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Aged and wheeled mobility in transit-oriented development: The capabilities approach

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Abstract

Transit-oriented development (TOD) aims to create pedestrian-friendly neighborhoods around transit hubs to improve urban mobility. However, it often overlooks the specific transportation needs of people with limited mobility. This study adopts Sen's capabilities approach (CA) and the concept of conversion factors to analyze how ordinary pedestrians, the elderly, and wheelchair users transform planned catchment areas into functional capability spaces. Our focus is on understanding these conversion factors, which highlight both environmental and individual constraints when converting resources into capabilities. Our findings reveal significant disparities in walking environments between the initially planned and the realized catchment areas, as well as disparities between individuals with and without physical limitations. This study complements established quantitative methods, enhancing the application of the CA for evaluation. It provides a more precise assessment of pedestrian infrastructure and advocates for inclusive design improvements in the context of TOD cities and an aging population.

Keywords: Transit-oriented development; Capabilities Approach; Potential mobility; elderly; Disability; Hong Kong

1. Introduction

People with disabilities account for nearly 16 percent of the global population, with more than half residing in urban areas (WHO, 2023). However, urban design often overlooks the mobility needs of this demographic, assuming universal accessibility without considering specific needs of individuals with varying capabilities (Dixit and Sivakumar, 2020; Eisenberg et al., 2020). Consequently, both developed and developing countries face significant challenges regarding mobility barriers in the built environment (Cheng et al., 2019; Eisenberg et al., 2017; Kunaratnam et al., 2022; Ruiz-Padillo et al., 2022).

For densely populated urban settings, pedestrian flow is typically grade-separated from vehicular flow through footbridges and subways to enhance traffic conditions and provide safe pathways. However, this grade-separated design is often at the expense of pedestrian convenience (Soliz and Pérez-López, 2022) and exacerbates mobility inequalities, particularly for people with mobility impairment (Chan et al., 2022a, 2022b; Xu et al., 2022). These structures are commonly found in busy areas and around metro stations, aligning with the principles of transit-oriented development (TOD) (**Figure 1**) adopted in cities such as Hong Kong (Loo et al., 2010), Tokyo (Cui et al., 2013), Singapore (Niu et al., 2019), Beijing (Guo et al., 2022) and Shanghai (Li et al., 2019). TOD, a planning strategy emphasizing high density, mixed land use, and pedestrian-friendly environment around transportation hubs, aims to increase public transport usage, alleviate traffic congestion and reduce air pollution (Chan et al., 2022b; Tsoi and Loo, 2023). Nevertheless, TOD typically caters to the general population rather than addressing the specific needs of people with limited mobility (Du et al., 2022; Duncan et al., 2021). In many cases, TOD planning overlooks the intricate travel demands of the older people and people with limited mobility.

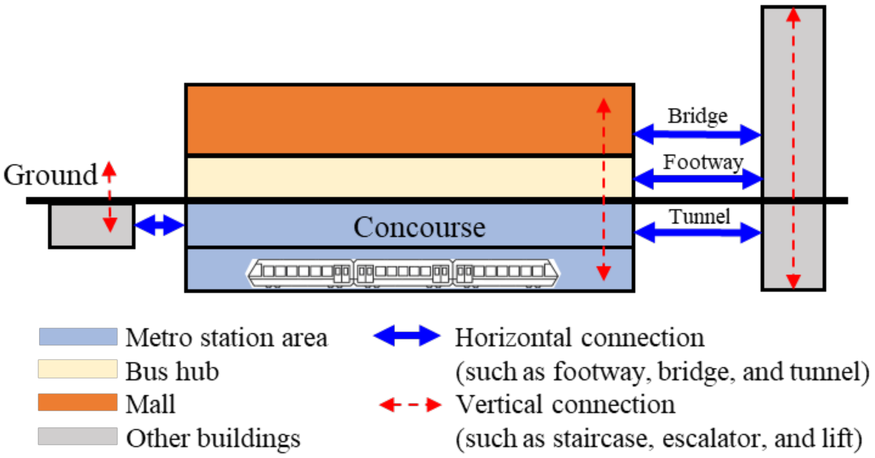

Figure 1 Illustration of horizontal and vertical connection of a typical TOD area

This article aims to develop an assessment framework for evaluating the walking environment around TOD areas, considering the capabilities of diverse pedestrian groups. We adopt Sen's (2003) capability approach (CA), specifically the concept of conversion factors, to assess environmental and individual factors influencing a person's ability to utilize the walking infrastructure (will be further discussed in Section 2). The assessment prioritizes inclusivity, addressing the needs of people with mobility limitations. Three user groups — ordinary pedestrians, the older people, and wheelchair users — are examined, representing varying mobility levels. Older adults and wheelchair users face increased risk of declining functionality and mobility, impacting their independence and overall quality of life (James et al., 2023). It is important to note that not all older individuals have mobility impairments, but aging can affect walking capabilities for a proportion of the population (Pinna and Murrau, 2018). Through a regional analysis in Hong Kong, we demonstrate the practicality of evaluating pedestrian friendliness and accessibility for different pedestrian groups, offering insights for enhancing inclusive walkability design.

2. Literature review

Sen's (2003) capability approach (CA), a normative perspective on human welfare focusing on individuals' actual abilities, has gained attention in transport planning literature (Beyazit, 2011; Cao and Hickman, 2019a, 2019b; Hickman et al., 2017; Vecchio and Martens, 2021). It asserts that the freedom to achieve well-being is morally significant, and well-being should be understood in terms of individuals' capabilities and functionings (Sen, 2003). The CA considers personal, sociopolitical, and environmental factors influencing one's ability to utilize resources for potential functionings. However, the CA lacks a precise theory of well-being, resulting in extensive discussions on its definition (Sen, 2008). In transportation planning, defining capabilities is crucial, and studies have assessed them based on various factors such as planned and actual behaviors (Ryan et al., 2015), desired and actual transportation situations (Hickman et al., 2017), and planned and potential/realized activities (Cao and Hickman, 2019b). Walkability and pedestrian accessibility (Blečić et al., 2015), particularly for disadvantaged populations (Bantis and Haworth, 2020), are linked to the CA. In this article, we adopt the CA to assess city walkability from a bottom-up perspective, considering both planning goals and actual capabilities.

The CA in transportation planning faces challenges due to its open-ended nature, causing a lack of consensus on effective quantification and application (Bantis and Haworth, 2020). Scholars have made efforts to measure the relationship between resources and capabilities/functionings. Conversion factors, introduced by Robeyns (2003), delineate the various capacities individuals have to transform resources into capabilities across personal, social, and environmental dimensions. While conversion factors play a crucial role in identifying capability heterogeneity, they are seldom explicitly addressed (Vecchio and Martens, 2021). Recent works address this gap, with Nahmias-Biran and Shiftan (2020) introducing a uniform conversion factor for transport scenarios, demonstrating its application in an activity-based accessibility model. Sherriff et al. (2020) qualitatively illustrate how personal, social, and environmental factors serve as conversion factors, emphasizing a feedback process shaping functionings. Achieved access enhances conversion factors and perceived accessibility in CA terms. However, measuring accessibility-as-capability is challenging due to the personal and fluctuating nature of conversion factors. Studies working with proxies acknowledge the imperfect nature of measuring accessibility, emphasizing the need to recognize the inherent approximation in studies involving population samples (Vecchio and Martens, 2021).

The open-ended nature of the CA also results in a blurred distinction between resources and conversion factors (Vecchio and Martens, 2021). Conversion factors are conventionally seen as elements highlighting constraints, providing insight into how resources contribute to capability attainment. Take the example of bicycle availability, which can function both as a private mobility resource and a conversion factor. Shared bikes can be viewed not only as resources but also as environmental conversion factors influencing bike accessibility (Sherriff et al., 2020). These, in turn, impact social conversion factors, including cycling practices and norms, affecting broader cycling behaviors. The same reasoning applies to footbridges, universally accessible structures for pedestrians. Assessing their accessibility involves considering various components, such as staircases, lifts, escalators, walkways, and ramps, based on factors like distance, walking speed, and capability. This nuanced approach to accessibility evaluation recognizes the diverse opportunities people have to convert resources into capabilities, rejecting a one-size-fits-all assumption.

