Towards walkability enhancement: A systematic review and future directions

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Abstract

Walking, as a transportation mode, contributes to not only individual well-being but also environmental sustainability. Though often neglected in the transport planning process that focuses primarily on motorized transport, its benefits recently have renewed interest to promote walking by enhancing walkability. In this paper, we conduct a systematic review of the walkability literature according to three aspects: (I) supply-side analyses that characterize, measure, and assess walking facility attributes in a built environment; (II) demand-side analyses that measure and model pedestrian behavioural response to a walkable environment; and (III) prescriptive approaches by stakeholder groups for developing strategies to enhance walkability. While recognizing the progress that has been made by previous studies, we conclude by exposing the challenges that remain and thereafter identifying potential research directions.

Keywords

Walkability; Built environment; Pedestrian behaviour; Stakeholder group; Transport planning

Preferred citation style

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1 Introduction

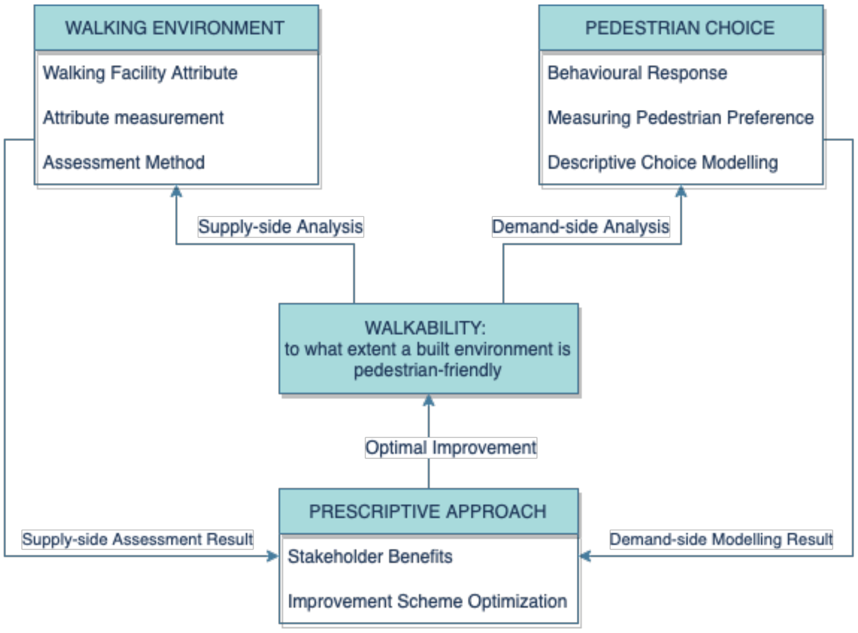
1.1 Background and motivation

Walking is a fundamental part of transport, way before motorized transport was invented, and is indispensable for virtually all itineraries, either serving as a connection between places or a transfer between different transport modes or constituting an entire trip on its own. Walking is also a healthy and sustainable mode of transportation, offering wellbeing to individuals and at the same time addressing environmental emission concerns. Unlike motorized trips, walking generates no greenhouse gas emissions, hence is an important treatment available to mitigate global warming. Though often overlooked in the past, its benefits have renewed the interest to promote walking by devising well-designed interventions and enhancing walkability. More walking in return will bring about the need for further walkability improvement, starting a virtuous circle.

Despite the benefits of walking and the need to formally recognize walking as a standard mode in transport planning, much of the existing transport planning still primarily remains on motorized transport. Research that investigates walkability falls far behind (Clifton et al., 2016a). Recent studies have begun to investigate what would contribute to a better walkable neighbourhood (e.g., Saelens et al., 2003b; Owen et al., 2004; Frank et al., 2006; Carr et al., 2010; Talen and Koschinsky, 2013)). In view of the emerging recognition and importance of enhancing walkability and incorporating walkability into integrated transport planning, it is an opportune time to take stock of what foundations past efforts have laid, and what critical research issues remain.

