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Article

Using a Space Syntax Approach to Enhance Pedestrians' Accessibility and Safety in the Historic City of George Town, Penang

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Abstract: Contemporary urban development places a critical emphasis on pedestrian environments, especially in historic cities like George Town, which is a UNESCO World Heritage Site in Malaysia. Although survey questionnaires effectively captured public perceptions of issues such as poor road connectivity, weak accessibility, crime and safety concerns in George Town, they fell short in providing a comprehensive understanding of the root causes. This study leverages space syntax theory to model and analyze George Town's unique pedestrian landscape, aiming to identify strategies for improving pedestrian networks in historical urban landscapes. Space syntax theory, known for revealing structural issues within urban contexts, is applied after a thorough examination of George Town's urban layout, climate, architectural features, and development policies. George Town employs an informal grid layout widely utilized in British colonial port cities to enhance overall efficiency. The predominant architectural form is the shophouse, which is characterized by a ground level designed for pedestrian movement known as the "five-foot way" and adapted to Malaysia's climate. Various axis drawing methods for the unique five-foot way under different circumstances are considered. The George Town special area plan (SAP) emphasizing heritage preservation guides development policies, thus requiring an inclusive approach to pedestrian environments. This enhances the practical significance of the current study, with the eastern and northern coastal areas serving as crucial focal points for investigation. This approach results in a comprehensive spatial model that captures the essence of George Town's pedestrian landscape. Evaluation using space syntax indicators such as connectivity, integration, intelligibility, and choice reveals issues like poor overall network connectivity, inadequate access to key attractions, suboptimal integration, concentrated pedestrian flows, and significant safety concerns, which are exacerbated by limited infrastructure on certain two-way roads and a lack of zebra crossings. The practical implications of this study include recommendations for enhancing pedestrian spaces along identified roads and strategically installing zebra-crossings. This research is significant for its focus on a historical city in a Southeast Asian developing country, deeply integrating local environmental characteristics and providing insights into urban planning and optimization, thereby serving as a reference for similar cities.

Keywords: space syntax; pedestrian environment; safety; walking; historic city; George Town

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1. Introduction

The importance of a well-researched pedestrian environment is gaining prominence in contemporary urban planning and design [1]. The pedestrian environments of cities not only dictate the flow of pedestrian movement but also embody an everyday aspect of urban existence. Such an environment plays a crucial role in improving public health, encouraging physical activity, and nurturing social interactions [2]. Simultaneously, numerous cities globally emphasize a pleasant pedestrian environment as a distinctive feature [3]. Their aim is often to position themselves as prime pedestrian-friendly tourism destinations, thereby elevating their appeal. To be truly conducive for pedestrian exploration, a destination must possess an extensive pedestrian network as this can invigorate tourism activities [4]. The significance of the pedestrian environment becomes particularly pronounced in historic cities. These cities, replete with a rich tapestry of history and culture, emerge as must-visit locales. For visitors, walking emerges as a primary way of immersing themselves in and appreciating this heritage, underscoring its geographical, experiential, and transformative facets [5].

While George Town, which serves as the capital city of Penang state, has played a pivotal role in driving the growth of the northern region of Malaysia for several decades, its history as a World Heritage Site commenced in 2008 upon its inscription by UNESCO [6]. The inscription had significant impacts on the city, including the purchase and conservation of heritage shophouses [7]. The rapid pace of tourism development in George Town has led to tourism commodification, resulting in changes in lifestyle, community development, and property market values [8]. The toponymic politics of place names in George Town have also played a role in shaping the city's identity, with contested narratives of multiculturalism and the renaming of streets [9]. In recent years, George Town has also embraced the creative city agenda, with various stakeholders involved in the process [10].

Gentrification, the repeal of the Control of Rent Act, and the increase in house prices and rentals have affected the affordability of housing in the area [8,9]. Livability and heritage inheritance have become challenges for the residents, with strict heritage management impacting the balance between residential and tourism sectors [10]. The growth of tourism has brought both positive and negative impacts, with concerns about the dislocation of local communities and the potential loss of living cultural heritage values. Overall, the George Town World Heritage Site has expanded significantly due to its historical importance and economic growth. However, this growth has given rise to critical issues such as housing affordability, livability, traffic congestion, pedestrian network challenges, and the preservation of cultural heritage.

A thorough analysis of its pedestrian framework can illuminate prevalent challenges in its current pedestrian landscape and suggest relevant remedies. This endeavor resonates with the vision of Penang's local authorities who are keen to optimize the reach of their pedestrian pathways [11].

However, research specifically focusing on the pedestrian environment of George Town is conspicuously sparse. Among the limited studies available, Noraffendi and Rahman [3] offered an important work examining George Town's walking milieu. Their empirical survey assessed tourist satisfaction against multiple indicators, culminating in a finding that underscores a significant concern that George Town, despite its stature as a World Heritage Site, is marked by a paucity of pedestrian walkways, leading to challenges in connectivity and continuity. While their research was instrumental in offering urban planners a window into tourist perceptions, it did exhibit certain limitations. Most prominently, it fell short of delineating specific zones within George Town that are in dire need of augmented pedestrian pathways, nor did it delve into the root causes behind the observed discontinuity and disconnection. It is precisely these areas of inquiry where the space syntax-centric spatial analysis method, as employed in this study, demonstrates superior efficacy.

Space syntax comprises a series of theories and techniques about space and society proposed by Bill Hillier and Julienne Hanson. Its strength lies in establishing mathematical models that can yield accurate visual numerical results and are conducive to precise positioning. In this study, the main focus is on its theory of natural movement, which emphasizes the predictive ability of street layouts in influencing pedestrian movement [12]. The theory of natural movement posits that streets that are more integrated, implying greater ease of access from other streets, will inevitably attract more pedestrian traffic. This postulation has been reinforced through subsequent studies [13]. Empirical evidence has illustrated a correlation between street integration and the availability of commercial land or destinations [14]. In essence, areas with a robust street network foster pedestrian traffic, partially due to an increased presence of commercial destinations. On the flip side, areas demonstrating higher levels of choice typify roads more likely to be chosen as routes, so they are prone to traffic congestion [15]. A higher degree of intelligibility in street patterns paves the way for a clearer understanding of the area, thereby reducing the likelihood of individuals losing their way [16].

Historic cities have always been a focal point in space syntax research and the related theoretical framework continues to be enriched. A key characteristic of this research is the use of space syntax to link the urban spatial layout and economic activities with the intrinsic values of historic cities. Liao et al. [17] selected Pingyao, Lijiang, Gulangyu, and Wuzhen, four representative historical towns, for their analysis. By integrating spatial syntax results with point of interest (POI) data, they discovered that areas with higher integration degrees had more concentrated tourism functions. This led to proposed optimization strategies for land use. This study demonstrated the applicability of spatial syntax to ancient Chinese cities but was limited to two-dimensional analysis, thereby lacking in-depth exploration and analysis of three-dimensional scenes. In a similar vein, Wang et al. [18] applied space syntax to Nanjing's historic region to establish a correlation between the spatial distribution of tourism services and the street network. Their research, utilizing data from location-based services, suggested optimal locations for transportation, accommodation, and leisure facilities to foster sustainable urban development, though it did not account for the influence of street level, landscape features, and economic indicators on service distribution.

Further emphasizing the importance of pedestrian environments, Wang and Zhou [19] advocated for the enhancement of these environments in historic areas through space syntax analysis. They focused on four key parameters to evaluate spatial structure and road network characteristics, aiming to improve pedestrian experiences and address transport challenges in cultural tourism areas. This approach stressed the need for feasibility analyses based on actual traffic and road conditions. Lastly, Xu et al. [20] introduced a novel space grammar approach to evaluate the experiential qualities of historic streets in Nanxun, focusing on factors like complexity, consistency, mystery, and legibility. Their findings highlighted the need for careful conservation and restoration planning to maintain these qualities in the face of development pressures. They also suggested that the study could benefit from additional experiential quality analyses, such as surveys, to better correlate residents' and visitors' perceptions with the spatial characteristics identified. Space syntax has proven highly effective in analyzing historical cities and their pedestrian environments, especially in assessing spatial structures and road networks. Its scientific efficacy in these domains is well established through extensive research. When combined with point of interest (POI) data, road hierarchy details, and three-dimensional imagery, space syntax enables more holistic analyses, linking urban spatial configurations to tourism and economic factors. Nonetheless, while it offers substantial insights, space syntax does not completely capture the perceptions of tourists and residents regarding urban streets. Despite this limitation, it serves as a crucial foundational tool for experiential research in urban studies.