The challenge of translating analytical results into transport policies is compounded by the perceived impracticality of the CA (Beyazit, 2011). Gaps in existing literature underscore the need to convert bottom-up approaches into normative indicators for policy and practice (Vecchio and Martens, 2021). Recent attempts using quantitative analysis, such as incorporating geographical data and smart card observations to model transition probabilities (Bantis and Haworth, 2020), and employing activity-based models and cost-benefit analyses (Nahmias-Biran and Shiftan, 2020)), have supplemented traditional evaluations of public transportation resources. In these studies, the CA serves as a normative evaluation concept aiming to enhance individuals' abilities across socioeconomic groups, with accessibility based on mobility big data or engineering models advocating for policy changes. As transportation-related social exclusion rises due to resource competition, policymakers seek insights into its causes. Emerging technologies and big data offer interpretable findings, supporting policy decisions.

To tackle the challenges mentioned earlier, this study first adopts the CA to overcome the limitations of the universal design approach in addressing the diverse and unique needs of individuals. In addressing the applicability challenges stemming from the open-ended nature of CA, we begin with the concept of conversion factors to quantify the diverse capacities individuals possess to transform resources into capabilities, spanning both personal and environmental dimensions. To ensure generalizability for policy and practice, we underscore the significance of leveraging diverse emerging and big datasets. This approach aims to create an assessment framework that examines the walking environment surrounding the TOD areas to evaluate the capabilities of different pedestrian groups.

3. Methodology

3.1. Study area and data

Hong Kong, chosen for its high population density and compact urban form (Loo et al., 2017, 2010), serves as the study area. The Mass Transit Railway (MTR) metro system, crucial for TOD, constitutes 37% of daily public transportation trips and up to 90% of all personal trips when combined with other public transportation modes, such as buses and ferries. The walking environment around metro stations is closely related to citizens' daily travel, especially considering 20.4% population aged over 65 and 1% using wheelchair (Census and Statistics Department, 2021). Improving the walking environment for those with mobility decline is crucial for an equitable community, supported by a recent household survey (Transport Department, 2014), indicating a need for pedestrian facility improvements. With 42% of the regional households, 43% of the employed population, and 75% of the commercial and office area located within 500 meters radius of metro stations (Yin, 2014), assessing the walking environment around the metro stations is vital for guiding walkability enhancements. To make Hong Kong more walkable, the assessment must consider the capabilities of the older people and wheelchair users. Utilizing 3D pedestrian network data from Lands Department and Transport Department[1] (**Figure 2**), we can evaluate the walking environment around the metro stations for all users, including ordinary pedestrians, the older people, and wheelchair users.

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[1] Data available at https://data.gov.hk/en-data/dataset/hk-landsd-openmap-3d-pedestrian-network

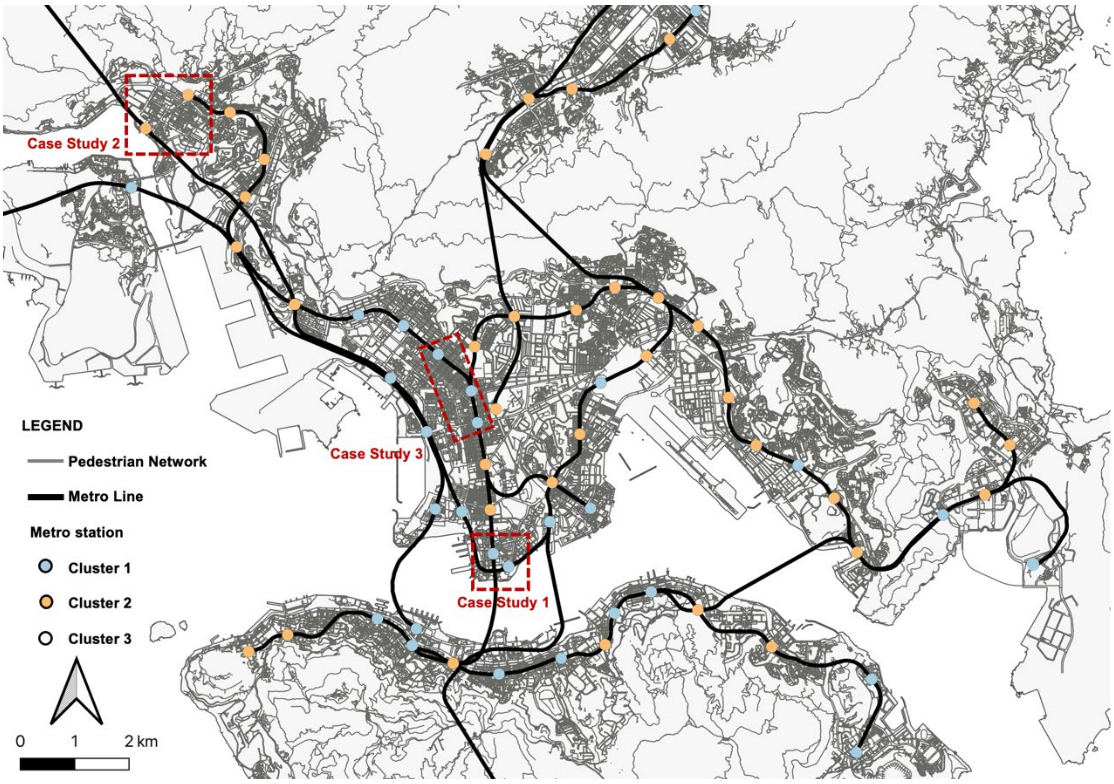


Figure 2 3D pedestrian network of Hong Kong (the color of metro stations indicating the cluster results described in Section 4.3)

3.2. Defining the station catchment

Defining the pedestrian catchment area is the prerequisite of such studies, with traditional techniques assuming a constant arbitrary threshold distance to station access (Ewing and Cervero, 2010). Determining station catchment areas relies on people's willingness to walk to stations, a topic of ongoing debate (Papa et al., 2018). For example, Guerra et al. (2012) suggested 400 m for trips from transit stations and 800 m for trips to stations. Various distance thresholds based on radial distance, walking distance, and walking time, are used in literature, as summarized in **Table 1**. To maintain consistency with the household survey on travel characteristics in Hong Kong (Transport Department, 2014), we set a 10-minute walking distance as the analysis unit, approximately equivalent to 800 m under ideal walking conditions with a speed of 1.3 m/s or 78 m/min (Lam and Cheung, 2000).

Table 1 Catchment area delimitation

Method	Threshold	Reference
Radial distance	400-800 meters	(Alawadi et al., 2021; Cardozo et al., 2012; Gutiérrez et al., 2011; Kuby et al., 2004; Su et al., 2021; Zhao et al., 2014; Zhou et al., 2020, 2019)
Walking distance	600-800 meters	(An et al., 2019; Atkinson-Palombo and Kuby, 2011) Bivina et al., (2019)
Walking time	8-15 minutes	(Desjardins et al., 2022; Singh et al., 2017; Su et al., 2019)

The application of the CA to catchment analysis can be demonstrated through a hypothetical scenario involving a wheelchair user relying on state-provided public transportation. For effective access to points of interest to and from stations, the wheelchair user depends on a barrier-free walking environment. This necessitates the presence of adapted city pathways, such as ramps, and mobility aids like lifts and stair climbers, which collectively represent environmental conversion factors (*ECF*). Disability, indicating an increased challenge in converting resources into personal mobility, is represented by individual conversion factors (*ICFs*). For instance, a reduced walking speed results in limitations on access within a given time interval, as many locations become inaccessible. Despite the prevalence of public transit, particularly the metro, in Hong Kong, a universally barrier-free walking environment around transit stations is not consistently available. Consequently, individuals with limited mobility experience constraints in accessing points of interest compared to ordinary pedestrians. The conversion factor, calculated as the ratio of desired to actual catchment within a specified time limit, serves as a quantitative measure of the accessibility disparity. This example highlights the practical application of the CA in evaluating and addressing mobility challenges for specific user groups within the urban environment.

3.3. Gathering evidence from the 3D pedestrian network

To analyze the features of walking environment around metro stations, we assess conversion factors within an 800-m network coverage area and a 10-minute reachable area for each station. Pedestrians can access any point in each direction when a footway is available. The coverage of the pedestrian links in different directions may be unbalanced. *ECF* is estimated based on the 800-m network coverage area, while individual capabilities to utilize the pedestrian facilities are considered within the 10-minute reachable area. The study framework is summarized in **Figure 3**, with detailed discussions in subsequent sections.

