculated the effect size as *Cohen's d* to measure whether or not μ_w was greater than μ_d or vice versa, μ_w was greater than μ_b or vice versa, and μ_b was greater than μ_d or vice versa

$$d_{d/w} = \frac{(\mu_d - \mu_w)}{\sqrt{\frac{(n_d-1)\delta_d^2+(n_w-1)\delta_w^2}{(n_d-1)+(n_w-1)}}} \tag{4}$$

$$d_{d/b} = \frac{(\mu_d - \mu_b)}{\sqrt{\frac{(n_d-1)\delta_d^2+(n_b-1)\delta_b^2}{(n_d-1)+(n_b-1)}}} \tag{5}$$

$$d_{b/w} = \frac{(\mu_b - \mu_w)}{\sqrt{\frac{(n_b-1)\delta_b^2+(n_w-1)\delta_w^2}{(n_b-1)+(n_w-1)}}} \tag{6}$$

where $d_{d/w},\ d_{d/b},\ d_{b/w}$ are the effect size of the difference between μ_w and μ_d, μ_b and μ_d, and μ_w and μ_b, respectively. While n_d, n_w, and n_b are numbers of sample sizes for DSNs, WSNs, and BSNs, and $\delta_d^2; \delta_w^2; \delta_b^2$ are variances for DSNs, WSNs and BSNs. *Cohen's d* divides the mean difference in route circuity by the pooled standard deviation. If the effect of WSNs exceeds the effect of DSNs on minimizing trip circuity, μ_d would be greater than μ_w (i.e. WSNs allow for more direct routes). Conversely, if the effect of DSNs exceeds the effect of WSNs on minimizing trip circuity, μ_w would be greater than μ_d (i.e. DSNs allow for more direct routes).

Results

The edge densities in the central districts are higher than those (i.e. edge densities) in the peripheries (Figure 4). Also, the densest edge density is found in the WSNs followed by the edge density of the BSNs. The average circuities of DSNs versus WSNs significantly differ in 11 out of 12 districts while average circuities of DSNs versus BSNs statistically differ by significant margins in all districts (Table 1). Only Prampi Makara district has average circuity of WSNs higher than that of average circuity of DSNs. Whereas the average circuities of BSNs are statistically different from average circuities of WSNs, but the *t-test* did not show a significant difference ($p > 0.05$). Thus, the null hypothesis for WSNs versus BSNs was rejected.

The mean distance of routes along DSNs (δ_d), BSNs (δ_b), and WSNs (δ_d) informs how much distance can be saved between DSNs versus WSNs, DSNs versus BSNs, or WSNs versus BSNs by taking a more direct mode of the trip. For example, the average WSNs in Daun Penh are 42.92 meters shorter than the average DSNs. However, there is little different mean distance between WSNs and BSNs. The differences of mean distance are correlated with SN sizes and larger spatial extents of the city's districts that require higher trip distance. Among the four central districts, the total lengths of SNs in Prampi Makara are the longest whereas SNs in peripheral districts, e.g. Pou Senchey, Dangkao, and Prek Phnov have the longest total street lengths as they are larger areas.

The districts with orthogonal street grids are likely to have the least average circuity of WSNs and BSNs while the peripheral districts with curvilinear residential SNs, such as in Chroy Changvar, Chbar Ampov, Dangkao, and Prek Phnov, have the most circuitous average for all SNs. The average DSNs are more circuitous than the average WSNs and BSNs in most districts. For example, the averages of DSNs circuity in Daun Penh district are 31.5 and 37.6% more circuitous than the average WSNs and BSNs, respectively. In contrast, Prampi Makara has an average WSN of 0.6% more circuitous than average DSNs. Comparatively, the average WSNs are less circuitous than the average BSNs in 7 out of 12 districts. The φ ratios and *Cohen's d* present significantly different percentages of DSNs versus WSNs and DSNs versus BSNs. The φ and *Cohen's d* of WSNs versus BSNs in five districts are negatively different.