To effectively enhance walkability, i.e., to what extent a built environment is pedestrian-friendly (Wang and Yang, 2019), considerations should be reflected in two aspects, namely the supply-side built environment and the demand-side pedestrian behavioural responses in a neighbourhood. Along this vein, we develop a schematic for the walkability enhancement process as shown in Figure 1 from the perspectives of (I) characterization of the supply-side built environment attributes, which are much more involved than those for vehicular traffic, (II) appraisal of the demand-side pedestrian responses to the built environment, and (III) development of prescriptive approaches for improving walkability based on the results from both the supply-side and demand-side analyses. To this end, the following questions will need to be holistically addressed. How to identify elements in the built environment that would increase people's propensity to walk? How to estimate or predict the outcomes of improvement schemes in pedestrian facility through rigorous quantitative modelling? How to select improvement schemes based on prescriptive approaches according to stakeholders' needs? These practical issues motivate this study to review the state-of-the-art walkability research and chart out future research directions.

Figure 1. Schematic of walkability enhancement



1.2 Review process

Following the issues in the schematic in Figure 1, we review and summarize the relevant walkability literature. Firstly, we review studies about the walking environment, which can be considered as supply-side characterization. The key elements related to walking as well as their ways of measurements and assessments are summarized. Secondly, we examine demand-side behavioural responses to the pedestrian facilities, including measures to collect pedestrian stated and revealed preferences as well as rigorous descriptive approaches, which are instrumental to establish the connections between supply and demand and to predict the expected outcomes given any new infrastructure facility. Thirdly, from the prescriptive perspective, we categorize various benefits generated from enhanced walkability that are appealing to the stakeholders, then review approaches for developing interventions towards walkability enhancement. Eventually, based on this systematic review, we expose and identify research gaps for future studies.

The relevant literature search is conducted via the database Web of Science in the field of ‘transportation’ or ‘transportation science and technology’. Three keywords (or alternates) are specified in the title, abstract, or keywords of articles, i.e., ‘walkability’, ‘environment’ (or ‘neighbourhood’), and ‘pedestrian’ (or ‘walking’). We then screen the list with these two inclusion criteria: (I) either on supply side, or on demand side, or on prescriptive perspective; and (II) based on quantitative analysis rather than qualitative discussion. Additional papers identified from the references of the selected articles are also included, which lead to the selection of 114 papers for this review, as listed in Appendix.

The paper is structured as follows. Section 2 describes the supply-side characterization including attributes of the walking facilities in a built environment, their attribute measurements, and assessment methods. Section 3 summarizes the demand-side pedestrian preferences, the ways they are measured, and the descriptive models to establish their relationship with the supply-side built environment. Section 4 discusses the benefits of enhanced walkability, types of stakeholders, and prescriptive approaches for enhancing walkability. Section 5 depicts the main findings and future directions.

2 Supply-side characterization: walking facility attributes in a built environment

In this section, we provide a review of the major walking environment attributes identified in the literature, an overview of the ways they have been captured via some forms of measurements, and a summary of methods to assess their performance. An understanding of how to capture the supply-side or walking facility attributes will help define prescriptive behavioural choice models in our subsequent discussion.

2.1 Walking environment and facility attributes

Various types of walking environment and facility attributes identified in the literature can be classified in the taxonomy in Figure 2. The taxonomy consists of three dimensions, namely: (I) macro-scale neighbourhood characteristics, its physical neighbourhood design, land use, and socioeconomic of people who work or reside there, etc.; (II) micro-scale pedestrian facility attributes, amenities, congestion, perceived safety, etc.; and (III) other attributes in the exogenous environment related to climate and weather, traffic and facility usage regulations or restrictions, etc.