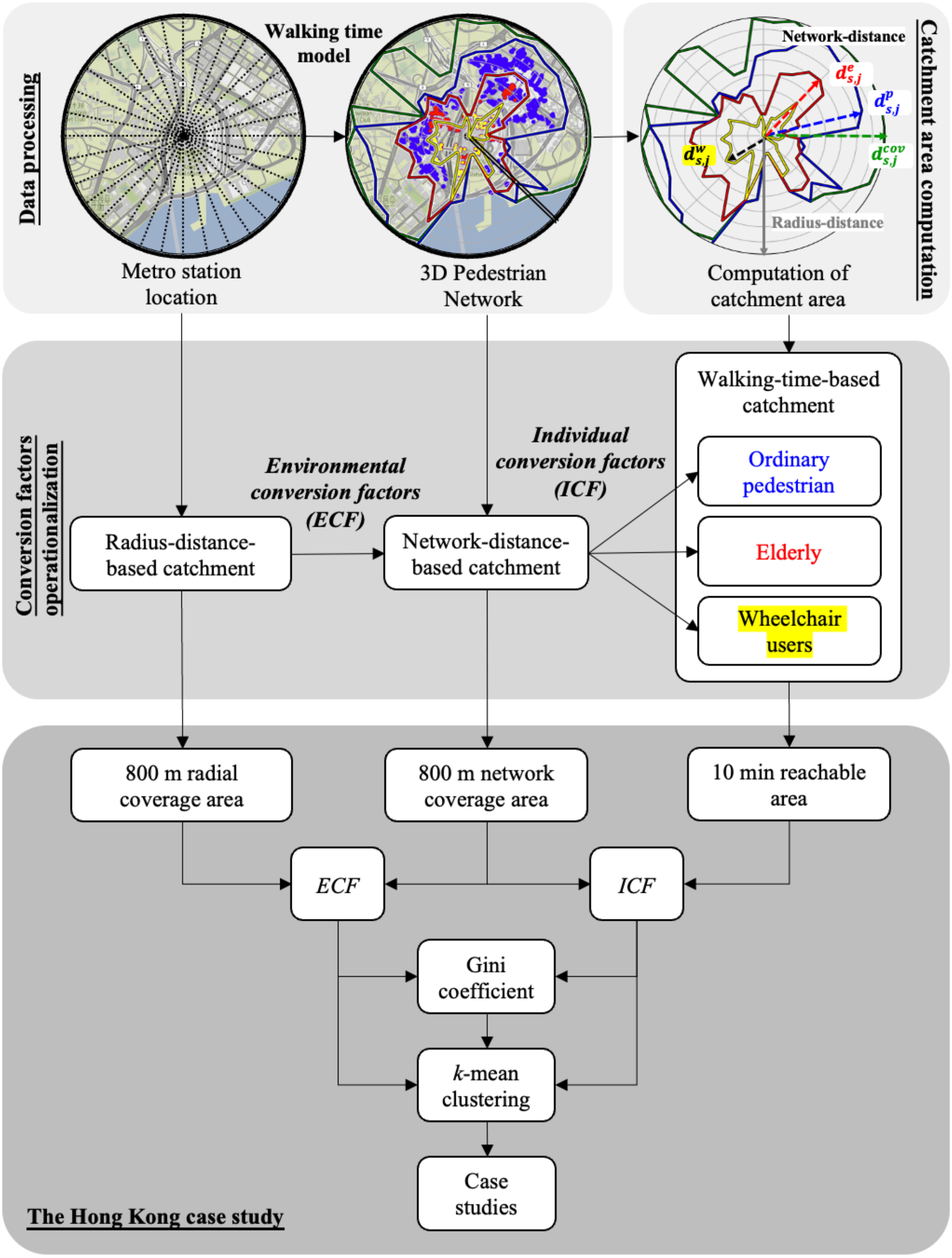


Figure 3 Study framework

3.3.1. Data processing

To delineate the catchment area of metro stations, it is essential to categorize pedestrian links and estimate the travel time for each link.

3.3.1.1. Classification of links based on the feature type

Pedestrian links are categorized into three feature types (**Table 2**): (a) flat surface, (b) staircase, and (c) electrical auxiliary lifting facilities. A flat surface refers to pedestrian links with relatively flat surface (slope < 0.08), accommodating ordinary pedestrians, the older people, and wheelchair users. This category includes footways, footbridges, crossings, subways, and ramps. Staircases connects platforms at different vertical levels, but this may pose challenges for older people and wheelchair users. Consequently, electrical auxiliary lifting facilities are commonly installed to address accessibility concerns.

3.3.1.2. Travel time model

For a sloping pedestrian road, the walking speed of adults is mainly determined by the slope, which can be modeled with Tobler's hiking function (Tobler, 1993):

$$v_i = 6 \times e^{-3.5 \times |g_i + 0.05|} \tag{1}$$

The average walking speed of adults is obtained as 5.04 km/h (1.4 m/s) on flat terrain according to Tobler. Lam and Cheung (2000) modified the free-flow speed to 1.3 m/s for outdoor walkways and 0.98 m/s for indoor walkways in commercial areas in Hong Kong. Adapting Tobler's hiking function to the local context, we modified the equation to yield an average walking speed of 1.3 m/s on flat surfaces without a gradient (**Table 2)**. For the older people, the average walking speed is 2.88 km/h (0.8 m/s) (Alves et al., 2020), and links with gradients over 0.08 are considered inappropriate for older commuters. We update Tobler's hiking function correspondingly. For wheelchair users, the travel speed for different slope ranges varied (Sonenblum et al., 2012).

For electrical auxiliary lifting facilities, we adopted the recommended travel speeds from the

HKSARG Electrical and Mechanical Services Department (2007), as summarized in **Table 2**. The travel time for a lift link is the sum of the waiting time for the lift and the gate closing time. Here, we set the waiting time for the lift as half the travel time of the lift and the gate closing time as 5 s. The assumptions regarding the travel time are also summarized in **Table 2**.

Table 2 Walking speeds for different types of pedestrian links

Pedestrian type	**Walking speed estimation**		**Reference**
Flat surface	Pedestrian	$v_i = 5.57 \times e^{-3.5\times\lvert g_i+0.05\rvert}$	Tobler (1993); Alves et al., (2020)
	Older people	$v_i = 3.4 \times e^{-3.5\times\lvert g_i+0.05\rvert}, g_i < 0.08$	
	Wheelchair user	$v_i = \begin{cases} 0.43\ \mathrm{m/s}, g_i < 0.04 \\ 0.2\ \mathrm{m/s}, 0.04 \le g_i < 0.08 \\ 0\ \mathrm{m/s}, g_i \ge 0.08 \end{cases}$	Sonenblum et al. (2012)
Staircases	Pedestrian	Upward: 0.5 m/s; Downward: 0.8 m/s	Choi et al. (2014)
	Older people	Upward: 0.3 m/s; Downward: 0.4 m/s	
	Wheelchair user	Inaccessible	N/A
Electrical auxiliary lifting facilities	Pedestrian	Lift: 1 m/s; Travelator: 0.9 m/s; Escalator: 0.75 m/s	Electrical and Mechanical Services Department (2007)
	Older people		
	Wheelchair user	Lift: 1 m/s; Travelator: 0.9 m/s; Escalator: inaccessible; Stairlift: 0.12 m/s	

Note: g_i is the gradient of pedestrian link *i*.

3.3.2. Catchment area computation

The procedure for an 800-m network coverage area and a 10-minute reachable area are calculated based on the 3D pedestrian network dataset. Firstly, we divide the compass bearings (centered at metro stations) into 36 equal-sized bins (i.e., 10° for each bin) labeled Θ, and the network-distance-based catchment can then be obtained by connecting the farthest points that can be reached with 800-meter radial distance in all directions. The farthest points in these bins are then connected to form a network-distance-based buffer.

For the time-based catchment area, we first calculate the link travel time by accounting for individual capabilities for utilizing walking infrastructures, and we search all reachable points that can be accessed within a 10-minute time constraint. We adopt the breadth-first search (BFS) algorithm, which is one of the commonly adopted graph traversal algorithms in the pedestrian wayfinding problem (e.g., Javadi et al., 2017; Torrado et al., 2016). Using the BFS searching, we calculate the walking time to each node from each station and set a travel time of less than or equal to 10 minutes as the terminal condition. Here, the walking time is estimated using the travel speeds summarized in **Table 2**. After identifying all the points reachable in 10 minutes from all stations, we outline the 10-minute reachable area by linking the farthest points in all directions.

3.3.3. Conversion factors operationalization

We operationalize the two types of conversion factors introduced earlier, *ECF* and *ICF*s, which quantify the walking infrastructure/environment and individual characteristics, respectively. The *ECF* is derived from the differences between the radius- and distance-based coverage areas of a station and is based on geographical and walking infrastructure constraints. The *ICF*s accounts for the features of the pedestrian links (type, ease of walking, and so on) and individual factors (normal pedestrians, the older people, and wheelchair users) using the 10-minute reachable area identified by the procedure described in **Section 3.3.2**.