2. Study Area

The study focuses on George Town's core zone, a designated World Cultural Heritage area and a part of its buffer zone, encompassing 1.54 km^2 (Figure 1). The inclusion of the buffer zone, which interconnects with the core zone's road network, augments the precision of analysis for the core zone.

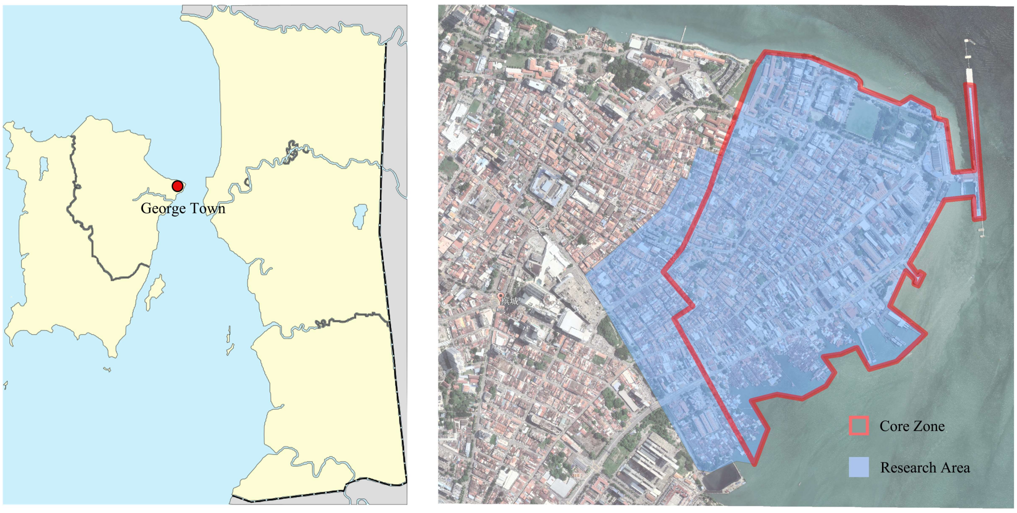


Figure 1. Map of the study area [21].

George Town, the administrative nucleus of Penang, Malaysia, ranks as the nation's eighth-largest city by population. Within its concentrated historical core of 19 km^2, it houses 158,336 residents according to the 2020 census, marking it as one of Asia's most densely populated areas [22]. Its historical and cultural gravitas drew an impressive 8.9 million tourists in 2019 [22]. Penang, where George Town is located, is one of the most developed states in Malaysia [23].

As a living embodiment of Penang's rich heritage, George Town mirrors Malaysia's multicultural tapestry and reflects its British colonial legacy. This cultural prominence earned its recognition as a World Heritage Site by the United Nations.

The city's urban structure adheres to an informal grid system that is a testament to colonial planning. British colonizers used two primary grid layouts in their colonies as follows: formal and informal. While the formal layout emphasized mathematical precision and order [24], the informal grid, despite its inconsistency, prioritized urban mobility and was frequently used in British colonial port cities across Malaysia and India [25].

A distinctive feature of George Town's cityscape is the prevalence of shophouses, as illustrated in Figure 2. These structures, typically spanning two to three stories, are prominent in the Southeast Asian landscape. Designed to fit narrow plots, they incorporate commercial areas on the ground level and in the residential spaces above. Their multifunctional design caters to residences, shops, and offices, highlighting their inherent adaptability. Typically, these shophouses are arranged in continuous rows, with a pedestrian walkway in front and a service road behind, thus creating an organized urban layout.

Figure 2. Shophouse in the study area.

The five-foot ways of Stamford Raffles, designed to protect pedestrians from the rain, are emblematic of shophouse architecture [26]. These covered walkways are one of the main pedestrian environments in George Town.

3. Materials and Methods

3.1. Policy Research

In this study, policy research is considered an essential reference for formulating research plans and strategic recommendations, with a key focus on the George Town special area plan (SAP) initiated in 2016. This plan, integral to the protection of the UNESCO World Heritage Site of George Town, is comprehensive in scope, emphasizing various facets of urban planning and heritage conservation [27].

At the core of the SAP is its emphasis on protecting George Town's heritage. The plan encompasses 111.98 hectares of the core zone and 150.17 hectares of the buffer zone, covering 5285 buildings including 83 Category I and 3890 Category II heritage buildings [28]. This highlights the unique approach required for historic cities, where the protection of valuable cultural heritage is often prioritized, recognizing that this may come at the cost of some economic benefits and tourist experiences. The challenge lies in balancing these sacrifices, for instance, by ensuring pedestrian safety and the integrity of heritage buildings, while enhancing pedestrian experiences. A critical aspect of this involves identifying and improving key sections that significantly affect the pedestrian environment to enhance the overall walking experience.

The SAP also underscores the creation and enhancement of public spaces, particularly along the northern and eastern waterfronts [28]. This reflects the practical significance of the study for the creation and enhancement of public spaces crucial for George Town's future development. Pedestrian environments, as fundamental public spaces connecting others, warrant particular attention. The northern and eastern coastal areas are worthy of being the focus of the investigation. Not only are these regions prominently emphasized in the document, but they also offer significant potential for improvement due to their coastal location and the fact that they have fewer historical buildings.

Lastly, the SAP emphasizes the importance of public participation, emphasizing the integration of public feedback into urban planning [28]. Previous studies on George Town's pedestrian environment using survey questionnaires have revealed public dissatisfaction [29]. This underscores the urgency of this research. Through understanding public sentiment and starting from the structure of the pedestrian environment, an in-depth analysis of the current issues offers a viable strategy for improvement.

3.2. Study Subject

This study examines the pedestrian environments in George Town, as shown in Figure 3, which are categorized into five main types as follows: sidewalks, residential roads, footbridges, five-foot ways, and town squares [30].

Figure 3. Five types of pedestrian environments in George Town.

Sidewalks are paths alongside streets, highways, or piers that are primarily made of concrete, paving stones, bricks, or asphalt. Elevated from the road and typically bounded by curbs, they may also feature green strips that separate them from the road and adjacent land.

Residential area roads primarily serve the residential community, implementing various traffic control measures such as speed limits to ensure pedestrian safety. These roads are typically one-way and, based on current observations, pedestrians can safely use them. Moreover, the areas on both sides of these roads predominantly consist of heritage buildings and the conditions for substantial improvements are generally limited. In order to maintain the relative integrity of constructing a pedestrian network, this study considers them as walkable environments.

Footbridges connecting two buildings are commonly referred to as “skyways”, while those serving both pedestrians and cyclists are called “green bridges” and are essential for sustainable transport.

The five-foot way is a distinctive sheltered walkway found in front of shops in regions like Malaysia, Singapore, and Indonesia. Its name implies a width of five feet, though actual sizes differ. This design, tailored to the local climate, profoundly influences the urban fabric of these areas [31].

A town square is an open public space, typically situated in the center of a traditional town, and serves as a focal point for community gatherings [32]. It plays a crucial role in the city’s pedestrian network, though it may not always be geometrically square.

3.3. Data Sources

This study focuses on George Town’s pedestrian environment, emphasizing road-based map data. The data sources comprise the three primary categories of OpenStreetMap (OSM) data, Google Maps, and on-site observation, each having unique values.

OSM data, the study’s foundation, include road data, architectural details, and points of interest (POIs). The extensive road data, covering various classifications, can be integrated with GIS data and imported into ArcGIS for preliminary pedestrian environment modeling. However, Zakaria and Ujang [4] indicate that while OSM is strong in positioning accuracy, particularly for roads, it lacks in completeness and thematic precision. This necessitates further validation and refinement.

Google Maps, with its navigation and street view features, is invaluable for cross-referencing OSM-derived GIS data. Its data, being more comprehensive than OSM’s, help identify discrepancies and overlooked aspects, especially in George Town’s core zone.

On-site observations, vital in the core zone, aim to capture the pedestrian experience and identify areas impeded by neglect or unauthorized obstructions, ensuring a comprehensive and accurate dataset.

3.4. Research Framework and Indicator System Construction

As shown in Figure 4, this study, anchored in space syntax methodologies, emphasizes four primary indicators of connectivity, integration, intelligibility, and choice. The selection of these four indicators emphasizes factors crucial to the pedestrian experience in George Town’s walking network, including accessibility, road connectivity, safety, and the logical layout of the network. All four indicators can be calculated using the DepthmapX developed for space syntax.

Connectivity, rooted in graph theory, is a pivotal metric for analyzing spatial patterns, especially in urban design. It denotes the number of direct links a space or node hold with adjacent ones. More connections imply higher connectivity and vice versa [16]. Highly connected spaces enhance pedestrian movement and commercial engagements due to their accessibility and interlinkages [15]. The study utilizes connectivity to initially assess pedestrian networks. The formula is as follows:

$$\mathrm{C}_{(\mathrm{x})} = \frac{\mathrm{k}(\mathrm{x})}{\mathrm{n}-1}$$

where $C_{(x)}$ is the connectivity of space x, k(x) is the number of spaces directly connected with x, and n is the total number of spaces.