Figure 2. The taxonomy of walking attributes

Class (Scale)	**Category**	**Element**	**Frequency**	**Walking Attribute**							
NEIGHBOURHOOD CHARACTERISTIC (Macroscopic)	**Social environment**	**Land use mixed**	66	Residence	Recreation	Commercial	Floor ratio				
		Socioeconomics	59	Population	Household	Employment	Income level	Car ownership			
	Physical environment	**Connectivity**	81	Walking distance	Walking time	Destination	Intersection	Alternative route			
		Permeability	29	Betweenness	Closeness	Accessibility	Entrance / exit	Continuity	Dead end	Ped-shed ratio	
		Coverage of POIs	77	Transit	Shopping mall	Housing estate	Market	Health care	School	Restaurant	
PEDESTRIAN INFRASTRUCTURE (Microscopic)	**Essential attribute**	**Roadways**	35	Width	Lanes	Speed	Buffer zone	Curb / fence	Traffic control		
		Sidewalk	60	Width	Length	Pavement	Slope	Barrier-free facilities	Shared lane	On-street parking	Setback
		Crossing	31	Signal	Cycle time	Safety island	Zebra line	Intersection types			
		Signage	12	Direction	Distance						
		Smart technology	4	Navigation	E-board	Real time information	Surveillance				
		Elevated facility	6	Escalator	Elevator	Footbridge	Tunnel	Stairs	Ramp		
		Indoor coverage	9	Covered shelters	Roof	Air conditioner					
	Auxiliary amenity	**Comfort**	31	Noise	Hygiene	Lighting	Air quality	Smell			
		Aesthetics	45	Street furniture	Greenery	Building design	Building façade	Building height	First floor	Building number	
		Convenience	31	Bench	Washroom	Parking	Convenience store	Garbage bin			
		Open space	24	Park	Sea / Promenade	Landscape	Yard				
		Opening hour	10	Booth	Dining	Construction	Service hour				
	Safety feature and perception	**Traffic**	27	Pedestrian	Vehicle	Shared lane					
		Security	24	Accident	Crime						
		Facility	23	Signals	Cycle time	Safety island	Zebra line	Curb	Surveillance	Width	
		Feeling	12	Lighting	Hygiene	Pet / animal	Police officer				
EXOGENEOUS ENVIRONMENT (Exogeneous)	**Controllable**	**Traffic**	28	Pedestrian crowdedness	Vehicle volume	Vehicle speed	Traffic accident				
		Intervention	2	Incentive	Right-of-way						
	Uncontrollable	**Climate / weather**	4	Seasonal	Daily						

2.1.1 Dimension I: neighbourhood characteristics

Neighbourhood characteristics represent macro-scale areawide elements in defining the walking environment, sometimes referred to as the urban form. It is further classified into two categories: the social environment of people who work or reside there, and the physical environment of the neighbourhood involving factors such as connectivity, permeability, and coverage of points-of-interest (POIs), etc.

Cervero and Kockelman (1997) was a seminal study on walkability, which examined how the 3D concept, i.e., ‘density’, ‘diversity’, and ‘design’, affect walking demand and mode choices. Specifically, ‘density’ is about the population, employment, and points of interest in the area; ‘diversity’ relates to the degree of mixed land use; and ‘design’ depicts the street network characteristics. Ewing and Cervero (2001, 2010) later produced a more general ‘5D’ framework, adding two more Ds, ‘destination accessibility’ and ‘distance to transit’. To ensure no omission in our taxonomy, this ‘5D’ framework can be mapped to our taxonomy in Figure 2, e.g., land use and demographics (density, diversity), connectivity and permeability (design, destination accessibility), and coverage of POIs (destination accessibility, distance to transit).

Comparing among the neighbourhood characteristics, Lamíquiz and López-Domínguez (2015) concluded that walking behaviours were more influenced by physical environmental elements than by social factors, and that safety was among the most important attributes affecting the walking choice. Due to its importance, we place safety perception as a micro-scale attribute associated with a pedestrian infrastructure facility, as described below.