The *ECF* is a measure of the adequacy of the pedestrian infrastructures around the metro station. $d_{s,j}^{cov}$ and $c_{s,j}^{cov}$ are the direct and relative distances to the farthest point in the j^{th} bin of the 800-m coverage area for station ***s*** separately. The *ECF* can be formulated as

$$ECF_s = \frac{\sum_{j \in \Theta} c_{s,j}^{cov}}{|\Theta|} \tag{2}$$

$$c_{s,j}^{cov} = \frac{d_{s,j}^{cov}}{800} \tag{3}$$

$c_{s,j}^{cov}$ is the relative distance that normalizes the direct distance $d_{s,j}^{cov}$ to a value in the range 0–1, and $|\Theta|$ is the number of bins (equal to 36 in this paper). A larger *ECF* value implies an infrastructure that better supports pedestrians' walking capabilities.

Based on the 10-minute reachable area of the stations, we calculate the *ICF*s considering the walking capability of different individuals:

$$ICF_s^n = \frac{\sum_{j \in \Theta} r_{s,j}^n}{|\Theta|}, n \in \{p, e, w\} \tag{4}$$

ICF_s^p, ICF_s^e, and ICF_s^w are the conversion factors for individual ***n*** from the groups of ordinary pedestrians, the older people, and wheelchair users, respectively. $r_{s,j}^n$ is the relative distance from the farthest point that individual ***n*** can reach to the farthest point of the 800-m coverage area in the j^{th} bin, which can be formulated as follows:

$$r_{s,j}^n = \frac{d_{s,j}^n}{d_{s,j}^{cov}} \tag{5}$$

*ICF*s evaluate the walking capabilities of different individual population groups. To discover the farthest arrival point of each station, more details regarding the pedestrian infrastructure, such as auxiliary facilities (i.e., escalator), walking impedance (slope, staircase), and the walking speed of different groups, are considered. This quantifies both the pedestrian friendliness of the environment and the pedestrian accessibility of the station.

3.3.4. Spatial disparity evaluation

Within the wider accessibility literature, the Gini index has been proposed as theoretically capable of quantifying accessibility related spatial disparity issues (Dixit and Sivakumar, 2020; Pike et al., 2012), and has been applied as an equity evaluation tool for different case studies (Azmoodeh et al., 2021; Chan et al., 2021; Jang et al., 2017). For each individual population group, we calculate the proportion of the relative distance in each direction:

$$p_{s,j}^{n} = \frac{r_{s,j}^{n}}{\sum_{j \in \Theta} r_{s,j}^{n}}, n \in \{p, e, w\} \tag{6}$$

Then, we sort $p_{s,j}^{n}$ ascendingly and estimate the Gini index of different individual population by

$$Gini_{s}^{n} = 1 - \sum_{j \in \Theta} (2p_{s,j}^{n} - \frac{p_{s,j}^{n}}{|\Theta|}), n \in \{p, e, w\} \tag{7}$$

The Gini index for the 800-m coverage area ($Gini_{s}^{cov}$) is calculated the same by substituting $c_{s,j}^{cov}$ for $p_{s,j}^{n}$ in Equation (6).

The smaller Gini index means the coverage area or the reachable area distributed equity in each direction. We assess the spatial disparity of reachable distance in 36 directions of individual population groups before and after applying *ICF*s:

$$GC_{s}^{n} = Gini_{s}^{n} - Gini_{s}^{cov}, n \in \{p, e, w\} \tag{8}$$

Here, $Gini_{s}^{cov}$ is used for eliminating the effects of the built environment and the before-and-after analysis allows us to evaluate the disparity effects of walking facilities related to the user's capability. A negative value of change indicates the group is of benefits from walking facilities that promote a more spatial equitable walking.

4. Results and discussion

4.1 Descriptive analysis of conversion factors

The distribution of the *ECFs* and *ICFs* is depicted in **Figure 4**. *ECF* is relatively high overall and *ICFs* show a normal distribution. The average *ECF* for all metro stations, which is derived from the differences between the radius- and distance-based coverage areas of the stations, is 0.79, and 62.9% of the stations have an above-average *ECF* score. This means the pedestrian links connected to the metro station within 800 meters cover about 79% of the area which shows enough walkways around metro stations. The average ICF^p, ICF^e, and ICF^w are 0.68, 0.47, and 0.17, meaning that the reachable area is reduced to 68%, 47%, and 17% of the 800-m coverage areas for ordinary pedestrians, the older people, and wheelchair users, respectively (the *ICF*s for the pedestrian links around the stations are shown in **Appendix A**). East Tsim Sha Tsui (ETS) station has the highest walkability for ordinary pedestrians, with $ICF_p = 0.96$. This means that ordinary pedestrians can reach almost all of the 800-m coverage area within 10 minutes. However, this does not mean that the walking environment around the station is better than that of other stations, as the *ECF* of the station is only 0.69. The walkability for the ordinary pedestrian of Tsim Sha Tsui (TST) station ranked second with a large *ECF* of 0.78. The dense and flat pedestrian links around TST station provide a convenient walking environment for ordinary pedestrians, the older people, and wheelchair users. ETS and TST are connected with tunnels that have good walking environments and provide high walkability for all individuals (as discussed in detail in **Section 4.3.2**).

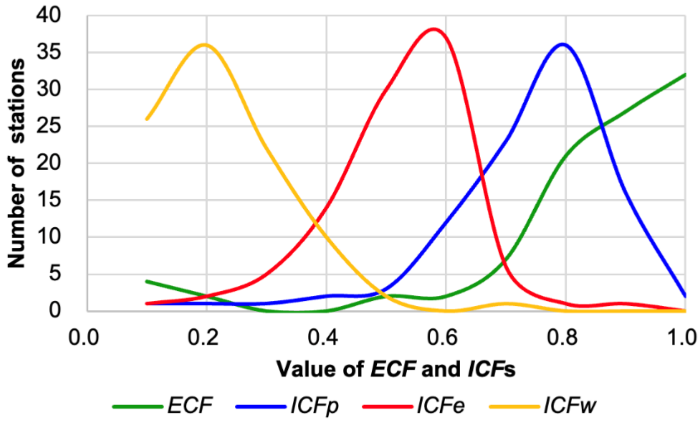
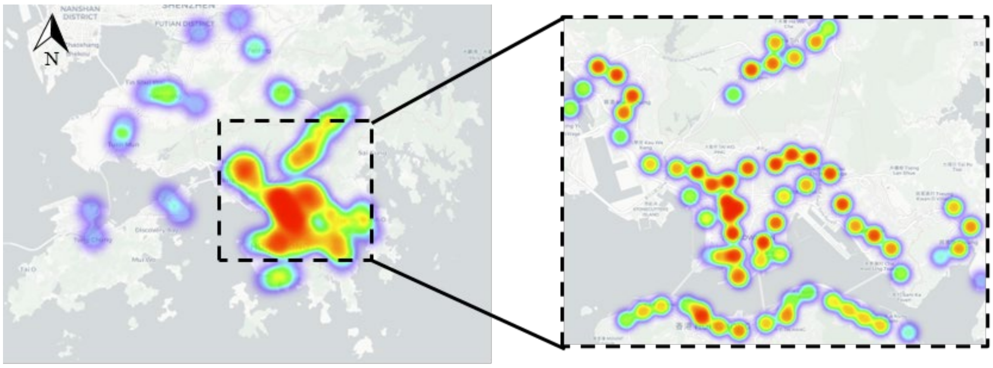


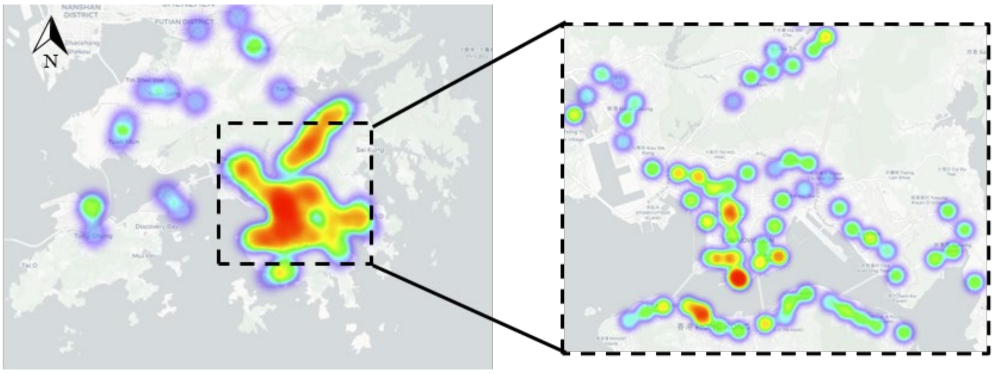
Figure 4 The statistical distribution of *ECF* and *ICF*s

Stations with poor walkability, such as Tai Wo Hau (TWH) and Choi Hung (CHH), usually have sparse pedestrian routes connected to them. Although these stations have sufficient pedestrian roadways (ECF_{TWH} = 0.97 and ECF_{CHH} = 0.96), their walkability is poor. These stations are surrounded by a highway, which is convenient for commuters who wish to transfer to another mode of transportation, such as a bus. However, pedestrians have to cross the roadway using a footbridge, tunnel, or crossroads to the commercial or residential areas around the station.