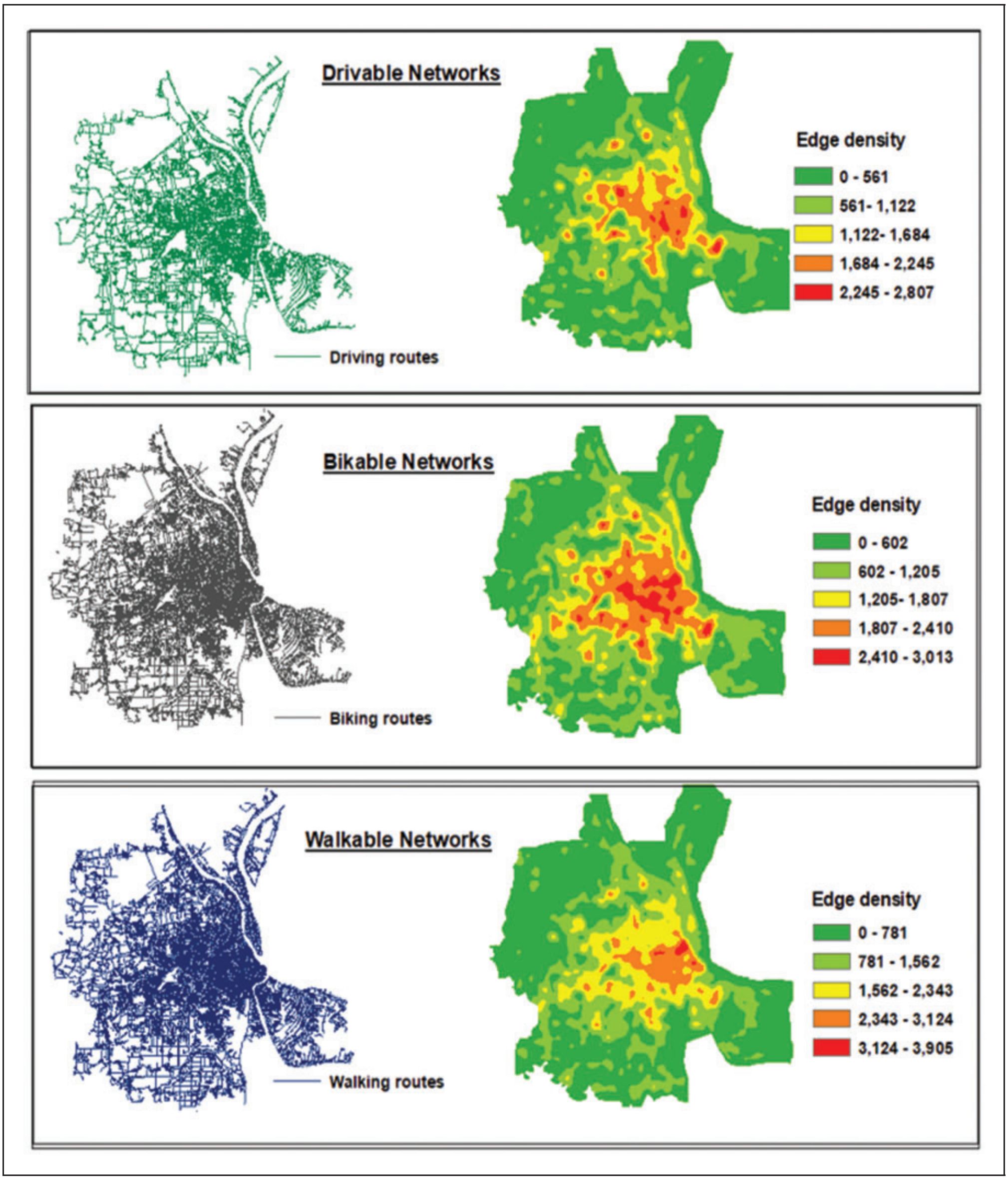

Figure 4. The spatial distribution of the edge density of driving, biking, and walking SNs.

Table 2 describes the different features of the three types of SNs. On average, the central districts have a higher average street per node than the suburban areas, ranging from 3.12 to 3.37 streets for DSNs, 2.88 to 3.11 streets for WSNs, and 2.85 to 3.09 streets for BSNs. In the central districts (e.g. Chamkar Mon), most intersections are four-way, whereas the peripheral district (e.g. Dangkao) features a mix of mostly three-way and dead-ends (Figures 3 and 5). Regarding node density metrics of DSNs, Prampi Makara and Tuol Kork have the highest densities of 140.15 and 104.14 intersections/km^2. Inversely, Chroy Changvar and Prek Phnov have the lowest densities of just 10.30 and 15.26 intersections/km^2, respectively. The node

Table 1. The average circuity of DSNs, WSNs, and BSNs in Phnom Penh.

