Investigating the Influence of Urban Density and Concentrations on Commuting Distance and Time: Empirical Evidence from Suhag City

Islam M. S. Abouelhamd
Department of Architectural Engineering, Faculty of Engineering, Asyut University

Ruth N. Onkangi
Interdisplinary Graduate School of Engineering Sciences, Kyushu University

Paulus van der Kuil
Department of Urban Development, Technical University of Berlin

Uwe-Jens Walthe
Department of City and Regional Planning, Urban Sociology, Technical University of Berlin

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Investigating the Influence of Urban Density and Concentrations on Commuting Distance and Time: Empirical Evidence from Suhag City

Islam M. S. Abouelhamd[1 & 2*], Ruth N. Onkangi[2], Paulus van der Kuil[3], Uwe-Jens Walther[4]

[1]Department of Architectural Engineering, Faculty of Engineering, Asyut University, Egypt.
[2]Interdisplinary Graduate School of Engineering Sciences, Kyushu University, Japan.
[3] Department of Urban Development, Technical University of Berlin, Germany.
[4] Department of City and Regional Planning, Urban Sociology, Technical University of Berlin, Germany.
*Corresponding author email: abouelhamd@Kyudai.jp

Abstract: *This study examines the influence of urban densities and concentrations on commuting distance and time in Suhag City, Egypt. Key parameters were investigated, such as urban centrality index (UCI), density profile, and built-up area ratio. The geographical information system (GIS) and the open-route service (ORS) tool were utilized to obtain a comprehensive urban analysis of the 62 tracked commuters over one month. Findings indicate a negative correlation between UCI and commuting distance and a negligible impact on commuting time. The high-density clusters, such as businesses and social services, can significantly reduce average commuting distance and promote non-motorized modal choices. Residents in high-density zones, particularly in the central business district (CBD) or sub-centers, tend to have longer trips compared to those in moderate-density areas within the inner urban zone. A weak inverse correlation was reported between the built-up area ratio and average commuting distance and time, except in the urban periphery.*

Keywords: Urban Density; Commuting Patterns; Urban Centrality; Street Network, Sustainable Commuting;

1. INTRODUCTION

Commuting patterns, a crucial aspect of urban transportation, holds significant importance for urban planners due to its consistent and predictable nature [1]. It serves as a valuable indicator for assessing traffic congestion, volume, and predicting transport-related emissions. Commuting patterns are closely tied to residents' decisions regarding work and residential locations. Extensive research has established a consensus that commuting patterns are strongly associated with the spatial structure of urban areas [2,3,4,5]. It involves regular and repeated travel between an individual's place of residence (origin) and their workplace, educational institution, or any frequently visited location within the metropolitan area, even if unrelated to work (e.g., commercial or recreational areas). It should be noted that commuting extends beyond the boundaries of one's residential district. These commuting patterns comprise various attributes, including distance, time, and cost (both direct financial and indirect environmental costs).

The scholarly discourse on the relationship between urban densities and commuting patterns has gained considerable attention, particularly after the emergence of megacities with intricate urban configurations. This extensive body of research underscores the belief that urban spatial structure fundamentally influences commuting patterns, which in turn are closely linked to various urban challenges such as traffic congestion, motorization, energy consumption, air pollution, and psychological and health issues [1,3,4,6,7,8,9,10,11,12,13,14]. Moreover, Urban density influences accessibility patterns and reflects the competition between land uses and traffic networks [5,15]. It is widely utilized as a metric in empirical studies [12,16]. It plays a vital role in determining the quality of urban life, affecting the provision of services and accessibility to public and private spaces, including public transport infrastructure [17]. Bertaud (2004) [18] emphasized the significance of urban densities in shaping traffic systems and predicting congestion hotspots. It encompasses various types, such as the concentration of human activities, buildings, and population, which are examined in the literature to understand their impacts on commuting patterns [12,19, 20, 21]. From the observed results, a densified mix of population, employment, and social services generally leads to reduced commuting distances, motorized trips, and vehicle miles traveled (VMT) [19,22]. However, the impact of density on commuting patterns remains inconclusive, with findings contradicting expectations of shorter commutes in high-density areas due to potential traffic congestion [4,12,15,23,24]. This highlights the unpredictable nature of densification's effects, which depend on other city characteristics. While the relationship between urban density and commuting patterns varies across cities, there is a gap in research concerning the influence of urban density distribution on commuting patterns, particularly with the population density profile across the city.