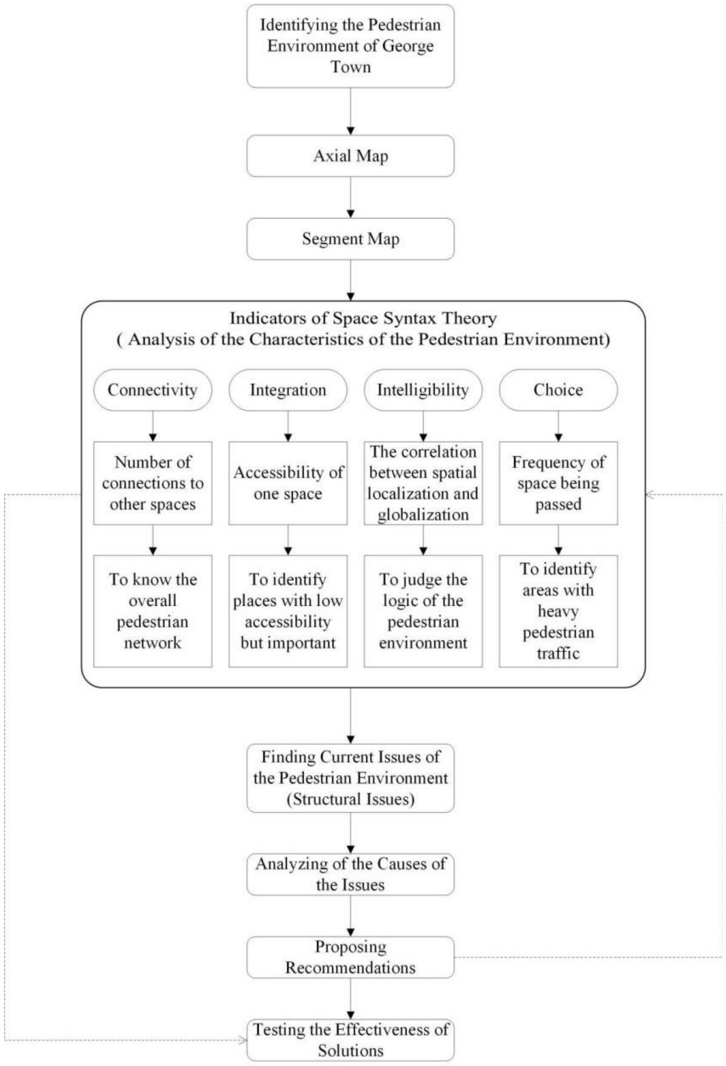


Figure 4. Research framework.

Integration measures the interconnectedness of a spatial element with its system, indicating its centrality and potential to attract traffic [33]. A higher integration denotes increased accessibility and propensity in gathering individuals. Integration bifurcates into global (encompassing entire spatial layouts) and local (focused on specific radii). This study primarily used local integration with a 400 m radius, a walking distance preferred by Malaysian adults [34]. In this study, integration was mainly used to evaluate the accessibility of different areas. The formula is as follows:

$$\mathrm{HH(x)} = \frac{2}{(n-1)(n-2)}\sum\nolimits_{j-1}^{n-1}\sum\nolimits_{k-j+1}^{n} r_{jk}$$

where r_{jk} is the shortest path from space j to space k and n is the total number of spaces.

Intelligibility represents the relationship between global (city-wide) and local (neighborhood-wide) integration, essentially quantifying the clarity of an urban layout from its broader configuration of individual sections [35]. This relationship is assessed through ordinary least squares (OLS) regression, using global integration as the independent variable and local integration as the dependent one. The resulting R^2 value indicates their correlation strength. R^2 values below 0.5 indicate weak correlation, those between 0.5 and 0.7 suggest moderate correlation, and those above 0.7 signify significant correlation [35]. Intelligibility was applied in this study to evaluate the logic and clarity of the walking environment.

Choice gauges how often a spatial element is used as the shortest path between two nodes, effectively indicating an area's pedestrian traffic potential. High choice values suggest heavy foot traffic [36]. In this study, choice was used to identify the business of pedestrian traffic in different areas. The formula is as follows:

$$\mathrm{Choice}_{(x)} = \frac{1}{(n-1)(n-2)} \sum_{j \neq x \neq k} \frac{a_{jk(x)}}{a_{jk}}$$

where $a_{jk(x)}$ is the number of shortest paths passing through space x from j to k and a_{jk} is the total number of shortest paths from j to k.

The research unfolds in three stages. Initially, a pedestrian model of George Town is crafted by identifying its pedestrian features, mapping them through the axial map of space syntax theory, and then transforming this into a foundational segment map. The second stage scrutinizes the segment map using the four space syntax indicators, thus identifying structural issues in George Town's pedestrian setup. The concluding stage, drawing insights from the previous analyses, pinpoints causes, suggests solutions, and constructs a refined segment map. The improvements are then validated using the aforementioned space syntax indicators and a discussion of its compatibility with the George Town Planning Program.

3.5. Research Strategies

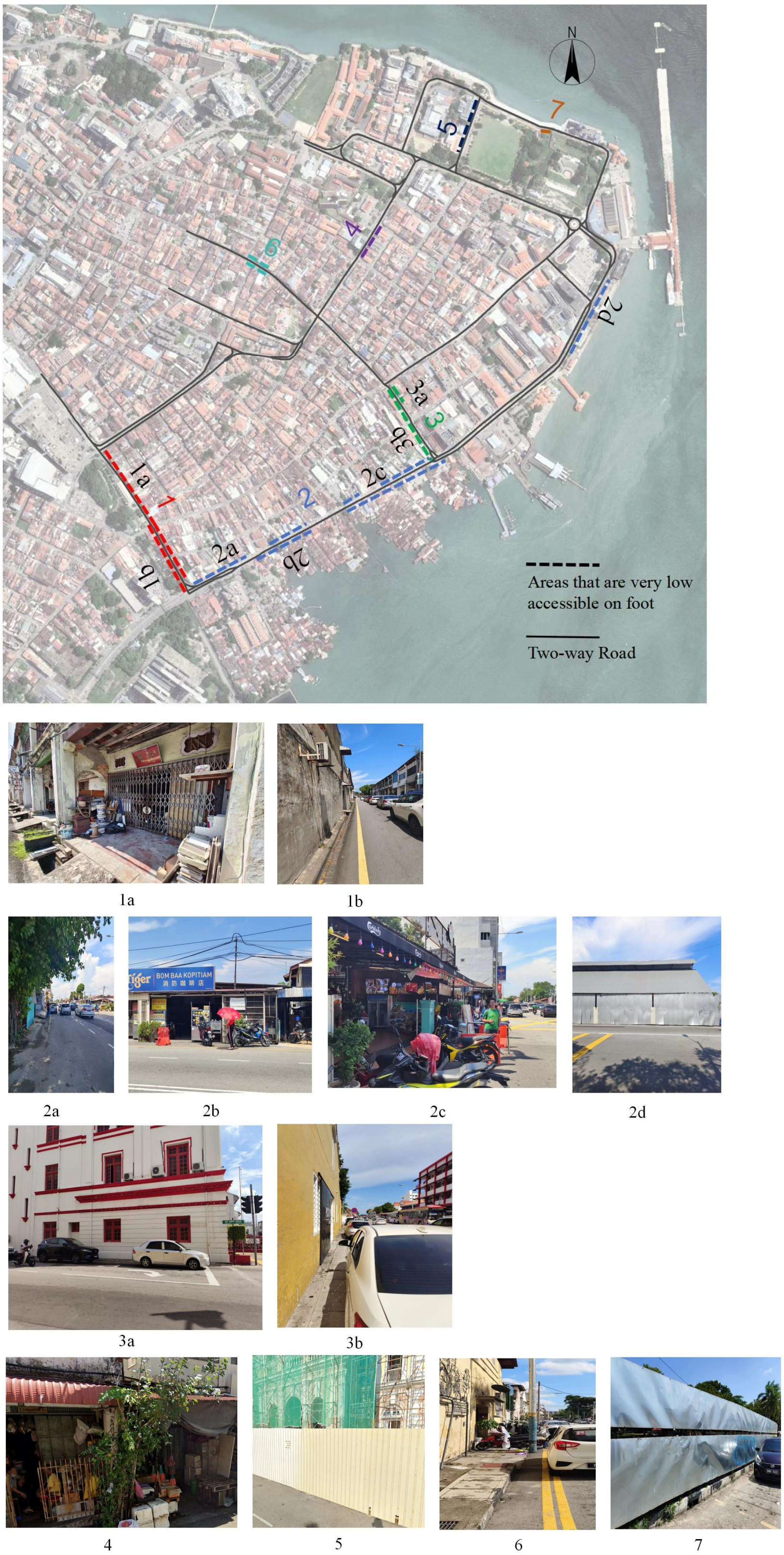
3.5.1. Identifying George Town's Pedestrian Environment

In this study, the pedestrian environment of George Town was identified as foundational for developing George Town's walking model. Five distinct categories have been discerned before of sidewalks, residential roads, footbridges, five-foot ways, and town squares [30]. Pathways in town squares and footbridges are independent, while sidewalks and five-foot ways typically border residential roads or two-way roads. In this study, residential roads, five-foot ways, and sidewalks are collectively deemed walkable environments. Their integration allows for considerable flexibility, obviating the need for distinct observations during the initial model construction; they constitute a unified walking space.