2.1.2 Dimension II: pedestrian facility

Pedestrian facility attributes affect the walking experience and are considered as micro-scale attributes here. We divide pedestrian facilities into three categories: essential attributes, auxiliary amenities, and safety features and perceptions. The first category directly affects the walking experience; the second enhances the comfort of walking, and the third discourages walking due to safety concerns.

Pikora et al. (2002, 2003) developed a framework, called systematic pedestrian and cycling environmental scan (SPACES), to uncover the facilities that may influence pedestrians from the functional, safety, aesthetics, and destination perspectives. This SPACES framework can be mapped to our taxonomy in Figure 2, where functional and destination factors can be categorized in essential attributes; aesthetics in auxiliary amenities; and safety in safety features and perception. Expanding the 3D concept by Cervero and Kockelman (1997), Lee and Moudon (2006) supplement a '3D+R' framework, with 'R' representing 'Route' which is considered as the essential attribute in our taxonomy. Handy et al. (2006) analysed the impacts of these attributes by incorporating travel attitudes and neighbourhood preferences, to exclude the potential self-selection bias, i.e., residents who prefer walking choose to live in a walkable area. The impacts of pedestrian facility attributes on pedestrian behaviours were significant after excluding the self-selection bias.

Safety features and perception play an essential role in walking, as Lindelöw et al. (2014) conducted psychological surveys and found that pedestrians put safety as the priority in their walk trips. Thereby, safety is placed in a separate category, including elements that are related to the sense of safety and security. For example, traffic signals and crosswalks can accommodate pedestrian crossing with convenience and safety. Separation of vehicular and pedestrian traffic provides a safer perception than mixed traffic in a shared lane. Neighbourhood safety performance can also be represented by several indicators according to ISO 37120:2018[1], e.g., property crimes, violent crime rate, number of police officers per 100,000 population, etc. A higher level of safety perception is conducive to a more walkable environment.

Most of the aforementioned studies investigated walkability for the U.S. and European contexts. When it comes to high-density Asian metropolises, for example Hong Kong and Singapore, other elements affecting walking may prevail. Cerin et al. (2011) pointed out that extra attention should be paid to air and noise pollution, crowdedness, complex public transport network, man-made obstacles (e.g., on-road and footpath parking), extensive indoor areas for walking, and unique types of destinations (e.g., diverse types of open-air and indoor food stalls). Loo and Lam (2012) focused on walking auxiliary facilities in Hong Kong, such as signage, elevated facility, and indoor coverage, and found that essential attributes have significant impacts on walking. Besides, Ferrer et al. (2015) stated that walking preferences could vary across time,

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[1] https://www.iso.org/standard/68498.html

due to the service hours of certain facilities like dining and shopping, indicating that walkability planning ought to include time-related factors.

2.1.3 Dimension III: exogeneous environment

Different from the previous two dimensions that are about attributes of the neighbourhood and pedestrian facilities, the exogenous environment refers to elements that are not directly part of the neighbourhood or facility design, but may affect the walking experience, and we classify them into controllable and uncontrollable elements.

One of the controllable elements is traffic conditions, such as vehicle volume and pedestrian crowdedness. They are somewhat controllable through regulations, such as speed limit, speed bump, traffic calming scheme, and one-way traffic. Landis et al. (2001) were among the first walkability studies to consider traffic conditions (volume and speed), which were then acknowledged to be an important determinant in pedestrian trips by subsequent research (Cunningham et al., 2005; Cerin et al., 2006; Ewing and Handy, 2009). Through surveying pedestrians and cyclists, Koh and Wong (2013) concluded that traffic risk and pedestrian crowdedness were of great importance in affecting the walking choice.