Furthermore, The literature has yielded insufficient results due to conflicting findings, limited examination of density profiles, and a focus on job-housing commuting rather than other daily trips. The complex forms of polycentrism have also been overlooked. The relationship between urban density and commuting patterns is influenced by various interrelated variables, including socio-economic and environmental conditions. Therefore, individual city case studies are necessary to account for these variations. Moreover, there is a lack of research examining the impact of urban density on commuting patterns in moderate-dense cities, which exhibit unique characteristics such as growing higher urban density areas, recent urban expansions, and distinct institutional factors. These factors, including informality and disparities in transport infrastructure and technologies, set these cities apart from their developed counterparts. This study aims to address the research gap through empirical investigations to understand how the spatial distribution of urban densities influences commuting patterns and traffic-related emissions.

2. METHODOLOGY

2.1. City Profile

Suhag City serves as the administrative capital of the rural governorate of Suhag, located 467 km south of Greater Cairo and 418 km north of Aswan. The governorate is a narrow strip along the Nile Valley, spanning 125 km in length [25]. With a population of 5.05 million in 2020, Suhag is the ninth most populated governorate in Egypt, representing 4.9% of the country's total population and 44.1% of the middle Upper Egypt region. The governorate covers an area of 11,020 km2 [26]. More information about Suhag City is stated in Table 1. The study area comprises the urbanized region within the city borders, spanning both sides of the Nile, between latitudes 26˚00'N and 27˚00'N and longitudes 31˚15'E and 32˚15'E [27]. Urbanization in the area has been observed from 1987 to 2012, primarily on fertile and arable lands [28]. However, urban expansion has extended beyond the valley, leading farmers to reclaim the desert fringes [25]. As Figure 1 illustrates, Suhag City is divided into eleven districts, while eight districts are located in the west, two expansive districts in the east, and an uninhabited island in the north. The Nile River and a railway with limited tunnels serve as physical barriers, dividing the city and impacting accessibility and connectivity [27].

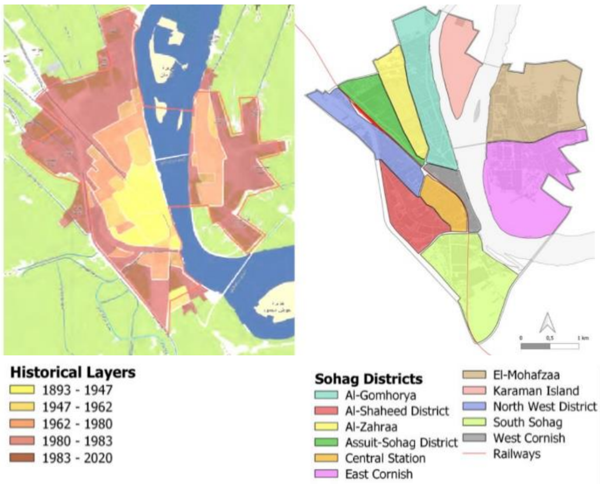


Figure 1. (a) The historical layers of Suhag city since 1893, and until 2020 [26]. (b) The main districts of Suhag city.

Suhag City has a population of 326 thousand inhabitants in the urban area, with an annual population growth rate of 2.5%, exceeding the national rate of 2.0%. The estimated population is expected to surpass 600 thousand inhabitants by 2030 [29]. The population density is relatively high, averaging around 608 inhabitants per hectare, with certain areas exceeding 800 inhabitants per hectare. However, some districts have low population density, particularly where the industrial properties locate. The high population concentration in a limited urbanized area significantly impacts social services and urban infrastructure. The urbanized area of Suhag City covers 866.6 hectares, with 68.4% dedicated to urban activities and the remainder allocated to streets and public spaces [26,30].

The transportation system in Suhag City is highly dependent on cars, with private vehicles and taxis accounting for around 60% of daily trips. The local mini-buses are the only available public transportation modal choice. It represents 15% of trips while walking, motorcycles, and bicycles account for only 14%, 9%, and 2%, respectively. The city has only 12 mini-buses stations with an average capacity of 350 vehicles per station. Approximately 79% of the streets are paved and in good condition, but 85% of these streets are designated for motorized vehicles, with limited pedestrian sidewalks and few established bike lanes. Traffic congestion is reported to be significant, with a congestion rating of 7.5 out of 10. The average commuting distances to workplaces, commercial destinations, and recreational areas are 2.6 km, 1.36 km, and 2.28 km, respectively [26,30]. The city exhibits four main types of street patterns. In the old districts like the central stations and West-Suhag, there is an organic layout with narrow car-free alleys. The city center features radial roads with multiple squares, but it experiences high traffic volume. In the northern part, due to informal urbanization, many districts have elongated grid patterns with limited intersections. However, most of the other districts have a conventional grid pattern with regular blocks. See Figure2.