This study primarily addresses the pedestrian areas alongside two-way roads, considering how their separation due to these roads creates independent walking environments. Safety concerns arise when these routes are affected or obstructed by illegal parking, store occupations, etc., potentially forcing pedestrians onto dangerous roads. This situation excludes the section from the pedestrian environment.

Utilizing OSM data, two-way roads in George Town are easily pinpointed, as denoted through the black lines shown in Figure 5. Given their limited number, on-site observations offer the most accurate depiction of the pedestrian environment on both sides. The on-site observations were conducted and street view data from Google Maps were analyzed, revealing persistent inadequacies in the pedestrian environment along certain sections. These road sections are identified as having very low accessibility since they lack pedestrian facilities or have unusable walking paths, forcing people to walk on vehicular roadways. Moreover, they constitute high-traffic two-way roads, exacerbating the difficulty and danger posed to pedestrians. The specific road sections are represented through dashed lines in Figure 5 and are distinguished through numbers 1–7 as well as various colors. The areas where issues are more concentrated, road sections 1–3, are denoted through numbers followed by letters a, b, c, to indicate different problem locations within these sections.

On road section 1, as indicated through the red dashed line, one side has five-foot ways, but they are poorly maintained and not consistently passable. The other side lacks proper pedestrian walkways, forcing pedestrians to walk on the dangerous vehicular roadway, which causes a very low level of accessibility and greatly impacts pedestrian safety and their walking experience.



1, 2, 3, 4, 5, 6, 7: Sections with very low level of accessibility on foot

a, b, c, d: Specific areas within the sections with a very low level of accessibility on foot

Figure 5. Areas that have a very low level of accessibility on foot.

Along road section 2, despite its density of shops and street food stalls drawing significant foot traffic, proper pedestrian pathways are either absent or heavily encroached upon by shops. This forces pedestrians to walk on the perilous roads, sometimes even while purchasing street food, thereby endangering their safety and disrupting traffic flow. It is noteworthy that this particular section aligns with the George Town SAP's emphasis on enhancing public space development in the eastern coastal region of George Town [28].

Road section 3 presents a mixed picture. While one side is generally well maintained, persistent illegal parking is noted in a particular section. The opposing side, however, is deficient in pedestrian areas.

Additionally, some other road sections (4–7) are impassable due to construction, illegal parking, or encroachment by shops.

3.5.2. Axial Mapping

In space syntax theory, the axial map uses axial lines to represent spaces [12]. For this study, it portrays George Town's walking environment. Hillier [35] outlined how the space syntax axial map replaces road space with a straight line, disregarding road width and grade. An axial line signifies the primary line of sight for movement within a built environment. In urban contexts, these lines connect various public urban spaces [16]. This study employs OSM data and Google Maps as foundational maps for axial line drafting, which is refined through on-site observations and created using ArcGIS 10.8 to ensure geospatial accuracy for further analysis.

The method of drawing the axial lines in these two situations needs to be described separately. These two scenarios are related to George Town's unique "five-foot way". Firstly, two-way roads are not walking environments due to their traffic intensity. For such situations, separate axial lines must represent the five-foot ways and sidewalks on both sides of two-way roads. If five-foot ways and sidewalks exist independently on one road side, a singular axial line ought to represent them, indicating the longest sightline for spatial movement [16]. When they coexist on one side, an encompassing axial line is required. The specific approach is shown in Figure 6.

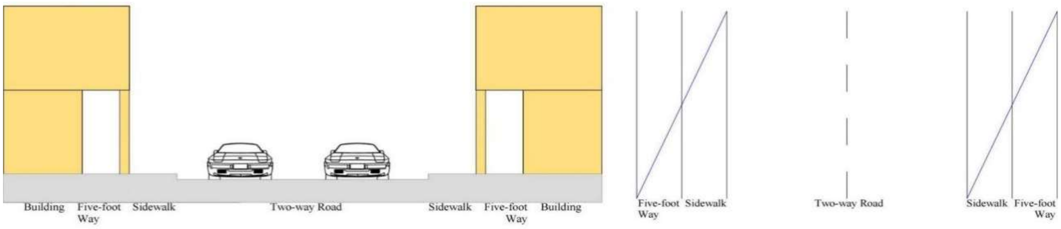


Figure 6. Axis drawing of sidewalks and five-foot ways on both sides of a two-way road.

Connections between pedestrian environments divided by two-way roads only exist through a zebra-crossing (Figure 7). This consideration is made from a safety perspective, ensuring pedestrian safety by mandating the use of pedestrian crosswalks (zebra crossings) for crossing traffic-dense roads. Otherwise, there are significant safety risks involved.

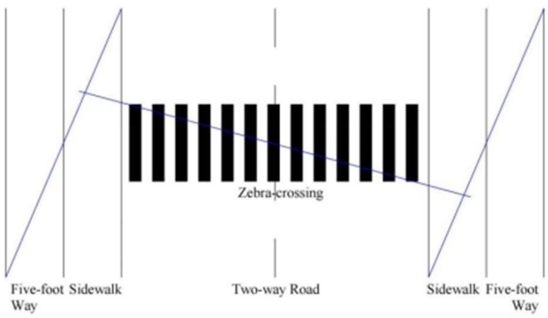


Figure 7. Axis drawing of zebra-crossing.

Secondly, in George Town's core zone, residential roads that are primarily one-way have pedestrian-friendly sides formed through five-foot ways or sidewalks. Observations confirm their frequent use by pedestrians. An axial line representing this common configuration spans the residential road and its adjacent pedestrian environments (Figure 8). This represents George Town's prevalent pedestrian layout.

Finally, the drawing of the entire study area's axis is undertaken following the method of drawing axes (Figure 9).

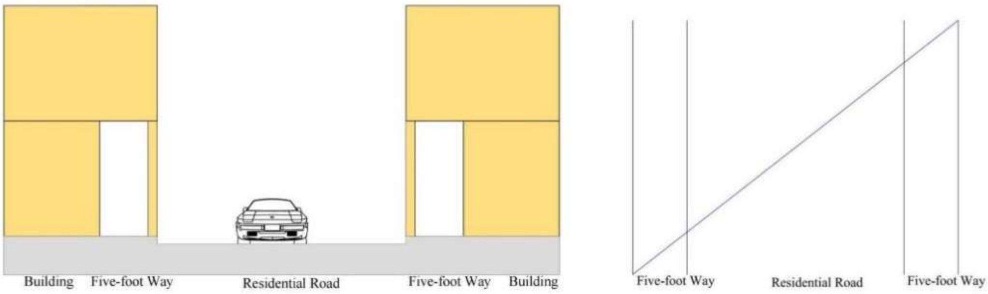


Figure 8. Axis drawing of walkable environments on both sides of residential roads.

Figure 9. Axial map of George Town.

3.5.3. Segment Mapping

Upon completing the axial map, it was integrated into the DepthmapX tailored for space syntax analysis. This axial map was transitioned into a segment map for further analysis (Figure 10). Segment analysis offers refined movement and spatial assessments.

Segment analysis is particularly advantageous for historic neighborhood studies from a pedestrian standpoint. It factors in metric distance and employs a metric radius to constrain computational elements in the segment model. Notably, it contemplates the angular relationship between segment units, termed angular segment analysis (ASA), providing a more accurate approach than traditional methods. This rectifies space syntax research limitations like neglecting spatial GPS coordinates and street metric distances [37]. Crucially, the segment analysis focuses on line intersection points, enabling effective examination of intricate spatial interrelations within neighborhoods and intersection point topologies. This method satisfies the nuanced spatial analysis demands of historic neighborhoods.

Figure 10. Segment map of George Town.

For the segment map, a measurement radius is essential, denoting each variable's measurement scope in the segment. In this research, the radius was determined through Malaysia's optimal walking distance for young people and adults: 400 m [34], This value takes Malaysia's hot climate into account as much as possible.