Interventions to promote and enhance walking are another controllable element. For example, the agency can allocate commute routes exclusively for non-motorized trips, which is developed in an integrated manner to improve both the city appearance and neighbourhood walkability by assigning right-of-way to pedestrians. In another example, the Mass Transit Railway Corporation (MTRC) in Hong Kong provides fare discounts as incentives to encourage passengers farther away to walk to their stations, to enlarge the catchment area of a metro station. Such an intervention produces a win-win situation by attracting more walking while at the same time increasing their ridership.

As for uncontrollable elements, weather and climate are two major components Böcker et al. (2013) provided a systematic review concerning the impacts of weather on daily travel activities, particularly walking and cycling. Clark et al. (2014) studied school trips and found that children's walking choices were significantly correlated with the weather conditions, i.e., temperature, precipitation, and wind speed. Carver et al. (2019) conducted a cross-sectional study and found different walking trip patterns in different seasons.

2.1.4 Summary remarks

Out of 114 papers reviewed, the frequency column in Figure 2 shows the number of publications that address the corresponding category. The top three attributes considered in macroscale neighbourhood characteristics include connectivity (81), POI (77), and mixed land use (66). Demographics is also common (59). As for microscale pedestrian facility attributes, the top three attributes are sidewalk (60), aesthetics (45), and roadway (35). Other common attributes include crossing (31), comfort (31), and convenience (31). As for the exogenous environment, traffic (28) stands out to be the most common. We note that this set of attributes is quite different from attributes that may affect vehicular route choices. This exposition illustrates what previous studies have covered and attributes that should be duly considered in setting up new studies. On the other hand, it also exposes what may be important and have yet to be covered.

As shown in Figure 2, attributes that have attracted relatively fewer studies include (I) elevated facility, such as lift and escalator, which helps overcome slopes or obstacles to access to different floors (Loo and Lam, 2012); (II) signage, such as directional indicator for way-finders (Lam et al., 2003); (III) smart technologies providing navigation and real-time crowdedness information.

2.2 Measurement of walking environment and facility attributes

Other than identifying the important attributes for walkability enhancement, their measurements are equally important for supply-side analyses. Lee and Talen (2014) reviewed the auditing methods and classified these measurements into in-person and secondary-source audits. The rapid development of techniques and methods using smart technologies, such as video clips, Google Street View, live cameras, has made them more commonly used to capture walking environment attributes with ease and objectivity. We therefore separate these measurements into three basic forms: in-field audit, measurement with map-based statistical information, and remote measurement.

2.2.1 In-field audit

In-field audit is an effective way to measure walking attributes, where observations or measurements are taken on site. Many audit tools, e.g., SPACE (Pikora et al., 2002, 2003), SWEAT (Cunningham et al., 2005), IMI (Day et al., 2006), PEDS (Clifton et al., 2007), MAPS (Millstein et al., 2013), etc, has been well-developed for this purpose. To cater to different neighbourhood characteristics, the audits should be adapted for different site-specific features. For example, IMI, originally developed for the US context, was later updated to fit for features in China (IMI-C, Day et al., 2013). Detailed comparisons of various audit tools were summarized by Clifton et al. (2007), Lee and Talen (2014), and Lefebvre-Ropars et al. (2017).

In-field audit typically covers micro-scale attributes and is recognized for its high reliability, i.e., producing consistent results under similar circumstances. The statistical indicators, intra- and inter-observer reliabilities are utilized to assess the reliability of an audit. Dichotomous variables were tested using the Cohen's Kappa statistic, accounting for the effects of chance agreement (Ussery et al., 2019), while the continuous and ordinal variables were assessed using one-way random effects single-measure intraclass correlation coefficients (Millstein et al., 2013).

Yet cost is a major limitation of an in-field audit (Lee and Talen (2014). Even though abbreviated versions of audits have been developed, e.g., the 91-item NEW-A (Cerin et al., 2011) within the SPACE framework and the modified version of MAPS (Ussery et al., 2019), the time and manpower costs remain substantial.