As Figure3 shows, the city center and sub-centers in the eastern and northern districts face significant traffic congestion, particularly on the main roads connecting the city to regional routes. These roads are heavily overcrowded, with traffic volumes exceeding 32,000 vehicles/day. Limited bridge connections further compound the issue, with one bridge located relatively far from the main urban hotspots. Consequently, average commuting distances and times are longer, especially during peak hours [26,30].

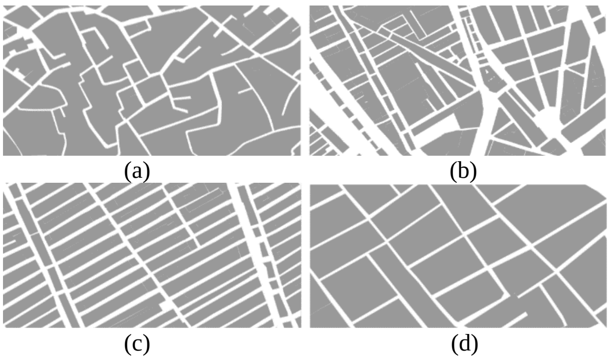


Figure 2. Different forms of street patterns as observed in urban blocks in Suhag city. (a) Conventional irregular pattern, (b) Radial pattern, (c) Elongated grid pattern, and (d) Conventional grid pattern.

Table 1. General Socio-demographic, Land-uses, and transport related Statistics of Suhag city.

Socio-Demographics			
Total Population (2006)	189,600 *	Total Population (2016)	307,000 *
Total Population (2020)	326,000 *	Population Estimation (2026)	374,900 *
Average Population Density	608 Cap./ha ***	Total Area	1286,7 Km^{2} ***
Average Family Structure	4.3 Cap. / Family **		
Population Growth Rate	2.5% Annually **		
Employment Sectors **	30% Agricultural Sector	17% Industrial Sector	53% other sectors
Unemployment Rate **	16%		

Land-uses & Structural Statistics ***			
Total Urbanized Area (Used for Building, Streets, or Public Spaces)			866.6 ha
Land-Uses Area	592.5 ha. (68.4%)	Streets & Open Spaces	274.1 ha. (31.6%)
Residential	295.05 ha	Multi-Functional	99.4 ha
Commercial	4.4 ha	Medical	10.7 ha
Governmental	14.4 ha	Recreational	29.1 ha
Educational	32.4 ha	Industrial	43.5 ha
Religious	4.3 ha	Cultural	3.9 ha
Other uses	29.6 ha	Vacant Land	25.8 ha
Average Buildings Height	15 m		
No. and Percentage of the Informal Settlements		9 settlements (21% of the Residential areas)	

Transport & Commuting Statistics ***			
No. of the Registered Vehicles	64,000Vehicles		
No. of the Public Stations	12 stations	The Average Capacity	350 Vehicles
% of the paved Streets	79% Paved		
Modal Share	33% Car – 27% Taxi – 15% Buses - 14% Walking - 9% Motorcycle - 2% Bike		
Average Commuting Distance To the workplaces	2.6 Km		
Average Commuting Time to the workplaces	29 minutes		
Average Commuting Distance to the commercial areas	1.36 Km		
Average Commuting Distance to the Recreational areas	2.28 Km		
Rate of traffic Congestions (Based on Surveys)	7.5 / 10		

*General Agency for Public Mobilization and Statistics in Egypt GAPMS, Link: https://www.capmas.gov.eg/Pages/Publications.aspx?page_id=5104
**General Organization for Physical Planning in Egypt, 2017.
****Data from open source GIS files.

2.2. Data and modeling

A portion of the dataset, including the urban spatial structure of Suhag City, was extracted from the "Open Street Map" database using Q-GIS. However, the data obtained from this source was incomplete, particularly for land uses, population densities, built-up densities, and transport-related data. Hence, three references were utilized to cover this limitation, recent datasets previously conducted at Asyut University, official urban maps from the General Organization for Physical Planning in Egypt (GOPP), and observed published data from Google Earth/maps. An online questionnaire was conducted to track a sample of random permanent residents to collect data for their daily commuting patterns (but responses were sent one time every week). The data includes but is not limited to the location of origin, place of employment/education, preferred commercial and recreational destinations, preferred modes of transportation, and the congestion experienced during their trips. The questionnaire responses from 62 participants were statistically analyzed and computed by the data inserted by GIS to examine the correlations between the addressed parameters.