3.5.4. Analysis of the Indicators

Utilizing space syntax theory, this study prioritizes the analysis of four key indicators of connectivity, integration, intelligibility, and choice in order to discern structural issues within George Town's pedestrian environment. The objective is not only to identify these issues but also to determine their causes and assess the effectiveness of suggestions.

Leveraging the segment map, Depthmap computes values for the aforementioned indicators. Individual space values, denoted as segments, can be processed by Depthmap and subsequently analyzed in ArcGIS. Given that the initial axial map was created in ArcGIS, data from Depthmap preserves its geographic coordinates, thereby optimizing integration with other GIS data for a holistic analysis of the structural issues of George Town's pedestrian environment.

Following the analysis, recommendations are proposed to address these structural problems. A revised pedestrian model is established and Depthmap is applied to the key indicators. These results are then juxtaposed with prior findings relating to the existing pedestrian environment of George Town, allowing for the verification of advice efficacy.

4. Results

This chapter evaluates George Town's pedestrian network using the space syntax indicators of connectivity, integration, intelligibility, and choice, delineating its prevailing features and challenges.

In the forthcoming analysis, five important areas in George Town that are designated from A to E will be discussed many times (Figure 11). The areas indicated through A, B, C, D, and E in this article are also uniformly the same areas. Area A represents the bustling commercial hub of Little India. Area B is notable for its significant tourist sites, including the Penang's street art and Cheah Kongsi Temple. Area C, located in George Town's east waterfront district, features the prominent Chew Jetty. Coastal area D houses landmarks such as Fort Cornwallis, while area E, which is near to the Sia Boey Urban Archaeological Park, functions as the gateway to George Town's core zone.

Figure 11. Important areas in this research.

4.1. Connectivity Analysis

Connectivity, a pivotal metric in spatial pattern analysis, denotes the number of connections between a space or node and its neighbors. Greater numbers of connections indicate higher connectivity [16]. This metric profoundly influences pedestrian movement, commerce, and the calculations of integration and choice values.

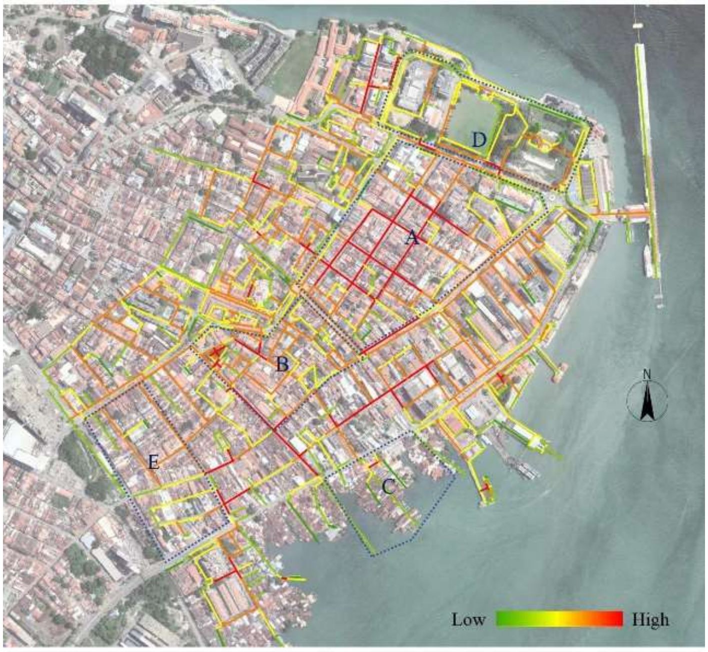
Figure 12 illustrates the connectivity of the study area, with shades closer to red signaling elevated connectivity values. The connectivity scores in this zone range between 1 and 6, with a median and average of 3 and a standard deviation of 1. Generally, connectivity diminishes outward from the central region.

Area A, known as Little India, is a commercial hub with high pedestrian activity and boasts the highest connectivity in this zone. Conversely, coastal areas, such as areas C and D, exhibit diminished connectivity. This is attributable to both a dearth of roads and the unavailability of pedestrian-friendly pathways. A more detailed understanding necessitates a combined review with the integration map.

4.2. Integration Analysis

Integration in spatial systems measures the relation of a specific element to other components, quantifying a space's capacity to attract traffic [14]. Higher integration denotes enhanced foot traffic attraction, accessibility, and potential as a commercial hub.

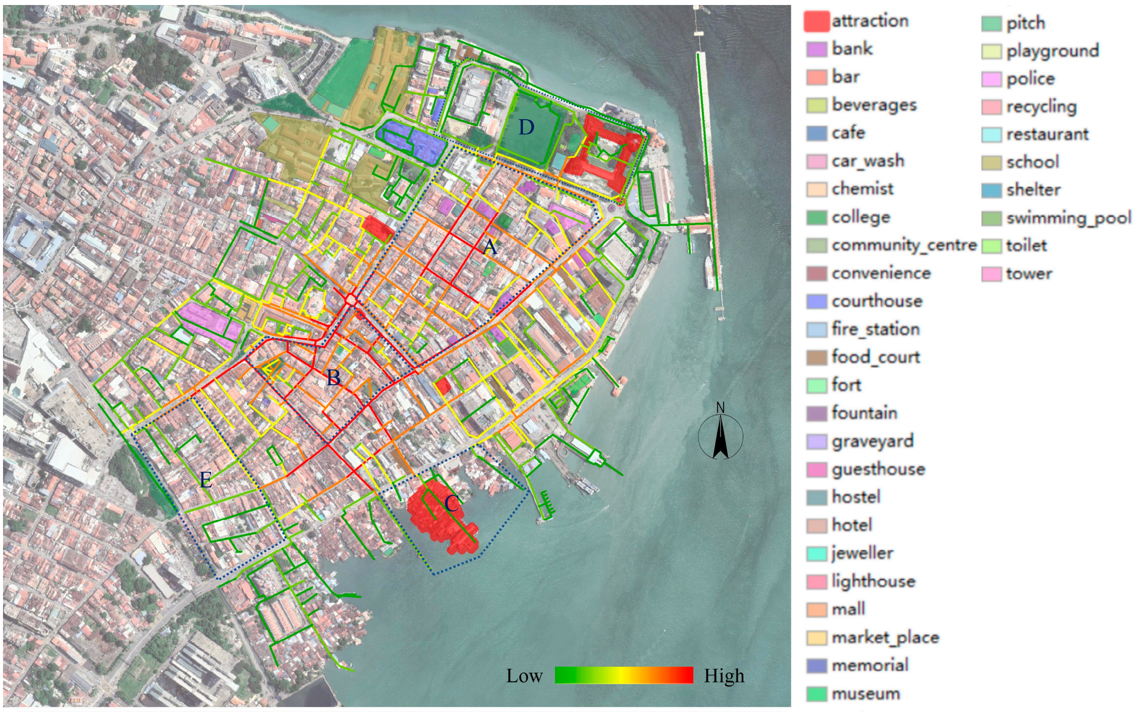
Figure 13 depicts the study area's integration within a 400 m radius. Redder areas signify higher integration. The values range from 2.57 to 93.73, with a mean of 34.36, a median of 30.3, and a standard deviation of 17.91. Despite the stark range, the data is relatively centralized, as evidenced through the close mean and median and low dispersion. The figure displays a central-to-periphery decline in integration, mirroring the connectivity distribution.



	Mean	Median	Standard deviation SD		Minimum	Maximum
Connectivity	3	3		1	1	6

Figure 12. Connectivity map of George Town.

Overlaying the integration map with points of interest (POIs) from OSM data (Figure 13), high-integration areas A and B coincide with George Town's tourist-dense regions. Specifically, A matches with Little India and B includes attractions like Penang's street art. These two areas are also important commercial areas in George Town, underscoring space syntax theory's validity.



	Mean	Median	Standard deviation SD	Minimum	Maximum
Integration(400m)	34.36	30.3	17.91	2.57	93.73

Figure 13. Integration map of George Town.

Conversely, zones C, D, and E, while significant—C contains Chew Jetty and D houses attractions like Fort Cornwallis—exhibit reduced integration. Their peripheral location might contribute to their lesser integration, but other factors exist. It is noteworthy that areas C and D, as explicitly stated in the SAP, are identified for enhancing public spaces in the northern and eastern coastal regions of George Town [28].

Figure 14 highlights zebra crossings in red and discrepancies at the ends of the two-way vehicular lanes in black. Clearly, areas with zebra crossings foster higher integration and walkability, whereas black-marked areas disrupt pedestrian flow, reducing integration. Notably, C, D, and E predominantly feature poorly maintained pedestrian paths and lack zebra crossings. Enhancing these pathways and introducing more crossings could potentially boost their integration, thus augmenting accessibility.