2.2.2 Measurement with map-based statistical information (MSI)

To reduce the manpower cost of in-field audits, MSI, e.g., digital maps and census statistics, may be used as substitutes to measure the walking environment attributes. For example, utilizing GIS, Parks and Schofer (2006) measured the pedestrian environment and showed consistent results with two audit systems: Pedestrian Environment Factor (PEF) and the Pedestrian Friendliness Index (PFI). Additionally, the availability of network and transportation data from commercial software like Google, Baidu, and Gaode Map makes it convenient and effective to assess the walking environment.

In fact, the trade-off between cost and precision exists for any measurement. MSI saves a considerable amount of manpower at the expense of accuracy since the data is generally captured in an aggregate macroscale form on an areawide macroscale (Dimension I), lacking the ability to capture microscale attributes (Dimension II), unless the network and GIS coding also contain such microscale information, which is getting more common recently.

2.2.3 Virtual audit via remote measurement

Balancing between manpower cost and accuracy, remote measurement is becoming popular with advanced internet technology. Online street view information enables measurements to be taken remotely instead of in-field audit, which substantially reduces the manpower costs. Clarke et al. (2010) were among the first to use Google Street View to audit the neighbourhood environment and produce as reliable results as in-field audit Shatu and Yigitcanlar (2018) developed a virtual street walkability audit tool for route choice analysis (SWATCH) to ease the burden of data collection process while maintaining the reliability of results. Lee and Talen (2014) demonstrated that the combined use of GIS and Google Street View was efficient, effective, and robust for measuring the walking environment. It is expected that, with the development of artificial intelligence (AI) and image recognition, remote measurements can be conducted automatically to be used by practitioners. A properly trained machine learning model with pre-defined walking attributes to be measured will be able to assess the virtual information either in the form of images or videos and provide microscale and/or macroscale information for walkability analysis.

2.2.4 Summary remarks

Measuring walking environment attributes involves a compromise between labour cost and precision. For measuring macroscale attributes (Dimension I), MSI seems to be an appropriate choice. For microscale elements (Dimension II), in-field audit can capture reliable information but with a higher labour cost. Alternatively, as is getting more common, remote measurements via online tools like Google Street Map provide a convenient way to characterize the walking environment without much loss of accuracy. Together with image recognition and AI techniques, it is anticipated powerful tools will be developed for collecting both microscale and macroscale attributes for walkability analyses.

2.3 Assessment of walking environment

After measuring various types of supply-side elements and attributes, this section summarizes the methods to assess the level of walkability of a supply-side environment. There are two types of assessments, which rely on evaluative ratings of the physical infrastructure and perception of the pedestrians, respectively.

2.3.1 Assessment based on evaluative ratings

Evaluative ratings are indices or indicators developed to quantify the walkability performance based on the supply-side walking environment and/or facility attributes. Typically, several attributes are integrated into one composite. We summarize the two types below.

Firstly, the walkability scale combines topological components in a neighbourhood to assess its walkability. For example, Walkability Index (Frank et al., 2010) is based on a linear combination of land use, residential and intersection density. And Walk Score[2] (WS), a normalized weighted sum of accessible POIs including grocery, restaurant, shopping mall, café, bank, park, school, bookstore, and entertainment facility, is a commonly used rating. Walking accessibility is another major evaluative rating that focuses on coverage of POIs (Loo and Lam, 2012; Gori et al., 2014; Sun et al., 2017). Wang and Yang (2019) systematically reviewed neighbourhood walkability scale assessment.

Secondly, the pedestrian level of service (PLOS) captures how pedestrians perceive the walking environment through their experience. Landis et al. (2001) was a seminal study on quantifying the walking environment for pedestrian travel. Compared to walkability scale mentioned above, PLOS is more concerned about micro-scale attributes that directly affect the walking experience, such as sidewalk width, pedestrian flow rate, shoulder width, on-street parking, barrier, buffer width, traffic lanes, traffic speed, etc. Readers may refer to Asadi-Shekari et al. (2013), Raad and Burke (2018), and Rodriguez-Valencia et al. (2020) for reviews of PLOS.