Spatial and quantitative urban analysis were investigated using geographical information system (GIS) tools. Figure 4 illustrates the spatial segmentation of Suhag City into seven urban zones based on their distance from the central business district (CBD). Each zone spans a depth of 500 meters. Thus, the last zone is located 3.5 km away from the CBD. These zones were instrumental in examining variations in urban density, urban centrality, and spatial clustering. Moreover, multiple points of origin were identified within each zone based on weekly responses from the participants, providing input data on commuting patterns and traffic conditions for each daily trip. Moreover, this study has utilized the Open-Route-Service (ORS) tool that allows access to most of the functions of urban transportation based on Open-Street-Map (OSM). This tool provides accurate commuting distance and time of an identified point of origin and destination within a study area. Moreover, it supplies precise buffer zones for a specific duration or length from the place of residence. Thus, it facilitates the assessment of proximity, accessibility, and connectivity to a chosen buffer area.

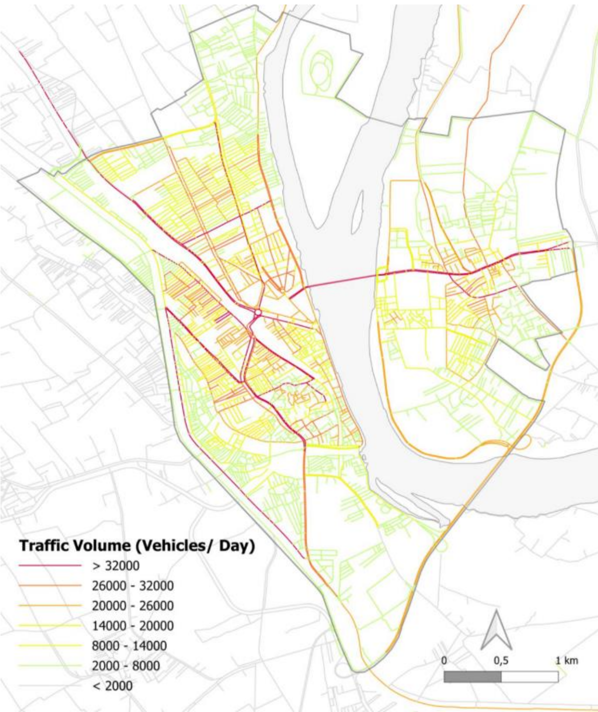


Figure 3. Map shows traffic volume in Suhag city (Base on Google Maps & Surveys, 2020).

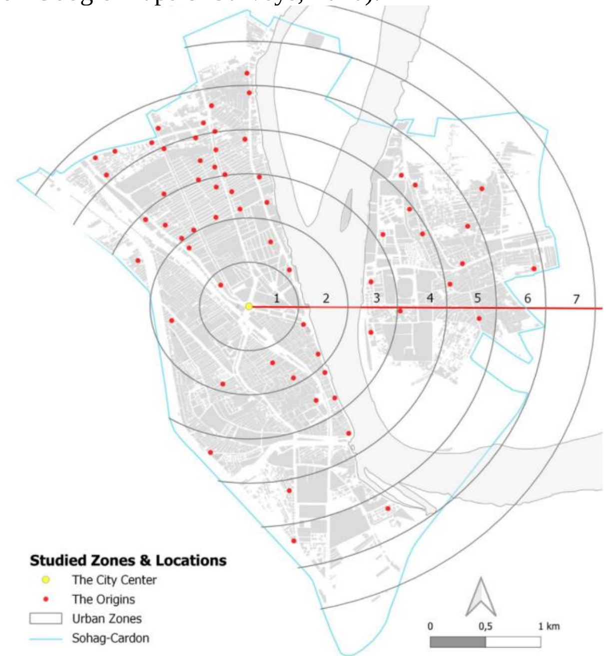


Figure 4. Map shows the identified urban zones and locations of the origin of the examined random daily trips by the conducted surveys.