District	Area (km^2)	μ_d	μ_w	μ_b	δ_d	δ_w	δ_b	$\sum d$	$\sum w$	$\sum b$	$d_{d/w}$	$d_{d/b}$	$d_{b/w}$	$\varphi_{d/w}$	$\varphi_{d/b}$	$\varphi_{b/w}$
Daun Penh	7.7	1.468	1.356	1.340	108.63	65.71	65.99	99.4	162.2	180.9	0.463***	0.522***	−0.071	31.5%	37.6%	−4.5%
Prampi Makara	2.2	1.288	1.290	1.286	88.10	72.49	76.15	49.6	67.8	60.7	−0.007***	0.008***	−0.017	−0.6%	0.7%	−1.3%
Tuol Kork	8.0	1.499	1.465	1.444	106.71	87.70	89.90	153.0	197.0	183.8	0.142***	0.224***	−0.092	7.4%	12.4%	−4.4%
Chamkar Mon	11.2	1.499	1.429	1.437	110.26	79.24	84.04	179.1	252.1	235.6	0.288***	0.252***	0.036	16.3%	14.1%	1.9%
Russey Keo	23.7	1.540	1.431	1.435	104.50	84.74	85.25	250.5	325.1	322.2	0.450***	0.430***	0.016	25.3%	24.3%	0.8%
Chroy Changvar	85.4	2.106	1.919	1.918	158.64	124.08	125.24	187.2	253.4	251.6	0.773***	0.767***	−0.004	20.3%	20.5%	−0.1%
Sen Sok	53.7	1.498	1.419	1.424	94.00	79.75	79.79	584.3	771.8	768.6	0.327***	0.302***	0.023	18.9%	17.5%	1.2%
Pou Senchey	147.9	1.588	1.520	1.516	99.22	90.33	90.56	887.9	1251.9	1250.0	0.280***	0.293***	−0.018	13.0%	13.9%	−0.8%
Mean Chey	28.6	1.424	1.364	1.368	86.30	76.75	77.62	319.7	423.5	420.4	0.249***	0.229***	0.018	16.6%	15.3%	1.1%
Chbar Ampov	86.7	2.018	1.882	1.896	134.47	119.83	120.68	347.5	488.2	483.9	0.562***	0.498***	0.062	15.4%	13.6%	1.6%
Dangkao	114.1	1.801	1.726	1.728	111.79	99.62	101.26	550.9	790.2	784.4	0.311***	0.299***	0.009	10.4%	10.1%	0.3%
Prek Phnov	115.3	1.933	1.821	1.825	119.77	113.76	114.36	283.6	457.9	459.0	0.463***	0.441***	0.018	13.6%	13.1%	0.5%

Note: μ_d, μ_w, μ_b are average circuity of DSNs, WSNs, and BSNs. δ_d, δ_w, δ_b = mean distance (meters) of routes along DNSs, WSNs, BSNs. $\sum d$, $\sum w$, $\sum b$ are total street length (kilometers) of DSNs, WSNs, and BSNs. Cohen's $d_{d/w}$, $d_{d/w}$, $d_{d/w}$ are the effect size of the difference between μ_w and μ_d, μ_b and μ_d, and μ_w and μ_b, respectively. The φ represents how much (%) μ_d exceeds μ_w, or how much (%) μ_d exceeds μ_b, and how much (%) μ_b exceeds μ_w. *** indicates a statistically significant difference between μ_w, μ_b, and μ_d at the $p < .001$.

densities for WSNs are the highest in Prampi Makara (248.41 intersections/km^2) followed by Daun Penh (193.45 intersections/km^2). Whereas, Chroy Changvar and Prek Phnov remain the least with 18.48 and 25.70 intersections/km^2. It is not much different for the node densities of BSNs, Chroy Changvar (18.27 intersections/km^2) and Prek Phnov (25.63 intersections/km^2) are still the least ones while Prampi Makara remains the district with the highest density of 213.37 intersections/km^2. The street densities are high for those SNs in the central districts although the different rates are not large. In addition, Prampi Makara has the highest linear kilometers of physical street/km^2 followed by Tuol Kork and Chamkar Mon. In contrast, Chroy Changvar and Chbar Ampov have the least linear kilometers of physical street/km^2. As a proxy of the block size, Chroy Changvar has the most extended average street segment length for all SNs, followed by Chbar Ampov and Prek Phnov because some parts of these districts are covered by riversides, catchments, ponds, and lakes.