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[2] www.walkscore.com

2.3.2 Assessment based on pedestrian perception

Walkability can also be assessed through pedestrian perception feedback. For instance, NEWS[3] is one widely used survey to measure pedestrian perceived walkability, i.e., their satisfaction about the walking environment, and adapted into different versions for site-specific characteristics, such as NEWS-A (an abbreviated version in the US, Cerin et al., 2006), C-NEWS (a Chinese version, Cerin et al., 2007), NEWS-I (an Indian version, Cerin et al., 2013). Guimpert and Hurtubia (2018) proposed a novel method to estimate the perceived walking neighbourhood (PWN) by asking respondents to mark their acceptable walking ranges. An area marked by more pedestrians represents better perceived walkability. Besides, there are questionnaires developed to investigate the attribute importance (e.g., Lindelöw et al., 2014; Golan et al., 2019).

2.3.3 Summary remarks

The assessment methods of the supply-side environment mostly capture the physical attributes of the physical infrastructure, which are thought to be relevant to reflect the walking choice or experience, but without directly accounting for the behavioural response from pedestrians in detail; and if pedestrian perception is captured, it is conducted in a rudimentary way, without sufficient granularity for rigorous choice analysis. Moreover, the attributes are considered to contribute equally to the rating or score, which is often not the case, as pedestrians may perceive or evaluate different attributes differently. In any case, future studies can construct topology- and utility-based walkability indicators by incorporating behavioural responses, perhaps expressed as different attribute weights, into the current ratings to overcome this limitation.

3 Demand-side analyses: behavioural response to a walking environment

From the demand side, this section first reviews pedestrian behavioural responses associated with the supply-side built environment and the measures to collect individual behaviour

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[3] https://activelivingresearch.org/sites/activelivingresearch.org/files/NEWS_Survey_0.pdf

information. We then summarize the underlying behavioural modelling approaches developed so far to establish relationships between supply and demand, which will lay a foundation for prescriptive perspectives on how to enhance walkability in a built environment.

3.1 Behavioural responses to walkability

Extensive literature has studied the impacts of a walkable environment on pedestrian behaviours as summarized by Wang and Yang (2019). Pedestrian behavioural responses represent their walking choices and preferences in the neighbourhood. We classify them into four types as follows:

(I) Walking demand. It is a common measure of walkability in the literature (e.g., Frank et al., 2005; Lee and Moudon, 2006; Sehatzadeh et al., 2011). The measures can be walking frequency, walking duration, total physical activity, etc.
(II) Mode choice. Considering walking as a travel mode alternative, studies revealed the influence of walkability on the mode share (e.g., Ewing and Cervero, 2010; Park et al., 2014, 2015; Halat et al., 2015; Moniruzzaman and Páez, 2016).
(III) Route choice. Studies showed significant associations between walkability and route choice, i.e., tendency to choose a more walkable route over other choices (e.g., Guo and Ferreira, 2008; Guo and Loo, 2013; Moran et al., 2018; Shatu and Yigitcanlar, 2018).
(IV) Destination choice. For example, Clifton et al. (2016b) developed a multinomial logit model to predict pedestrian destination choices.

3.2 Measure of pedestrian preference

After recognizing various kinds of behavioural responses to walkability, how to measure and collect such information are at the crux of demand-side analysis. There are two ways to capture their behavioural choices, namely revealed preference and stated preference methods.

3.2.1 Revealed preference (RP) measurement

RP reflects the actual decisions made by pedestrians under existing walking conditions. It can be conducted by pedestrian tracking survey (PTS) and travel diary survey.