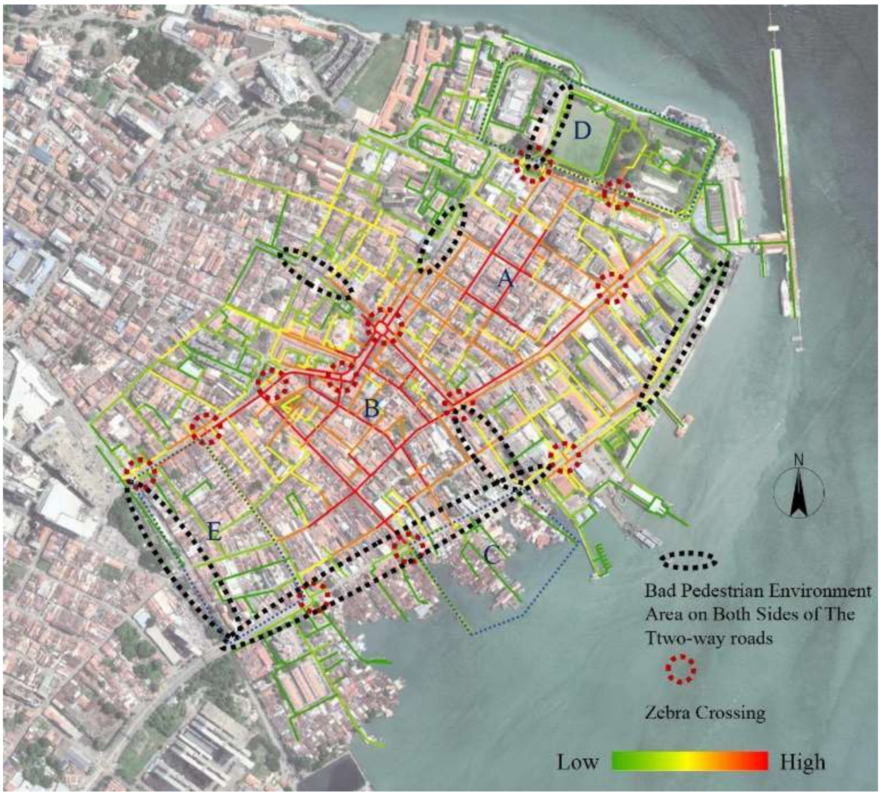


Figure 14. Analysis of integration map.

4.3. Intelligibility Analysis

Intelligibility denotes the relationship between a space's global and local aspects [35]. It is quantified using the ordinary least squares (OLS) regression between global and local integration, symbolized through R^2. A larger R^2 value implies a stronger correlation between global and local facets, suggesting an enhanced clarity of street patterns and better navigational understanding [16].

In this study, global integration is the independent variable, with local integration (radius of 400 m) as the dependent variable. These results are depicted in Figure 15. The computed R^2 value is 0.593, signifying a moderate relationship between global and local integration. However, as previously mentioned, George Town utilizes an informal grid layout, a design developed to enhance urban efficiency, with its spatial arrangement being highly logical. Therefore, its intelligibility, which reflects the walkability logic of the environment, should possess a higher value. Addressing the previously noted issues on two-way roads could potentially enhance this area's intelligibility.

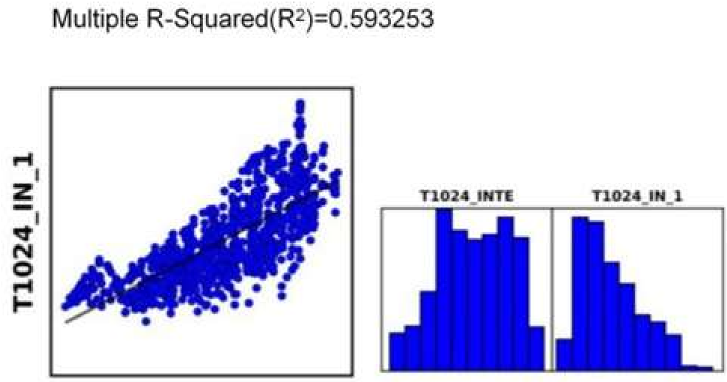
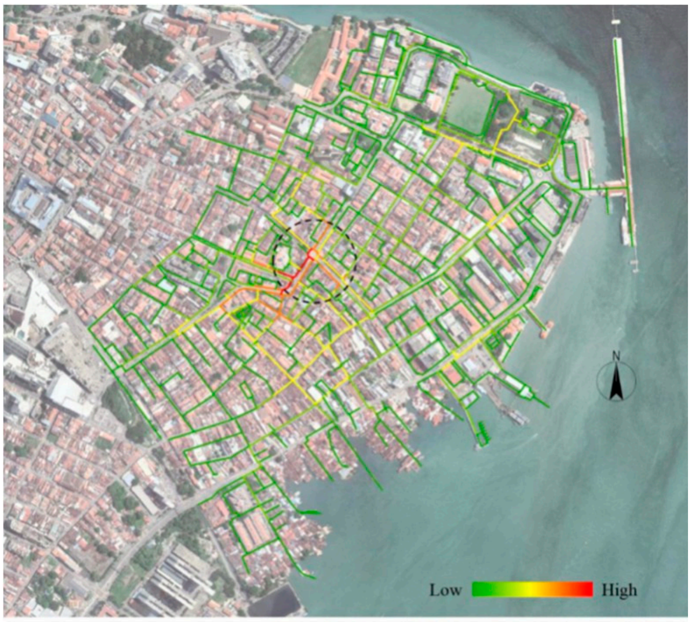


Figure 15. OLS diagnostics.

4.4. Choice Analysis

In space syntax theory, "choice" denotes the likelihood of a particular spatial element being used as the shortest topological route between two nodes [36]. A higher choice value implies a greater state of being traversable and potential traffic congestion.

Figure 16 illustrates the choice for an area with a 400 m radius. A redder hue indicates a higher choice value. There is a stark disparity between the maximum (12,996) and minimum (0) choice values, with a mean of 962 and a median of 498. The high standard deviation of 1406 signals significant data dispersion and an uneven concentration of choice in specific road sections.



	Mean	Median	Standard deviation SD	Minimum	Maximum
Choice(400m)	962	498	1406	0	12.996

Figure 16. Choice map of George Town.

The choice map reveals areas encircled in black with markedly higher choice values, marking them as prime transportation hubs. This happens to cover the intersection of two important roads. This crossroad links major George Town landmarks, justifying its elevated choice value.

The stark disparity in choice values suggests that areas with elevated values might experience undue traffic stress, thus impacting travel experience and safety. Given certain walkway imperfections, they might influence overall choice values. Inadequate walkways might be less factored into choice calculations, causing certain routes to be overrepresented and inflating values.

5. Discussion and Findings

5.1. Existing Structural Issues of George Town's Pedestrian Environment

In a thorough assessment of Georgetown's pedestrian environment, four key dimensions were evaluated as follows: connectivity, integration, intelligibility, and choice. The findings indicate several structural shortcomings in the current layout. Firstly, the absence of pedestrian facilities sometimes forces pedestrians to walk on motor vehicle lanes, posing significant safety risks to them. Secondly, there is a noticeable deficiency in walkability, especially towards attractions on the periphery of the designated study zone, which compromises pedestrian mobility within the area. Moreover, despite its irregular grid pattern, George Town's intelligibility score is lower than expected. Indeed, a higher level of environmental legibility based on its urban morphology might have been expected. Thirdly, an evident over-reliance on a limited number of high-choice road segments leads to exacerbated traffic pressures on these pathways. Lastly, a plausible factor exacerbating these challenges is the lack of designated pedestrian zones flanking certain two-way streets and an inadequate provision of zebra crossings. Introducing this infrastructure could potentially ameliorate the area's connectivity and accessibility. However, such hypotheses warrant rigorous empirical validation in future research endeavors.

5.2. Recommendations for the Pedestrian Environment's Structural Issues

Prior sections detailed structural issues in the study area's pedestrian environment, such as limited accessibility to attractions, traffic congestion in specific segments, and unexpectedly low intelligibility. Notably, bidirectional vehicular sections lacking pedestrian spaces on both sides showed decreased integration, implying reduced accessibility. In contrast, areas with zebra crossings indicated better integration and thus greater accessibility.

To address this issue, the study will fill in gaps in pedestrian areas on bidirectional roads and increase zebra crossings based on OSM's POI data. Axial maps will be updated (Figure 17) and converted into segment maps to compute the key variables of connectivity, integration, intelligibility, and choice. Post-improvement data will be juxtaposed against the original to validate the hypothesized outcomes.