Moreover, the spatial distribution of closeness centrality and betweenness centrality for each SN shows the relative importance of each node (Figure 5 and Table 2). The critical nodes are concentrated in the center of these SNs due to their grid-like orthogonality. The closeness centrality of each SN is very small and the same for all districts (0.1%) but

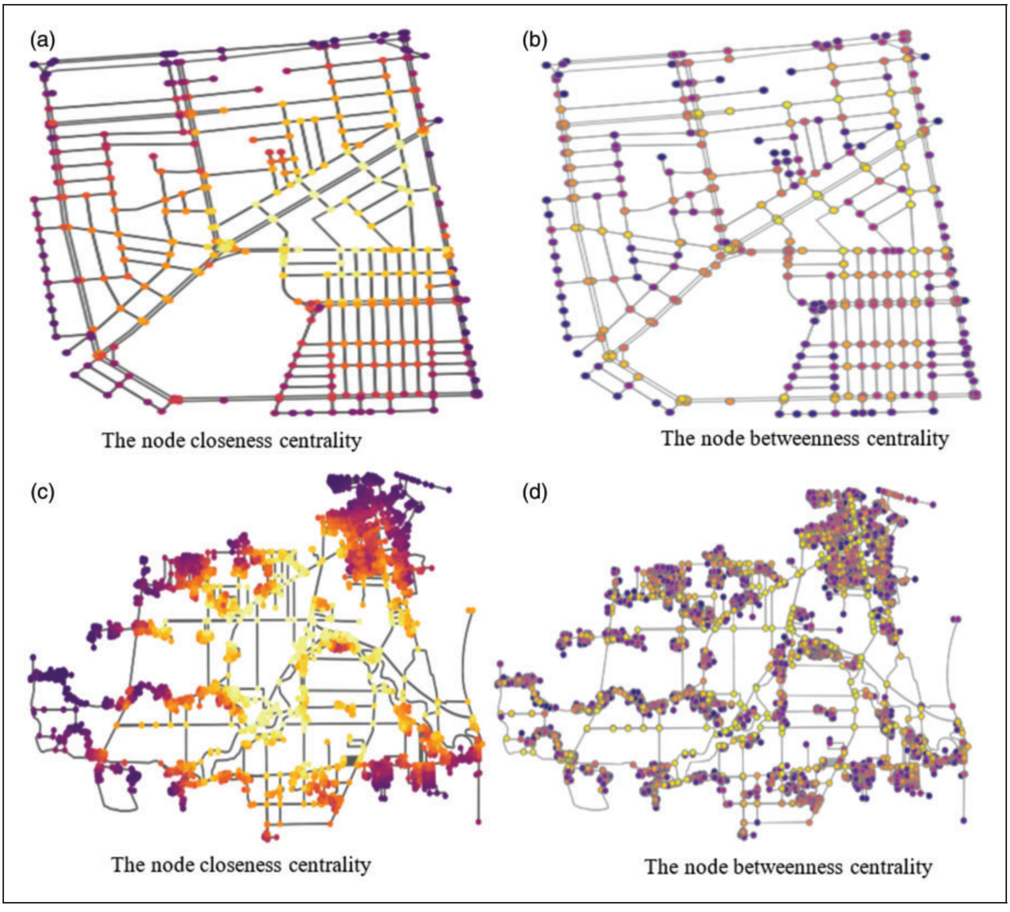

Figure 5. Distribution pattern of closeness and betweenness centrality of DSNs in the central (Prampi Makara (a) and (b)) and outer districts (Dangkao (c) and (d)) of Phnom Penh. The darker the color, the lower the closeness and betweenness centrality.

Table 2. The measures of three types of SNs in Phnom Penh.