2.3. Measuring methods

Distribution of the employments is the main criterion that determines the degree of centrality, among other several criteria such as landmarks, traffic volume, and retail. However, this study has measured the urban centrality by using the proposed location coefficient index (LCI), which introduced by Florence (1948), or as it recently modified and called Urban Centrality Index (UCI) by Pereira et al., (2013) [31]. This index measures the degree of centrality and concentrations of the workplaces within the city. See formulas (1) and (2). However, the range of (LC) is from zero to (1-1/n). If (LC) equals or close to zero, this means that the economic activities are dispersed without urban concentration forces, while values close to (1-1/n) indicate that these activates are concentrated or centralized in a specific area within a particular zone or district of the city.

$$S_i = E_i / E \qquad (1)$$

$$LC = \frac{1}{2} \sum_{I}^{n} \left| s_i - \frac{1}{n} \right| \qquad (2)$$

Where S_i represents the share of jobs in zone or district i; E_i the number of jobs in zone or district i; E is the total number of workplaces in the city; LC refers to the location coefficient index; and n is the number of employment locations in the CBD.

The most common metrics of population density are used in this study to be comparable with other findings [32]. It is the permanent population per hectare as Eq. (3) shows. However, the density distribution index (DI_i) is calculated by dividing the population density in the specific location i to the distance between the CBD and that location. See Eq. (4).

$$d_i = p_i / s_i \qquad (3)$$

$$DI_i = d_i \;/ u_i \qquad (4)$$

Where d_i is the population density of in the location i (Capita/ Hectare); p_i is the total permanent inhabitants in the location i; s_i is the total land area in that location (Hectare); DI_i represents density distribution index or density profile index; and u_i is the distance from location i to the CBD.

Moreover, built-up density is measured as the ratio between the actual built-up area and the total urbanized area without considering the rural or water areas in the whole city. The value of built-up ratio should be in the range between zero and 1. While values closer to 1 refer that the area has a high built-up intensity with a limited area for the public and open spaces, the values closer to zero indicate that it is a very low built-up density.

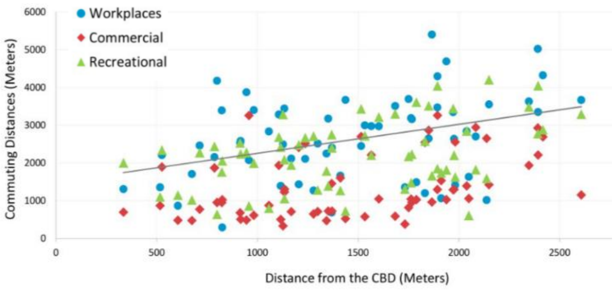
$$B_i = A_i / A_t \qquad (5)$$

Where B_i is the built-up density in zone or district i; A_i is the built-up land area; and A_t is the total land area.

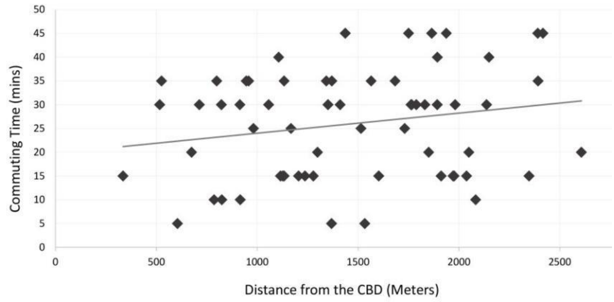
3. RESULTS

3.1. Effect of Urban Centrality/Concentration

As most of the literature substantiated, the average commuting distance and time have a positive relationship with the distance of the origin from the CBD. The trend line was varied by the purpose of commuting. Notably, the average commuting distance to the workplaces rises by increasing the distance from the CBD at a rate greater than commuting to the recreational destinations, which likewise is higher than the commuters to commercial areas. However, in the distance 1.5 km from the CBD, the commuting distance and time are increased by around 1 km and 17 minutes, respectively. See Figure 5 (a) and (b).



(a)

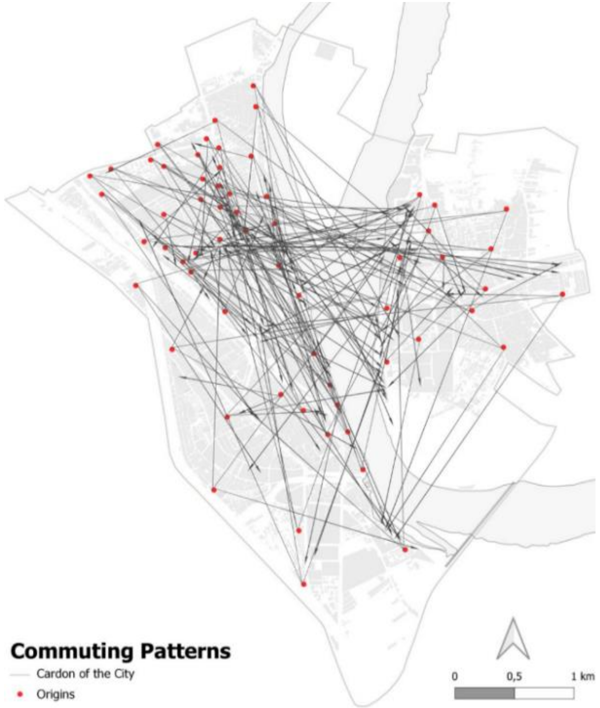


(b)

Figure 5. The relationship between the distance of the place of residence (Origin) from the CBD and commuting distance (a) and time (b) to the workplaces, commercial, and recreational destinations during the weekdays in Suhag city.