4.2 Spatial disparity in accessibility for different individual population groups



(a)



(b)

Figure 5 The spatial distribution of (a) *ECF* and (b) *ICF*s

The spatial distribution of ECF and ICF_s^p are visualized in **Figure 5** (detailed results are provided in **Appendix B**). The stations with higher ECF and ICF_s^p concentrate in the same area. However, there also is a big difference when taking a closer look. Stations with higher ECF do not mean a high ICF_s^p. The walking environment around these stations has more impendence, such as the staircase, that can be improved in future plans. Sham Shui Po (SSP), Prince Edward (PRE) and Mong Kok (MOK) have the smallest Gini index for all individual population groups means the walking facilities are equitably distributed around the metro stations. These stations, situated in the old district of Kowloon West, present a layout of a chessboard (as discussed in detail in **Section 4.3.4**). Overall, the current walking environment in different directions is inequity for wheelchair users. For example, Tuen Mun (TUM) station have a small Gini index for normal pedestrian and the older people while this index for wheelchair user is relatively larger.

Eliminating the effects of the built environment by GC_s^n, all individual population groups can benefit from the walking facilities around Disneyland Resort (DIS), Lo Wu (LOW), Asia World Expo (AWE), Airport (AIR), and Sunny Bay (SUN) stations. All these stations have special purposes: LOW is connected to border control; AWE and IDS are connected to the theme park;

and SUN is connected to the transportation hub without residential and commercial buildings around it. On the contrary, all individual population groups have less walking assistance around Quarry Bay (QUB), Tai Wo Hau (TWH), Ho Man Tin (HOM), and Tsuen Wan (TSW) stations. These stations are located at the foot of the mountain and the user's capability is weak in the hill direction. This leads to the reachable area inequity distributed in each direction.

4.3 Case studies

4.3.1 Clustering analysis

Some representative cases are presented in this section to further analyze the pedestrian links connecting the metro stations. First, the k-means clustering algorithm is applied to the database to divide the station into groups, which are described and evaluated by their similarities and differences in terms of conversion factors. The details of the k-means clustering are not described here, because the method has been widely discussed (e.g., Jain et al., 1999) and applied in the transportation geography literature (e.g., Chan et al., 2021; Pieroni et al., 2021). The stations are grouped into three categories, as detailed in Appendix C. This classification is based on normalized *ECF* and *ICF*s indicators, with Min-Max normalization (Patro and sahu, 2015) being utilized (as shown in **Figure 2** and **Table 3**). Cluster 1 stations have smaller *ECF* and larger *ICF*s compared with Cluster 2 stations, indicating a geographically less reachable areas but a more inclusive environment for active travel in Cluster 1. Cluster 3 stations are generally located in special-use areas such as border crossings (i.e., Lo Wu and Lok Ma Chau), airports, and theme parks (AsiaWorld-Expo and Disneyland Resort). Here, we select three representative study areas from Clusters 1 and 2 in general urban areas for a more detailed analysis on how the urban design, street network, and specific features of the urban space make influence on mobility of different individuals:

Case study 1 — Cluster 1: The Tsim Sha Tsui business area: areas with one of the largest conversion factors for all individual population groups

Case study 2 — Cluster 2: The "city of bridges" in a residential area Tsuen Wan: an elevated walkway connecting most points of interest

Case study 3 — Cluster 2: Kowloon West old district: the chessboard network layout with medium performance in terms of conversion factors

Table 3. Descriptive statistics of clusters based on *ECF*, *ICF*s and *GCs*

Average	ECF	ICF_s^p	ICF_s^e	ICF_s^w	GC_s^p	GC_s^e	GC_s^w
Cluster 1	0.79	0.80	0.62	0.39	0.73	0.72	0.67
Cluster 2	0.90	0.66	0.46	0.17	0.84	0.84	0.81
Cluster 3	0.05	0.30	0.33	0.45	0.19	0.18	0.14
Case 1	0.75	1.00	0.92	0.71	0.69	0.67	0.67
Case 2	0.87	0.63	0.42	0.23	0.76	0.87	0.63
Case 3	0.99	0.82	0.60	0.43	0.79	0.77	0.71

4.3.2 Case study 1

Located at the southern tip of the Kowloon peninsula near Victoria Harbour, TST and ETS stations are typical cluster 1 stations that feature moderate *ECF* but high *ICF*s among other stations. These cluster 1 stations are generally integrated to nearby TODs and connected to an extensive network of active travel infrastructures as illustrated in **Figure 6.** While the moderate *ECF* in TST and ETS stations could be explained by their coastal topological characteristics, the high *ICF*s are the result of the extensive pedestrian subway network integrated with metro stations, TODs, and parallel surface streets. The pedestrian subway network, often equipped with travelers, connects more than half of 27 exits shared by the stations to surface streets and major shopping centers in the area, thus providing direct and barrier-free pathways to minimize the walking distance and time from the stations. Tsim Sha Tsui was also developed with ample surface streets to facilitate the movement of pedestrians in the older part of the area. The station coverage is therefore maximized to almost all 800-m catchment areas as shown in **Figure 6**, and a pedestrian-friendly neighborhood for all population groups is formed compared to other regions.

Yet, the result still reveals that the multi-layered pedestrian facilities may lead to degradation of accessibility to people with disadvantages in walking. For example, although mobility-aid facilities are provided, pedestrians would still need more time and effort to access the landscape platforms and waterfront in East Tsim Sha Tsui from metro stations as they have to move between levels and cross the footbridges from underground subways or metro exits at surfaces. In this case, the degraded walkability and pedestrian accessibility are not caused by the hilly terrain, but by the practice of prioritizing traffic capacity for vehicular movements. It prompts the need for comprehensive pedestrian network and urban designs and assessments to enhance walkability for all from a human-centric approach, rather than simply relying on mobility-aid facilities like lifts and escalators.