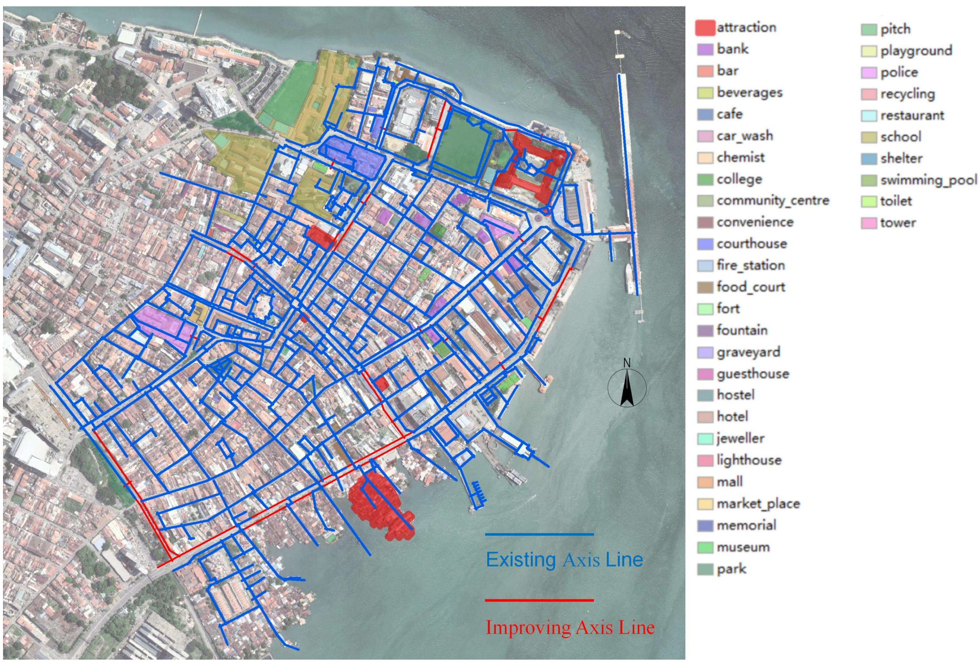
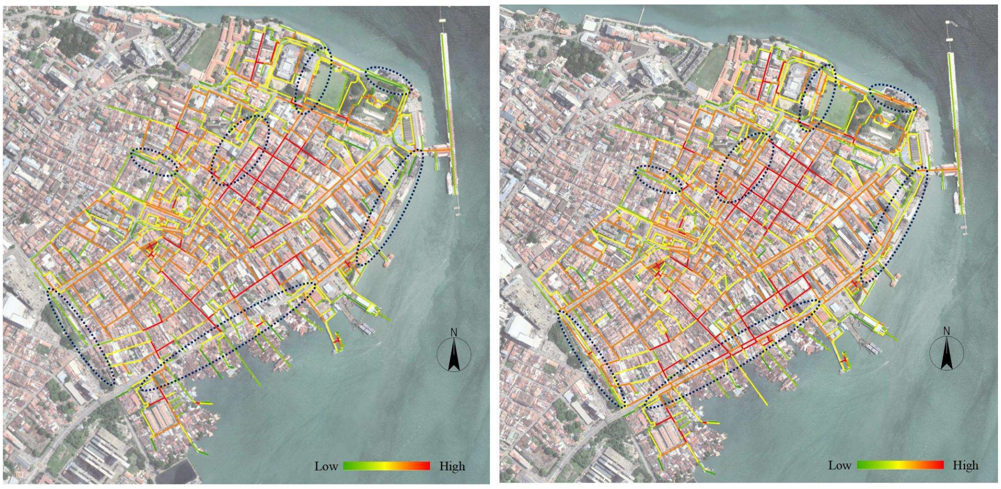


Figure 17. Improved axial map.

5.3. Validation of the Effectiveness of Related Recommendations

By evaluating the improved pedestrian network, the effectiveness of the recommendations can be well tested.

Connectivity. While overall changes appear modest (Figure 18), with the median value shifting from 3 to 4, specific local areas, delineated by black ellipses, exhibit enhanced connectivity. This corresponds with added segments that reinforce pre-existing pedestrian routes, thus cultivating a more cohesive walking environment.

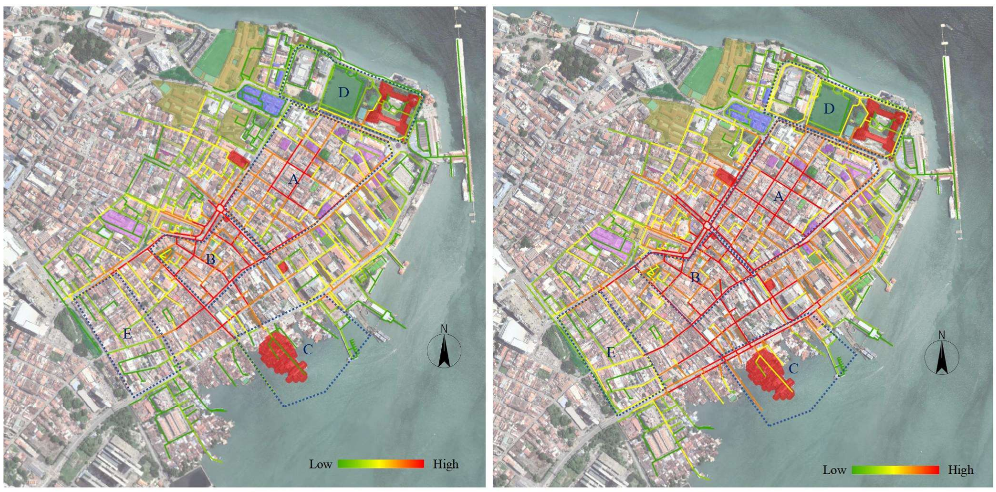


Connectivity Map (existing) Connectivity Map (post-improvement)

	Mean	Median	Standard deviation SD	Minimum	Maximum
Connectivity-existing	3	3	1	1	6
Connectivity-post improvement	3	4	1	1	6

Figure 18. Comparison of connectivity: post-improvement and existing condition.

Integration. Marked changes are evident (Figure 19) and metrics like the mean, the median, standard deviation, and extremities have risen. Areas C, D, and E, while originally demonstrating limited accessibility, have observed pronounced improvements that are particularly evident in zones C and D. Consequently, landmarks like Chew Jetty and Fort Cornwallis are more pedestrian-friendly. Even the high-integration areas of zones A and B benefited from urban structural refinements.



Integration Map 400m (existing) Integration Map 400m(post-improvement)

	Mean	Median	Standard deviation SD	Minimum	Maximum
Integration(400m)-existing	34.36	30.3	17.91	2.57	93.73
Integration(400m)-post imorovement	43.43	40.64	20.07	7.08	118.49

Figure 19. Comparison of integration: post-improvement and existing condition.

Intelligibility. Correlating with integration shifts, intelligibility underscores the synergy between global and local integration. The R^2 value for intelligibility has improved from 0.593253 to 0.638714 and is illustrated through a condensed scatter plot (Figure 20). This represents a heightened spatial cognizance, augmenting the overall pedestrian navigation.

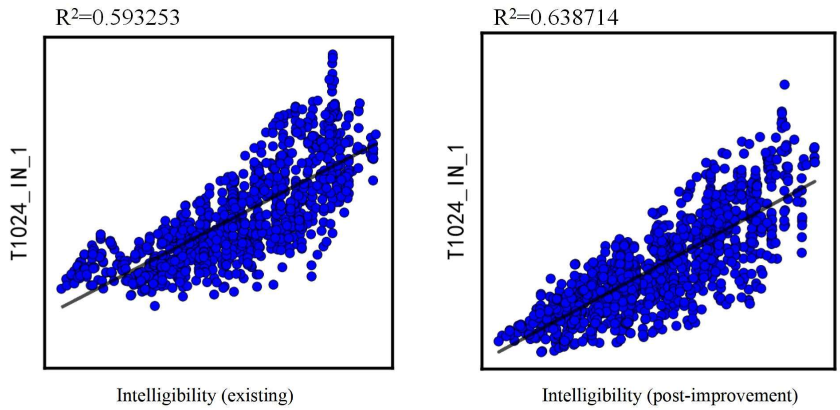
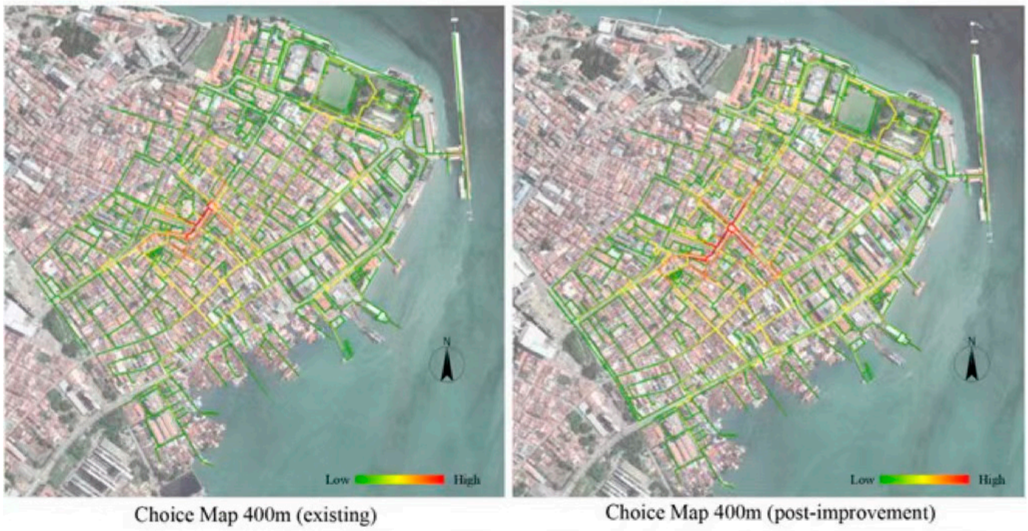