Spatially, the commuting network in Suhag City indicates a constrained dispersal city model. That means the city has a weak CBD and some sub-centers. Most of the workplaces are dispersed in/outside the CBD in random locations. That leads to partly scattered commuting patterns in random destinations. The spatial distribution of the urban centrality index (Degree of employment distribution) confirms that the city has two distinguishable aggregated employment centers. One of these centers locates in the eastern districts, where the educational and governmental facilities lie, and the second is in the northwest side, where most of the retails are concentrated. Additionally, the city has other weak employment centers distributed in different neighborhoods in the south and west districts. See Figure 6 (a) and (b).

Based on the hypothesized zoning of the city by distance from the CBD (as stated in Figure 4), and although the city has a low urban centrality index in the CBD (less than 0.5), it has a high value in the zone between 1 and 1.5 km far from the CBD (0.75 in average). A second peak was also recognized 2 km from the CBD. This result proves the previously mentioned outcomes that the city has two major employment centers, and the western center is more active than the eastern part. See Figure 7. Moreover, an inverse relationship was reported between the urban centrality index and the average commuting distance. That means living in a high-employment centralized area in the city leads to considerably shorter daily commuting distances and does not exceed 1.75 km on average to the desired destinations. See Figure 8.



(a)

(b)

Fig 6. (a) the spatial commuting patterns in Suhag city. (b) The spatial distribution of urban centrality index (employment centers).

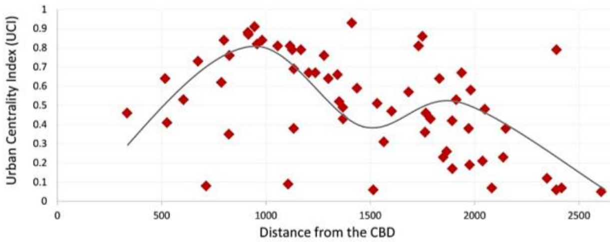


Figure 7. The relationship between urban centrality index and the distance from the CBD in Suhag city.

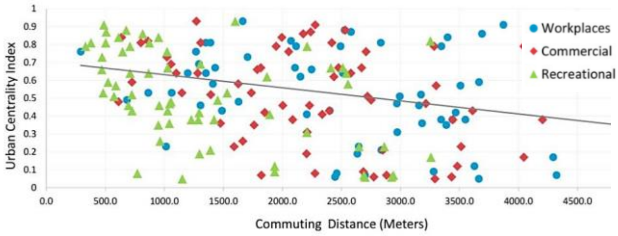


Figure 8. The inverse relationship between urban centrality index and average commuting distance in Suhag city.

3.2. Effect of Urban Densities

The results revealed that population density and spatial distribution densities are two crucial factors that can affect commuting patterns in Suhag City. From the chart of density profile in Figure 9, the city has a low population density (less than 250 cap. /hectare) in the CBD due to the educational, recreational, and administrative services. The highest density occurs in the distance between 0.6 to 1.2 km from the CBD, with an average value of more than 400 cap./hectare. However, in the range between 1.3 and 2.0 km from the CBD, the city has a drop of density to 250, as in the case of the CBD. There is a secondary peak spot between 2.0 and 2.5 km from the CBD, where most of the population lives on the eastern side. The periphery has a low density with a slightly decreasing population density until the urban fringe. In conclusion, the city is spatially decentralized into multiple urban hot spots, and that is one of the strengths which could facilitate the management of commuting patterns and reduce the time/distance consumed daily per capita.

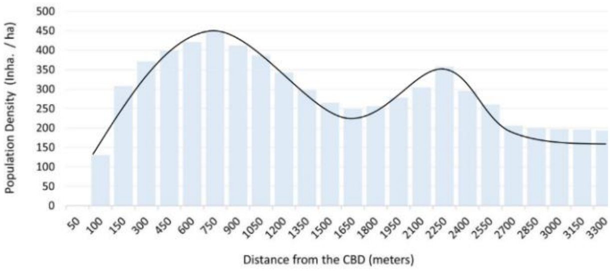


Figure 9. Density profile of Suhag city, as it has a form of multiple high-dense spots.