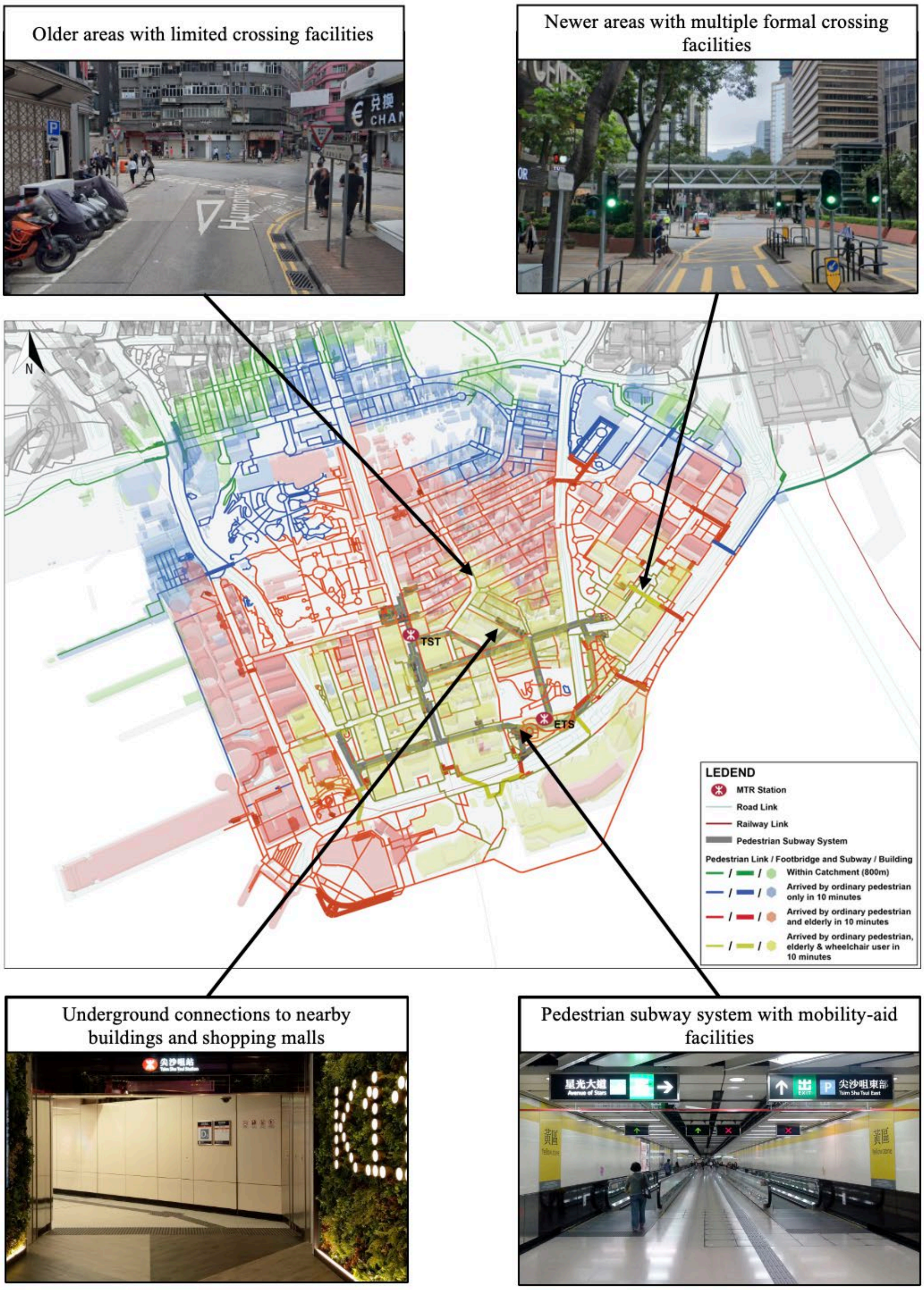


Figure 6 The walking environment of the catchment area of TST and ETS stations

4.3.3 Case study 2

Pedestrian bridges are embraced by high-density cities as a solution to avoid the interference of pedestrians with traffic on roads and increase the connectivity of public spaces (e.g., residences, transit stations) (Wang et al., 2016). As a part of the TOD, elevated walkway systems are sometimes developed to connect metro stations with shopping malls, residential blocks, and public buildings. Tsuen Wan elevated walkway system is a typical example of this approach. Located midway between Tsuen Wan West (TWW) and Tsuen Wan (TSW) station, the system is the longest covered footbridge network in the city, which improves the connectivity of the metro stations and the walking environment in between. Facilitating with similar urban setting of integration to TODs and extensive active travel infrastructures network as Tsim Sha Tsui area in Case Study 1, this area has drawn our attention with its lower results on *ICF*s even with larger geographically reachable areas.

The key differences identified between these two areas are the urban setting of metro station exits and the provision of route choices to cater mobility capabilities of individual groups. Although the exits of metro stations are situated on the footbridge system that shading a convenient pedestrian network elevated above the surface and improved the walkability from metro stations to surrounding areas, the reachable areas for pedestrians, especially those with disadvantages in walking, are bounded to a linear form along the footbridges as illustrated in **Figure 7**. In contrast, areas without connection to the footbridge system are suffered by low accessibility as the route choices from metro stations to these areas are limited by the vertical connections between footbridges and surface streets. In certain sections of the bridge network, they depend on connections to entrances of buildings and malls, which can result in reduced accessibility in those areas. In the western section of the study area, pedestrian crossings primarily depend on separate bridges, with no signalized at-grade crossings available. This outcome aligns with the assertions made by Soliz and Pérez-López in 2022, indicating that footbridges can sometimes favor continuous motor-vehicle traffic and perpetuate mobility disparities. These footbridges are not pedestrian friendly elements within the context of grade-separated pedestrian systems, which are designed to minimize pedestrian traffic and prioritize the efficient flow of motor vehicles. This also justifies the low *ICF*s of these two stations and the low Gini index (i.e., spatial inequity in accessibility caused by the uneven distribution of walking facilities). Moreover, the elevated layout increases the travel impedance of wheelchair users to access the metro system when they are heavily relying on mobility-aid facilities, leading to low ICF_s^w.

It is also noteworthy that the performance of *ICF*s in TWW is even lower than that of TSW built decades earlier, revealing that pedestrian network design in recent years may not be desirable for all population groups to access the metro stations. Whilst exits of TSW connect to pedestrian footbridge directly, exits of TWW form a “seamless integration” with mega-structure consisting of shopping malls and residential blocks. Such structures developed under the “Rail plus Property” (R+P) model by MTR have been prevalent since the 1990s, which seeks to harness the commercial potential of passengers (Cervero and Murakami, 2008). Despite the comfortable walking environment provided by the privileged malls, pedestrians, in this case, may be forced to detour due to the complicated internal layout design inside the malls. Such designs might be both unintentional, as a compromise to the structural limitations; and intentional, aimed at increasing pedestrian flows and staying time to maximize commercial benefits. Thus, it requires more walking distance and time for pedestrians originating/destinating outside the shopping malls, which further explains the low *ICF*s in Tsuen Wan. The case reinforces the need for detailed pedestrian network designs and assessments to improve walkability and connectivity of metro stations for all user groups to cater their capabilities (Blečić et al., 2015).

Figure 7 The walking environment of the catchment area of the TSW and TWW stations

4.3.4 Case study 3

Mong Kok (MOK), Prince Edward (PRE), and Sham Shui Po (SSP) stations are located in an old high-density mixed land use area on the Kowloon Peninsula. These three stations feature high *ECF* but moderate *ICF*s, demonstrating the typical pedestrian networks in old districts with minimal vertical spatial hierarchy – surface chessboard surface street morphology with some footbridges or tunnels in the busiest areas. Regarding the *ECF*, the flat terrain in the area and the extensive surface street network contribute to the high *ECF*. On the other hand, the chessboard street layout as shown in **Figure 8** helps pedestrians in orientation and wayfinding, which facilitates them to reach their destinations by direct routes. The *ICF*s of these stations reflect the accessibility under the chessboard road layout. For ordinary pedestrians, the $ICF_{MOK}^{p} = 0.82$ are lower than those stations with ample pedestrian facilities in Case 1 but higher than those that solely rely on the grade-separated network in Case 2. It is also notable that the spatial disparity between population groups in this area is minor compared to the above cases, Extra distances for vertical movements, which significantly lengthened the traveling time of disadvantaged groups, are not needed in this case.

This case study has demonstrated the accessibility of different population groups under the at-grade chessboard layout, which further highlights the importance of organic integration and connection of station exits, surface street networks, and multi-layered pedestrian facilities.