Figure 20. Comparison of intelligibility: post-improvement and existing condition.

Choice. Although choice map alterations seem understated, statistical data (Figure 21) indicate that metrics like mean, median, standard deviation, and peak values have diminished. This suggests a reduced congestion in previously high-traffic pathways, allowing for more diversified pedestrian options.



	Mean	Median	Standard deviation SD	Minimum	Maximum
Choice(400m)-existing	962	498	1406	0	12,996
Choice(400m)-post improvement	718	293	1187	0	8816

Figure 21. Comparison of choice: post-improvement and existing condition.

In essence, enhancements like supplementing pedestrian zones along bidirectional lanes and incorporating zebra crossings have profound implications for George Town's pedestrian infrastructure. These elements bridge local areas, thereby bolstering road cohesion, accessibility, clarity, and traffic distribution. Practically speaking, many bidirectional lanes already possess potential pedestrian pathways. Challenges lie in areas where sidewalks are scant or where existing pedestrian facilities, such as five-foot ways, are misused for parking or commercial activities. Proper regulation can drastically elevate the pedestrian milieu.

5.4. The Novelty of the Study

The innovation of this study lies in its unique focus on the historic city of George Town, Malaysia. Previous research on George Town's pedestrian environment has been limited and predominantly relied on questionnaire methods such as Awanis [29]. This study, however, adopts an approach that examines the physical spatial aspects of George Town's walking environment, utilizing space syntax theories and techniques.

It is crucial to note that George Town is a historically significant city with distinctive features that encompass its urban layout, architectural forms, and status as a UNESCO World Heritage Site and that couple with its unique development policies. Therefore, this study was commenced by thoroughly understanding the urban characteristics of George Town, integrating the SAP to formulate the research strategy. For instance, its informal grid urban layout, unique shophouse architecture, and integrated pedestrian spaces, like the five-foot ways, differ significantly from Western modern cities and historical towns in China, thereby representing a historical city type unique to Malaysia. This study adapts space syntax to this city type using specific considerations like the axial representation of five-foot ways, the exploration of the informal grid's inherent logic, treating residential roads as part of pedestrian spaces, and aligning suggestions with George Town's development plans. These constitute the main innovative aspects of this study.

On a technical level, this study employed traditional research methods related to space syntax and drew on experiences from other studies, enhancing the objectivity of the research outcomes. This includes distinguishing road hierarchies, conducting on-site inspections to move beyond a two-dimensional analysis, and integrating space syntax with POI data to analyze pedestrian environmental issues around significant landmarks. In summary, this research fills a gap in space syntax studies for cities like George Town, offering significant insights for future planning and research on similar city types.

5.5. Limitations and Prospects

This research investigates the rationality of George Town's pedestrian network structure and is an integral aspect of exploring its walking environment. The study has limitations but offers scope for further exploration.

Primarily, the study adopts a macroscopic view, focusing on the broader pedestrian network rather than specific road sections. Notably, it highlights sections with high integration, which are prone to congestion, and high selection, often being traversed by pedestrians. Such sections warrant a detailed analysis. Through careful observation and targeted pedestrian surveys, the walkability of these sections can be assessed. Consequently, effective strategies can be formulated, optimizing resource utilization in renovating historical districts.

In terms of theoretical foundations, this study relies on space syntax theory, which is grounded in Hillier's "space determinism". While effective in various contexts due to its reflection of planners' intents and historical activity patterns, this theory has recognized limitations [23]. As noted by Esposito et al. [38], space syntax, with its rigorous methodology, is proficient in predicting pedestrian behaviors based on urban configurations. However, it may neglect nuances such as emotional factors influencing human choices. For instance, the impact of a popular online review can significantly alter a shop's footfall. To address this limitation, modern advancements allow for the refinement of space syntax accuracy by integrating big data from mobile signaling, thus providing insights into real-time pedestrian patterns.

In summary, this research provides a focused examination of George Town's pedestrian landscape and offers valuable insights. Indeed, it presents a starting point and leaves with it avenues for deeper exploration.

6. Conclusions

Using a quantitative approach centered on space syntax theory, this study models and analyzes George Town's pedestrian environment. The research thoroughly examined

George Town's walking environment characteristics, focusing on road compositions and axis drawing methodologies. The pedestrian network of George Town was analyzed using Depthmap in conjunction with GIS data.

This study addresses deficiencies in previous research on pedestrian walkability in George Town. Previous studies highlighted accessibility and safety issues in George Town's pedestrian environment from pedestrian sensing. However, they faced challenges in explaining the underlying reasons behind pedestrians' perceptions. This study took a comprehensive approach, starting from spatial form analysis and then closely integrating George Town's urban layout, architectural features, climatic conditions, and development plans. It constructed a spatial model that effectively reflects the characteristics of George Town's pedestrian environment. The findings reveal structural deficiencies in George Town's pedestrian network, leading to poor accessibility, weak connectivity, concentrated pedestrian traffic, and safety issues at some key landmarks. The research further delves into the spatial factors causing these issues. The superiority of spatial form visualization is evident. In maps centered around four key indicators—connectivity, integration, intelligibility, and choice—one can noticeably discern how these values fluctuate in relation to certain key streets. These indicators, in turn, correspond to the pedestrian network's connectivity, accessibility, understandability, and frequency of passages. Closer examination of these key streets reveals that most are dual-direction main roads lacking safe pedestrian space, including areas significantly impacting spatial dynamics such as the absence of safe pedestrian crossing facilities like zebra crossings. These factors greatly influence pedestrians' choices and safety, thereby affecting their overall walking experience.

By simulating an ideal pedestrian environment that addresses these issues, significant improvements in spatial accessibility, connectivity, intelligibility, and overly concentrated pedestrian flows were observed. Solutions include ensuring safe pedestrian spaces on both sides of certain dual-direction roads, which can be achieved through strict enforcement against illegal parking and storefront encroachments on sidewalks as well as by adding more pedestrian paths. Additionally, installing zebra crossings at key locations to ensure pedestrian safety is recommended. These decisions are made with deep consideration of the nature of George Town as a World Cultural Heritage site, aiming to minimally alter the internal structure of George Town's heritage and focusing instead on the traffic of main roads.

The research aligns with George Town's current planning and development strategy. The identified road segments in this study play a crucial role in the overall structure and are situated on both sides of the main roads, having fewer heritage buildings and a potential for improvement. The eastern coastal area is particularly concentrated with regard to the increase in pedestrian space, coinciding with the SAP's explicit designation of enhancing and increasing public space development. The study suggests elevating pedestrian environment development up to a top priority level in public space construction and considering it as the foundational space that connects other public areas.

Hence, the research findings are not only relevant to the specific case of George Town but also have broader implications for other heritage sites in the Southeast Asian region. The insights gained from this study can inform decision-making processes related to the design of heritage zones, infrastructure development, and the creation of pedestrian-friendly spaces. This has practical applications in enhancing the overall heritage zone management experience and addressing challenges related to accessibility, transit-oriented development (TOD), and cultural heritage preservation.

Finally, given the focus on a UNESCO World Heritage Site like George Town, the research contributes to the ongoing discourse on the revitalization of heritage areas. By offering findings on pedestrian barriers and spatial structures, the results provide insights into how to address the obstacles that come with balancing the needs of new development with the preservation of cultural heritage. This has implications for enhancing livability and maintaining the unique historical character of a historical zone.

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