		District											
Types	Measure	Daun Penh	Prampi Makara	Tuol Kork	Chamkar Mon	Russey Keo	Chroy Changvar	Sen Sok	Pou Senchey	Mean Chey	Chbar Ampov	Dangkao	Prek Phnov
DSNs	n	573	356	982	1068	1818	884	4695	6970	2946	2004	3833	2006
	η	68.46	140.15	104.14	86.26	75.27	10.30	73.25	37.39	73.75	26.93	29.05	15.26
	ρ	66.07	136.61	90.99	76.81	56.64	7.80	55.77	27.22	53.45	19.49	20.92	10.02
	γ (km)	38.1	38.9	35.0	33.7	24.6	5.2	22.3	12.8	19.6	12.6	11.5	6.6
	ς (km)	11.9	19.5	16.2	14.5	10.4	2.2	9.1	4.8	8.0	4.7	4.2	2.2
	δ (km)	108.63	88.10	106.71	110.26	104.50	158.64	94.00	99.22	86.30	134.47	111.79	119.77
	α	3.32	3.37	3.03	3.12	2.66	2.68	2.68	2.59	2.56	2.58	2.59	2.4
	Ϛ	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	Ϭ	0.029	0.034	0.021	0.017	0.014	0.030	0.008	0.006	0.012	0.002	0.008	0.029
WSNs	n	1746	631	1602	2220	3091	1586	7640	11052	4460	3228	6354	3379
	η	193.45	248.41	169.89	179.31	127.97	18.48	119.20	58.69	111.65	43.38	48.16	25.70
	ρ	162.09	225.18	141.04	148.94	88.72	13.31	85.17	41.28	78.41	30.60	33.57	17.14
	γ (km)	35.7	53.0	41.6	40.5	26.9	5.9	23.9	13.2	20.9	13.08	11.9	6.9
	ς (km)	18.0	26.7	20.9	20.4	13.5	3.0	12.0	6.6	10.6	6.6	6.0	3.5
	δ (km)	65.71	72.49	87.70	79.24	84.74	124.08	79.75	90.33	76.75	119.83	99.62	113.76
	α	2.89	3.11	2.88	2.90	2.5	2.58	2.55	0.52	2.5	2.52	2.51	2.41
	Ϛ	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	Ϭ	0.013	0.022	0.015	0.011	0.012	0.022	0.007	0.005	0.010	0.013	0.007	0.023
BSNs	n	1932	542	1481	1972	3048	1568	7611	11016	4391	3177	6229	3369
	η	204.52	213.37	157.06	159.28	126.19	18.27	116.84	58.50	109.92	42.69	47.21	25.63
	ρ	171.18	190.93	128.53	131.58	87.40	13.09	83.37	41.12	76.83	30.16	32.74	17.10
	γ (km)	38.1	38.9	35.0	33.7	24.6	5.2	22.3	12.8	19.6	12.6	11.5	6.6
	ς (km)	19.1	23.9	19.5	19.0	13.3	2.9	11.8	6.6	10.5	6.5	5.9	3.5
	δ (km)	65.99	76.15	89.90	84.04	85.25	125.24	79.79	90.56	77.62	120.68	101.26	114.36
	α	2.89	3.09	2.85	2.89	2.499	2.57	2.55	2.52	2.494	2.52	2.5	2.41
	Ϛ	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.01	0.001
	Ϭ	0.012	0.026	0.017	0.013	0.013	0.023	0.007	0.005	0.011	0.014	0.007	0.024

BSNs: bikeable street networks; DSNs: drivable street networks; WSNs: walkable street networks.
Note: Number of nodes (n), node density (η), intersection density (ρ), edge density (γ), street density (ς), average street segment length (δ), average street per node (α), closeness centrality (Ϛ), and betweenness centrality (Ϭ).

the betweenness centrality of all shortest paths passing through an average node in the central districts is lower than the peripheral districts. For instance, Prampi Makara has 3.4, 2.2, and 2.6% of betweenness, whereas Prek Phnov has 0.8, 0.7, and 0.7% of betweenness for DSNs, WSNs, and BSNs, respectively.