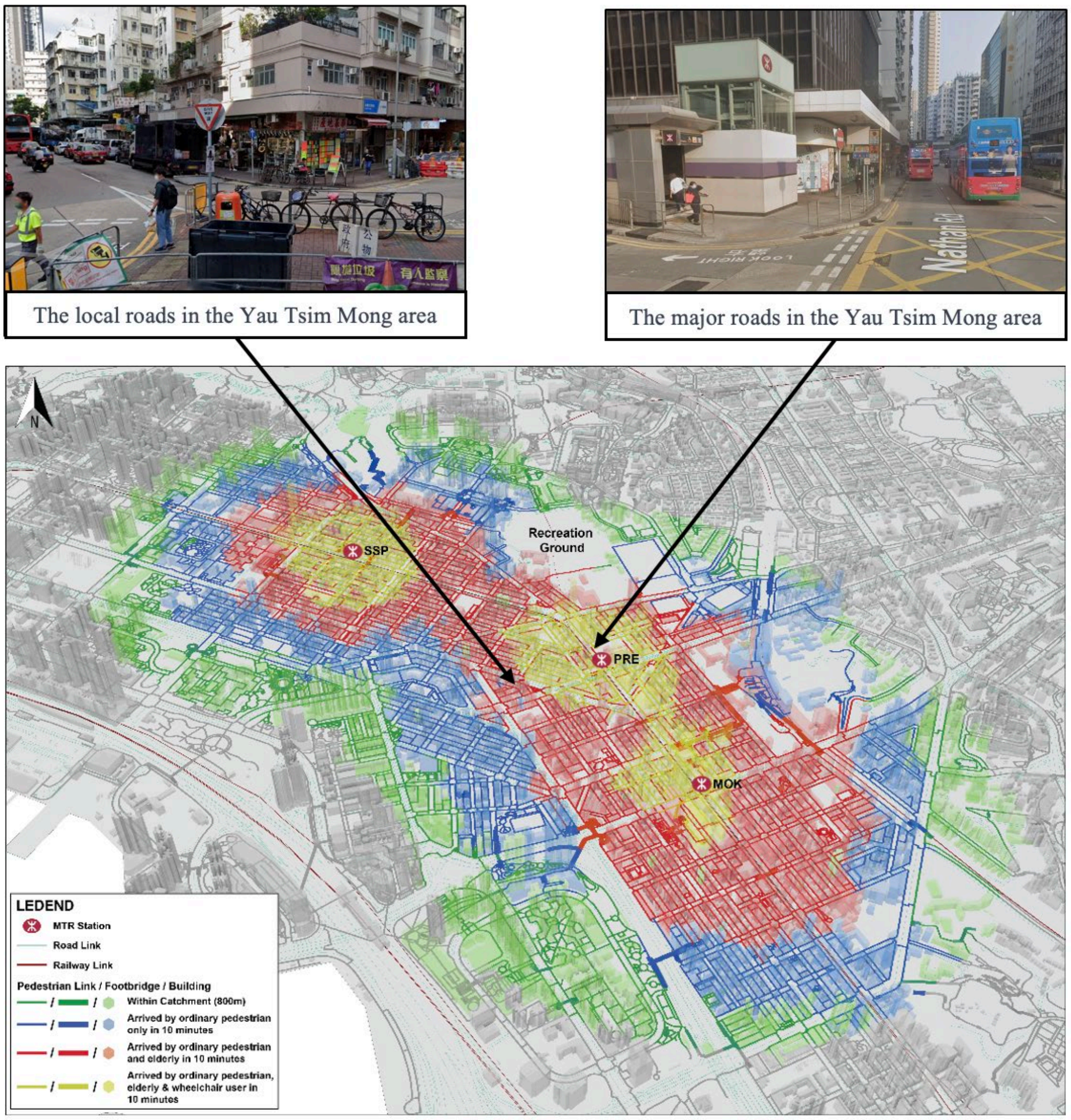


Figure 8 The walking environment of the catchment area of MOK, PRE, and SSP stations

5. Discussion and conclusions

We examine the capabilities of different social groups around the metro stations. Using the concept of conversion factors, we analyze three different catchment area delimitation methods, namely, the radius-based, distance-based, and time-based catchment methods, to assess the performance of walking infrastructures in metro station areas. We consider the three methods as a hierarchy: radius-based catchment, which ignores the geographical and physical constraints, operates at the lowest level of detail. By applying an *ECF* to it, we obtain the distance-based catchment, which considers a set of environmental constraints that affect pedestrian accessibility. Finally, to consider individual mobility capabilities, *ICF*s are used for each individual population groups (i.e., ordinary pedestrians, the older people, and wheelchair users), and a better correspondence with reality is obtained.

5.1. Potential of the CA in transportation planning

The proposed methods for operationalizing the concept of conversion factors can serve as a basis for developing quantitative assessment techniques from the CA lens, while "quantifying walkability is an essential step in the sustainable mobility transition" (Loo, 2021). Conversion factors can be used as measures and combined with a 3D pedestrian network to represent key aspects of the CA.

First, the measures evaluate the environmental and individual factors that affect users' potential mobility. The results demonstrate how the CA can form the foundation for consistent evaluative approaches that could be applied to different walking environment in Hong Kong. In contrast to other approaches that focus on fairness in transportation, the CA stands out as particularly suited to account for the wide diversity of individuals. It not only considers how mobility resources are distributed but also how these resources differently impact people's opportunities based on personal characteristics, aspirations, and choices. This insight underscores the importance of tailoring accessibility solutions to individual capabilities. Second, they integrate the traditional transportation planning practices of defining the station catchment and service areas to estimate the overall walkability performance in station areas. By evaluating only the spaces that are effectively available to the individual, as the CA implies, the principle of marginal utility can be applied to accessibility as the quantity of a good or service. The CA has the potential to provide a more equitable evaluation of TOD neighborhoods, as it is derived from the potential mobility that people possess, given their personal and environmental circumstances. We demonstrate its usefulness for defining population groups with limited mobility and formulating inclusive urban mobility policies and practices. Finally, this paper specifically focuses on improving the limited use of the CA for evaluative purposes and its potential adaptability in other contexts related to walking and the built environment. It seeks to strike a balance between the "general" and "specific" aspects of the transportation planning. This includes recognizing the existence of diverse pedestrian individuals while still planning for groups. This approach also extends to the places we plan for by identifying clusters of station areas with common features. It explores the possible factors that explain variations in accessibility disparities among pedestrian groups and across different geographical and urban design contexts.

5.2. From transit-oriented to people-oriented development

Under the TOD business model, many metro stations offer seamless pedestrian interfaces with shopping malls and an array of land uses (Barber, 2020), the development of which served to fund a system that prizes walkable pedestrian environments. This is reflected in one of the case studies in the Tsim Sha Tsui business area. The connectivity of shopping malls inside or near the stations is boosted by the multi-layered pedestrian network and auxiliary facilities. In conjunction with instances in a Tsuen Wan residential district, these cases point to an underlying bias toward automobile usage that prevails in Hong Kong. Pedestrians enjoy the advantages of a well-connected system of grade-separated structures, such as bridges and subways, which are linked to a prioritized array of land uses and development. However, this configuration exacerbates issues of mobility injustice by placing those who lack access to these pedestrian amenities at a disadvantage. Although the capital and social values of multilevel pedestrian networks have long been recognized (Tan and Xue, 2014; Tang et al., 2020; Zhao et al., 2020), the social and spatial disparities are relatively less discussed (Barber, 2020; Soliz and Pérez-López, 2022).

Recently, the people-oriented paradigm has emerged, inspiring urban scholars (Blečić et al., 2021; Loo, 2021), local government (e.g., UK Department of Transport, 2021), and even grassroots movements (e.g., Street Reset, 2022) in promoting walkability. In this regard, walkability planning extends beyond just traffic speed and transport efficiency. It encompasses the experiences and well-being of people who can conveniently travel to places they find relevant and attractive. This includes the "physical and mental health of people (notably the older people)" and "wheeled" walking traffic, that is, pedestrians who use wheelchairs, prams or other mobility aid on the pedestrian networks" (Loo, 2021). Unlike one-size-fits-all solutions, such as the Universal Design for all, the CA recognizes the need for adaptive and context-specific interventions. It acknowledges that individuals have different factors affecting their capabilities, encompassing personal characteristics and external circumstances. This understanding promotes a nuanced approach to accessibility that addresses diverse needs. However, while we recognize the significant value of the "more specific" CA for understanding accessibility, practical and pressing questions about its application in different contexts remain. In this paper, we adopted CA and Gini index to evaluate the reachable areas of different individual population groups and their spatial disparities, providing a quantitative evaluation of walkability which considers the difference in walking capability in the context of 3D walking environment. The results highlight the influences of the street network, urban designs, setting of metro station exits and internal features of TODs on mobility of individuals with diverse capabilities. It should be acknowledged that there is no particular design and not possible to provide route choices and facilities that meet everyone’s capabilities considering geographical and resource limitations. To this end, the methodology proposed in this study could be adopted by urban professionals to conduct comprehensive and inclusive walkability analysis in the design stage to enhance connectivity between spaces to minimize the mobility barrier based on the local profile and situation.

5.3. Limitations and way forward

We recognize the diversity within pedestrian groups, and this diversity is the driving force behind our article. Our goal is to distinguish between various mobility preferences and requirements by highlighting how environmental and personal factors interact to transform resources into valuable capabilities. Unlike other similar studies that rely on survey data and are limited to a study area (He et al., 2016; Lu et al., 2018), our method, which applies computational models to multiple spatial datasets, can provide a more efficient regional overview of infrastructural provision, before commencing in-depth qualitative (e.g., interview, focus group) and quantitative (e.g., count survey and modeling) investigations for a specific area. The adoption of conversion factors can help planners identify the potential problems of each station area by factoring in the characteristics of the walking environment and the mobility capabilities of marginalized groups. Our results can serve as a foundation for further explorations of the accessibility in other cities under three-dimension perspective, with their local contexts and urban settings.