The total average population density is relatively high, about 350 Cap./hectare, especially when calculated by the total built-up area ratio (without considering the open areas). That is one of the weak points of the city. Moreover, there is an imbalance in the population distribution between the eastern and western sides (about 72% of the population lives on the western side). This imbalance itself is not a problem. However, it generates many challenges when most of the residents in the dense areas on the west side commute to their workplace, whereas the majority exists on the eastern side. That enormously causes high traffic volume in the limited capacity of the bridges and the internal roads. Figure 10 shows the population density distribution.

Furthermore, there is an inverse correlation between the density distribution index and commuting distance and time, regardless of the type of the intended destination. Accordingly, the residents in the moderate and high-dense areas close to the CBD (in the urban core) or in the high-dense areas and range 1 to 2 km away from the CBD (in the inner urban areas) have a short average commuting distance and time (less than 2.5 km). In contrast, the residents in the low-density areas, where they live close to the CBD (which rarely exist in the city) or in the low or moderate-density spots in the fringes, have relatively long average commuting distance and time. However, there are some exemptions in specific locations, particularly the residents close to the city's landmarks. See Figures 11 and 12.

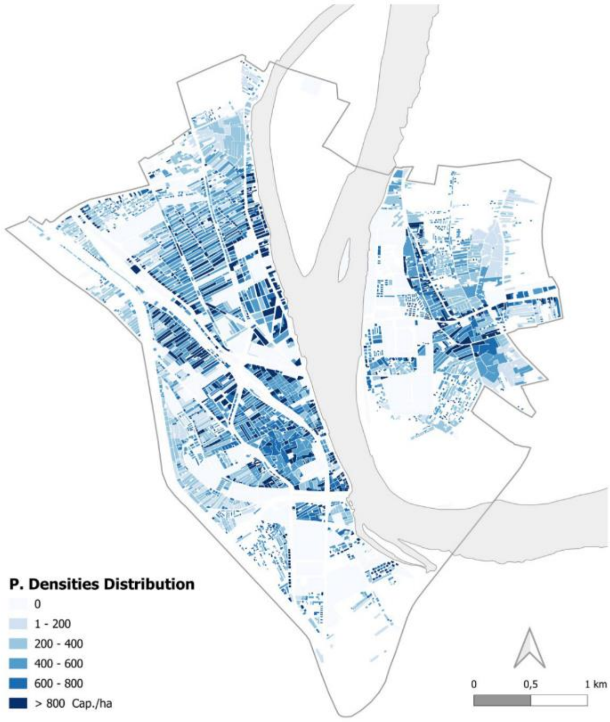


Figure 10. Map shows the distribution of population densities in Suhag city.

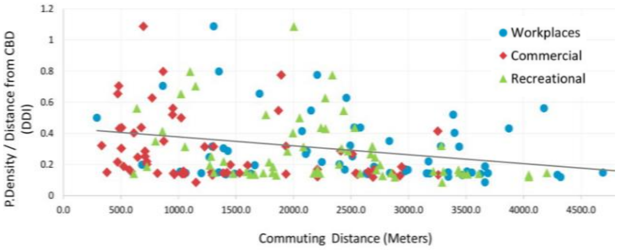


Figure 11. The relationship between density distribution indexes (DDI) and commuting distance in Suhag city.

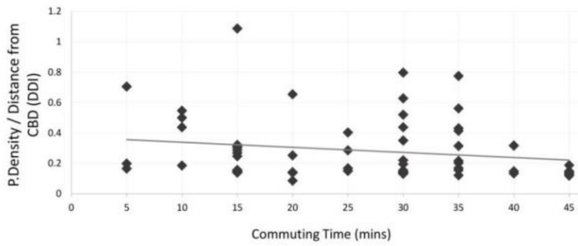


Figure 12. The relationship between density distribution indexes (DDI) and commuting time in Suhag city.