Discussion

Analysis of SNs' characteristics

The findings demonstrate significantly different characteristics of SNs in the central and peripheral districts. The one-way streets and densities of nodes, edges, and intersection are the factors affecting average circuity between the city center and its peripheral areas. Geometrically, the shortest-average distance and higher edge and node densities make the central districts more accessible for mobility and thereby they are potential hubs to connect the districts to the core SN corridors. The important nodes in the peripheral districts, e.g. Dangkao district, are critical chokepoints linking one side of the SNs to the others.

This phenomenon makes the SNs in the peripheral districts more prone to disruption if the most important nodes fail (e.g. due to a traffic jam and flood) than those in the central districts under similar conditions (Witte et al., 2012). This happened in New York City where the surrounding highways that have high link betweenness centralities are located in floodplains (Kermanshah and Derrible, 2017). Besides, the primary street systems may run at crosscutting diagonals that provide direct routes across the districts where local or small streets could not match. Geographically, Phnom Penh is located at the confluence of four rivers where the connections of the western districts to eastern districts pass through bridges and via ferries. Thus, the effect of automobile-only DSNs in these districts exceeds the effects of WSNs and BSNs on route directness. Some one-way routes in DSNs may be accessible to pedestrians and cyclists in both directions. In contrast, WSNs and BSNs may be inaccessible to vehicular drivers while some streets and bridges may be unavailable to pedestrians and cyclists. The different topographies, transport technologies, and design paradigms have affected the urban form and SNs in this city where more newly constructed parts of SNs in the peripheral districts are laid out less efficiently than older parts in the central districts. The future designs and development of SNs in this capital should pay more attention to the peripheral districts. Meanwhile, it is crucial to differentiate street lanes for vehicular, cycling, and walking traffic so as to protect pedestrians and cyclists from vehicular accidents.

Phnom Penh is like other cities in Southeast Asia (ASEAN) whose designs and architecture were influenced by European styles during colonization, for example Manila (1570 by Spanish), Jakarta (1619 by Dutch), Singapore (1819 by British), Yangon (1834 by British), Ho Chi Minh (1859 by French), and Phnom Penh (1866 by French) (Dick and Rimmer, 1998). However, the issues faced by ASEAN member states are different and yet make ASEAN a competitive community through partnerships. Singapore is the only country that has the most cost-efficient public transportation networks where its people can have access to different modes of travel, including public buses, taxis, trains, monorails, subways, and expressways (Wang et al., 2016). In contrast, Cambodian people have limited access to the necessary services and infrastructure, living far distances from work and services, and are at the highest risk of traffic accidents and flooding (World Bank, 2017). The first public buses were put into use in 2014; and in 2018, only 13 bus lines were available on the main streets in the city. Lack of alternative modes of travel forces residents to use private transportation. The city's registered vehicle fleet volume reached 442,972 cars and 1,601,451 motorbikes in 2016. Some SNs in Thailand are likely the same as in SNs in Cambodia. Although SNs in Thailand have been extensively developed since the post-Second World War era, accessibility of SNs to walking and cycling is also a key issue (Pongprasert and Kubota, 2017). Unlike other countries in Asia, e.g. China, Korea, Japan, and India where remarkable research on SNs has been done, such research in ASEAN is very scant. Many studies have been conducted on an individual network basis, such as walkable streets for tourists (Henderson, 2018), a relationship between land use and road network connectivity (Patarasuk, 2013), metro network (Fesselmeyer and Liu, 2018), network connectivity between old and new urban areas (Said and Mohamad, 2017), and modes of transport networks (Andong and Sajor, 2017). Thus, SNs remain an important research direction for other cities in the region.