Although we aim to move away from a one-size-fits-all approach, we must acknowledge its inherent limitations. Nevertheless, our approach based on conversion factors can be expanded when we have access to data concerning the mobility constraints and preferences of different pedestrian groups, such as through surveys. This data can potentially help us identify and cluster additional groups of pedestrians with distinct personal conversion factors, including factors related to physical condition (disability or fitness), gender, network knowledge, navigation skills, and specific abilities (e.g., cycling proficiency). We recognize this as both a limitation of our current research and an avenue for future exploration.

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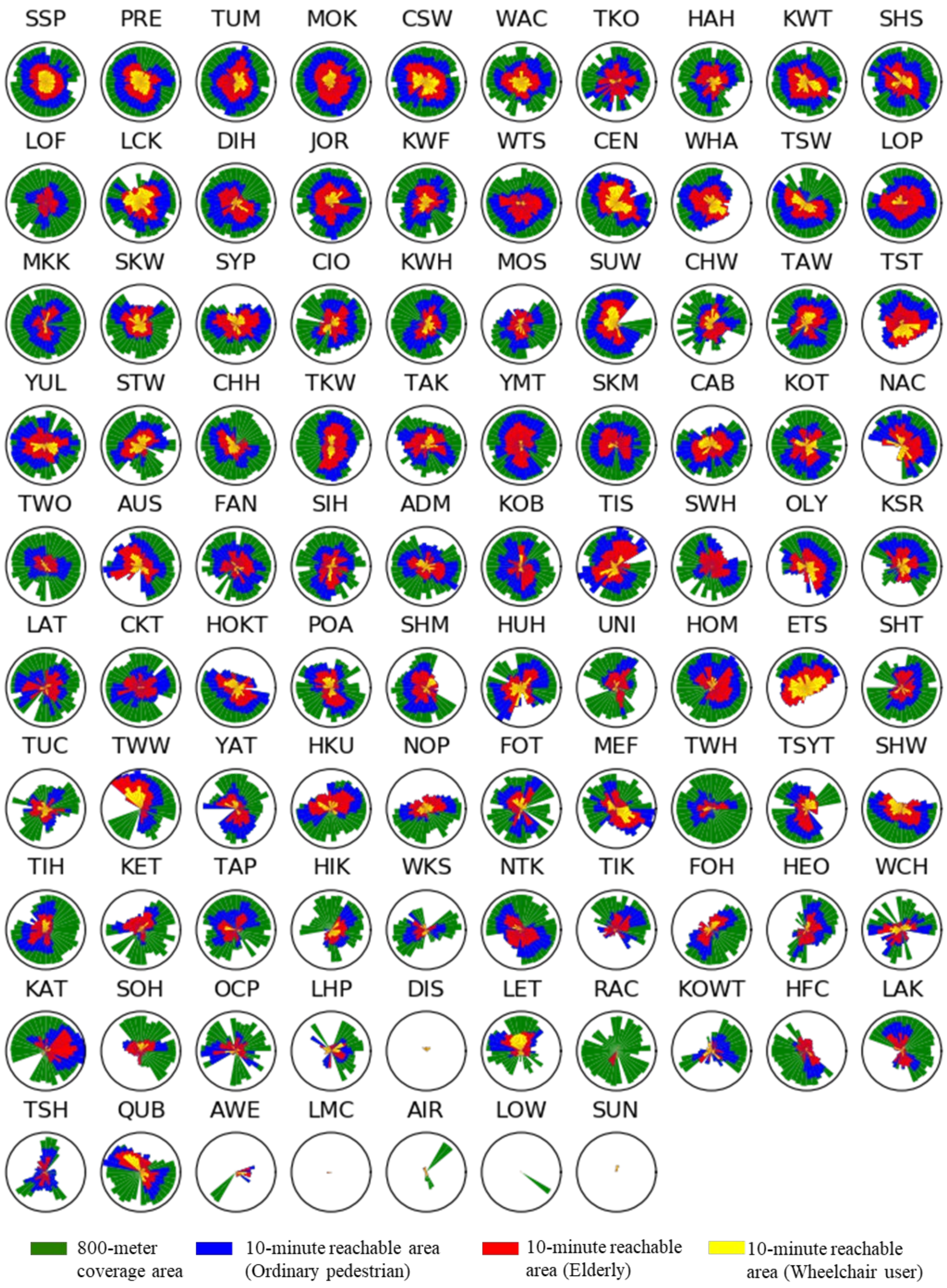
Appendix A Value of conversion factors for all metro stations

Station	ICF^p	ICF^e	ICF^w	Station	ICF^p	ICF^e	ICF^w	Station	ICF^p	ICF^e	ICF^w
ETS	0.96	0.85	0.61	WAC	0.74	0.53	0.27	LET	0.66	0.54	0.25
TST	0.95	0.73	0.26	KSR	0.73	0.51	0.21	TSW	0.65	0.39	0.16
WHA	0.90	0.68	0.32	KOWT	0.73	0.40	0.31	LAT	0.64	0.36	0.05
TIS	0.90	0.63	0.16	WCH	0.73	0.55	0.24	TUC	0.64	0.46	0.20
HOKT	0.86	0.56	0.30	FAN	0.73	0.40	0.06	KWH	0.63	0.36	0.14
CSW	0.85	0.57	0.30	FOH	0.73	0.54	0.23	SHT	0.63	0.43	0.07
TSH	0.84	0.39	0.09	MEF	0.73	0.54	0.18	MKK	0.63	0.29	0.07
LCK	0.83	0.60	0.39	SUW	0.72	0.42	0.21	QUB	0.63	0.48	0.21
LOP	0.83	0.55	0.11	HEO	0.72	0.52	0.13	KET	0.61	0.49	0.10
CAB	0.83	0.56	0.25	CHW	0.72	0.51	0.19	TIH	0.61	0.40	0.12
MOK	0.82	0.56	0.19	WTS	0.72	0.45	0.05	SOH	0.60	0.54	0.06
YUL	0.82	0.53	0.18	LHP	0.71	0.52	0.30	TWW	0.59	0.38	0.12
CEN	0.82	0.60	0.32	NOP	0.71	0.60	0.26	TAP	0.59	0.29	0.03
SHM	0.81	0.57	0.18	ADM	0.71	0.42	0.16	FOT	0.59	0.37	0.14
SHW	0.81	0.64	0.36	POA	0.71	0.46	0.18	OCP	0.59	0.43	0.10
HUH	0.81	0.56	0.31	HFC	0.71	0.60	0.05	KAT	0.58	0.37	0.10
SYP	0.81	0.59	0.25	NTK	0.70	0.47	0.04	AIR	0.56	0.56	0.46
JOR	0.80	0.52	0.17	SIH	0.70	0.44	0.11	LAK	0.56	0.41	0.09
OLY	0.80	0.59	0.22	DIH	0.70	0.44	0.12	TWO	0.54	0.30	0.08
TSYT	0.79	0.57	0.25	TAW	0.70	0.44	0.17	UNI	0.53	0.42	0.07
KWT	0.79	0.54	0.23	SKM	0.70	0.40	0.05	CHH	0.53	0.34	0.14
TUM	0.78	0.52	0.18	HOM	0.69	0.42	0.07	WKS	0.53	0.36	0.18
SSP	0.78	0.52	0.30	CIO	0.69	0.45	0.12	LOF	0.53	0.33	0.01
PRE	0.77	0.51	0.31	HKU	0.69	0.50	0.15	HIK	0.47	0.34	0.13
SHS	0.77	0.48	0.18	KOT	0.69	0.43	0.19	TWH	0.42	0.20	0.04
NAC	0.76	0.51	0.24	YAT	0.69	0.44	0.14	LOW	0.42	0.42	0.42
AUS	0.76	0.53	0.23	CKT	0.68	0.41	0.02	AWE	0.33	0.29	0.11
YMT	0.76	0.47	0.04	HAH	0.68	0.47	0.16	SUN	0.31	0.31	0.31
TKW	0.75	0.51	0.14	KWF	0.68	0.43	0.19	DIS	0.25	0.25	0.25
TIK	0.75	0.54	0.03	SWH	0.68	0.49	0.01	LMC	0.11	0.11	0.10
TAK	0.75	0.51	0.16	SKW	0.68	0.55	0.26	RAC	0.06	0.06	0.02
TKO	0.74	0.52	0.04	KOB	0.68	0.34	0.06	**Average**	**0.68**	**0.47**	**0.17**
MOS	0.74	0.50	0.14	STW	0.68	0.47	0.26		* Lower than average value		

Appendix B The catchment area of metro stations



Note: Order of stations is sorted by the average of Gini index.

Appendix C k-means clustering results (Elbow method for optimal k)