From another perspective, the distribution of built-up densities indicates a decentralized compact form of city. The urban core is relatively narrow and does not exceed 0.5 km in depth. It has an average of 0.6 built-up ratio. However, the inner urban is a wide zone, where approximately 65% of the total area, 78% of the population, and 72% of the commuting network occur. Thus, it has a significant impact on traffic volume and congestion. The periphery consists of sub-urban with a limited area, and the urban fringe, which extends to 4 km from the CBD. The results indicated a weak inverse relationship between the built-up ratio and average commuting distance and time. Except in the case of the residents in the periphery with a lower than 0.5 built-up ratio, it has high commuting distance and time. The commuting patterns in the inner and core urban areas have an inconsiderable relationship with the built-up density. Therefore, the built-up ratio is not an influencing factor to determine the characteristics of the commuting patterns as the other examined variables of urban spatial structure. See Figures 13 and 14.

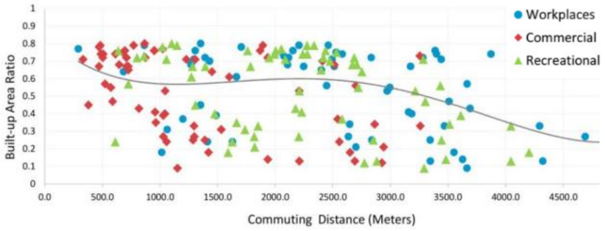


Figure 13. The inverse relationship between built-up area ratio and commuting distance in Suhag city.

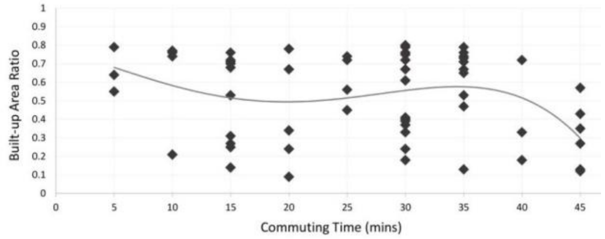


Figure 14. The inverse relationship between built-up area ratio and commuting time in Suhag city.

3.3.1. Balancing of population density distribution within urban zones

Spatial planning measures must be meticulously controlled to achieve equilibrium in population distribution, employment density, urban and transport infrastructure capacity, and social services. The objective is to accommodate residents optimally, avoiding both shortages and overburdening. Housing programs should be cognizant of creating diverse settlement patterns with varying levels of urban density. While these strategies might face challenges, particularly in old city districts, it nevertheless catalyzes urban development and renewal endeavors. Admittedly, this approach may necessitate amendments to existing urban regulations; however, it culminates in a more organized cityscape and reducing average commuting distances and times.

3.3.2. Maintaining high-dense clusters in the inner urban zones

Substantiated by the empirical evidence, inner urban zones encompasses a plethora of commercial and recreational land uses, strategically distributed in sub-centers, while also serving as a crucial physical link between the urban core and its suburbs. Hence, spatial planning measures ought to configure the inner urban region as high-density clusters, featuring a substantial or moderate built-up ratio to accommodate a proportional number of housing units and essential social services. The pursuit of heightened population and built-up densities holds the potential to preserve more land for economic activities and transport infrastructure. Consequently, this strategic approach assumes a pivotal role in mitigating traffic congestions, curbing traffic-induced emissions, and thwarting further degradation of the urban environment.

3.3.3. Reducing population density in the CBD and sub-centers

A paramount approach revolves around implementing a well-tailored strategy within central and sub-central locales characterized by elevated employment and commercial densities. The overarching aim is to alleviate the strain on transportation infrastructure, particularly in regions where a substantial proportion of residents embark on daily commutes to their respective workplaces. Notably, this strategy is not geared towards diminishing the average commuting distance. On the contrary, it advocates for an augmentation in commuting distance to workplaces. Nonetheless, the salient benefit lies in the potential reduction of both commuting time and traffic congestions, thereby fostering a more efficient urban mobility landscape.

4. CONCLUSION

Spatial and quantitative urban analysis were conducted employing geographical information system (GIS) tools, specifically the Open-Route-Service (ORS) based on Open-Street-Map (OSM), which granted access to a comprehensive set of functionalities. This tool accurately provided commuting distance and time between identified origins and destinations within the study area, along with precise buffer zones of specified duration or length from the residential locations. Consequently, it facilitated the evaluation of proximity, accessibility, and connectivity to designated buffer areas. The findings revealed that residents residing in high-density areas within the central or sub-central regions tend to have longer commuting distances compared to those residing in moderately dense spots in the inner urban area. Additionally, there exists a weak inverse correlation between the built-up area ratio and average commuting distance and time, except in the context of urban peripheries characterized by a built-up ratio lower than 0.5. These results hold significant implications for advancing our comprehension of the interplay between urban spatial structure and commuting patterns, thus aiding in the implementation of practical measures for traffic and transport management.

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