Policy implications

Our results suggest that different strategies should apply to promote walking and cycling accessibility in Phnom Penh to reduce vehicular dependency. The design of WSNs and BSNs must provide multiple routes with continuous clear paths to reach destinations at a shortest-distance. Walkability and bikeability increase as more destinations can be reached along routes with better safer facilities to support walking and cycling (Lowry et al., 2012; Rahul and Verma, 2018). For instance, a study on the buffered two-way bike lane in Pennsylvania Avenue, Washington, DC found a 250% increase in cycling levels during peak commute hours two years after the installation of bike facilities (Goodno et al., 2013). To ensure safety for pedestrians and cyclists, it is crucial to provide physically separated, protected walking and cycling infrastructure on major streets with high-volume vehicular traffic (Pucher and Buehler, 2017). Although SNs in the central districts of this study show better accessibility than those in the peripheral districts, neither central nor peripheral districts have proper designs and facilities to separate the pedestrians and cyclists' routes from vehicular traffic. It is important to re-design some streets by replacing some two-way roads with roads that are one-way for cars and two-way for other modes. Preventing hawkers from illegal parking and occupying the street would enlarge street space and improve safe accessibility. Also, providing sufficient infrastructure, including bicycle lanes, sidewalks, pedestrian crossings, pedestrian ramps, cycle tracks, signage and wayfinding, traffic calming at neighborhood streets, greenery streets, and improvement of safety at edges and intersections, could increase levels of walking and cycling (Buehler and Dill, 2016). However, such designs and facilities have not been made available in Phnom Penh to date, and traffic accidents and congestion have thereby become the worst issue in the capital. It is an immediate need that the government should focus on improving SNs as a matter of urgency and shift from the vehicular dependency to an active mode of transportation (i.e. walking and cycling). Furthermore, poorly planned roadways and the rapid expansion of urbanized areas in the peripheral districts have a huge negative impact on street development in these districts. To avoid urban sprawl and disruptive SNs, practical land use and appropriate land use development control are necessary. Proper preparation for a street design manual is also necessary to guide newly constructed streets so as to plan and design new streets that will provide more accessibility to walking and cycling in the city.

Conclusion

This study provides an in-depth analysis of drivable street networks (DSNs), walkable street networks (WSNs), and bikeable street networks (BSNs) of Phnom Penh. The topological and geometric characteristics of SNs in the central districts are more accessible to walking and biking than the peripheral districts. Therefore, WSNs and BSNs in the central districts tend to allow for more direct routes than DSNs. The important nodes in the peripheral districts are critical chokepoints linking one side of the SNs to the others. These SNs are more prone to disruption if the most important nodes fail.

To promote sustainable urban mobility, future designs of street layouts that equip with WSNs and BSNs infrastructure should be of priority. Urban residents prefer living and traveling in a place with the shortest-distance of SNs to the destinations, safe and convenient navigation, and accessibility to services. Planners should incorporate facilities, services, and safety of walking and biking in the peripheral districts, such as Mean Chey, Pou Senchey, and Dangkao districts, where there are textile factories and workers with bustling traffic. The improvement of SNs in these districts may reduce travel demand into the central districts and catalyze out-migration to suburban areas. This will significantly reduce traffic congestion, high population density, and promote sustainable urban development.

This study suggests that using a network approach could allow planners to estimate the effects of making changes to the network and thus yield cost savings. However, this is a local-level study which investigated only Phnom Penh and is limited because SNs in other locations are varied by urban types, technologies, time, and designs. Further research will need to be sensitive to these differences. Future research could use OSMnx and OpenStreetMap data to compare different times of SNs at the national level or be expanded to gain more insights about regional city planning in Southeast Asia or globally. This study also only highlights the potential and need for further studies on SNs to answer the questions of "where to be built" and "what to be built" in the Phnom Penh, in order to improve accessible and safe SNs for pedestrians and cyclists.

The extant study outlined a method for extracting, analyzing, and visualizing spatial distribution and SNs to create an evidence base for planning specific routes that are relevant to the local contexts. With the help of OSMnx and code chunks (see online supplementary material), future studies could use this method to analyze urban morphology and SNs for other cities and reproduce datasets for SNs. Although OSMnx allows users to download different types of SNs, it is unable to extract different years of SNs from OSM data. This may pose another challenge for researchers who use OSMnx to analyze and compare the developments of SNs in different time series.

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Acknowledgments

Authors sincerely thank Prof. Geoff Boeing who develops OSMnx that is a valuable and convenient research tool to extract the data from OpenStreetMap for this study. The authors also gratefully thank Leo Atwood, a Canadian English language editor and Dr Earl Bailey for proofreading and editing this manuscript. The authors unforgettably express sincere gratitude to the Editor Dr Daniel Arribas-bel and the anonymous reviewers for their constructive comments on earlier versions of this manuscript.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This research was supported by Boya Post-doctoral Research Program, Peking University and by Senior Fellowship Program at Center for Khmer Studies, Cambodia.

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