Providing respondents with some accelerometers and GPS equipment to track their physical activities or trajectories is a popular way of PTS adopted by many studies (e.g., Saelens et al., 2003a; Frank et al., 2005; Neatt et al., 2017; Williams et al., 2018). This is convenient but its accuracy is a concern. Respondents may forget to wear the equipment, and GPS signals may not be precise. Other ways of PTS include intercept and unobtrusive tracking. Guo and Loo (2013) conducted an intercept tracking survey on the street and asked respondents to mark down their routes taken on a map and their personal characteristics. Unobtrusive tracking is to get pedestrians the origin, destination, and route choices by following but without noticing them (Lassarre et al., 2012; Kim, 2015). Such method was efficient as far as the sampling rate is concerned. However, Shatu and Yigitcanlar (2018) criticized unobtrusive tracking on ethical and privacy grounds and its inability to obtain information on socio-demographics and travel attitudes of respondents.

Travel diary survey is to collect details of participants' journeys within a certain period. Craig et al. (2003) developed the international physical activity questionnaire (IPAQ) to measure the duration and frequency of walking. It has been used and validated over 12 countries, and commonly accepted as an effective self-reported questionnaire to measure walking demand.

3.2.2 Stated preference (SP) measurement

SP survey, or stated choice experiment, is the other important way, especially for scenarios that may not yet exist or are under planning (Brown, 2003). It captures pedestrian stated travel choices among a set of transport alternatives, practical or hypothetical. Compared to RP measurement, SP survey can offer: (I) a much broader range of choice sets and wider magnitude of walking attributes; (II) convenience in data collection without requiring a detailed network; and (III) flexibility in designing the choice contexts depending on the survey purposes.

Kelly et al., (2011) designed an SP survey to determine the relative importance among factors that influence pedestrian activity and walkability. Koh and Wong (2013) developed on-street stated choice experiments to obtain pedestrian route choices. To reduce the number of choice tasks in SP survey whilst ensuring its accuracy, orthogonal fractional factorial designs and sometimes procedures to test artefact errors (e.g., the tendency to choose the left-hand-side alternative) are adopted (e.g., Liu et al., 2020). Hensher et al. (2005) provided comprehensive design instructions for SP surveys.

3.2.3 Summary remarks

In addition to SP and RP, measuring pedestrian behavioural responses also requires their individual characteristics, e.g., age, gender, education, personal income, car-ownership, etc. Besides, RP information does not always exist, especially when measuring the potential outcomes of a project under planning. With the ability to describe the hypothetical environment under planning, SP offers an approach for estimating and forecasting the potential usage of the planned facility. Therefore, combining SP and RP methods can provide more comprehensive understandings of pedestrian behaviours (Ben-Akiva and Morikawa, 1990; Bhat and Castelar, 2002).

3.3 Descriptive models development

This section summarizes descriptive approaches that have been used to model demand-side effects given walking facility attributes. Other than basic statistics, such as mean, standard deviation, correlation coefficient, etc., there are two descriptive approaches, namely supervised and unsupervised learning.

3.3.1 Supervised learning

Considering the demand-side effects as a function of supply-side attributes, supervised learning intends to reveal such relationships. Two kinds of approaches are used depending on the type of output, continuous or discrete. Instead of providing a generic review, this paper focuses on the modelling efforts for walkability analysis.

Continuous output. Linear regression is commonly used for a continuous dependent variable (e.g., Frank et al., 2006; Parks and Schofer, 2006; Millward et al., 2013; Erath et al., 2017; Lefebvre-Ropars et al., 2017) in the basic form:

$$Y = \boldsymbol{X}\beta + \varepsilon \tag{1}$$

where $\boldsymbol{X}$ is the attribute set, Y is the effect, ε is the error term, and β is the set of coefficients to be calibrated.

Although (1) is straightforward and interpretable, it is subject to limitations that may distort the result accuracy. One is the assumption for independence of observations, i.e., no statistical associations between two independent samples (Fotheringham and Rogerson, 2009). However, according to Tobler' Law (Tobler, 1970), there may be a spatial autocorrelation between observations taken close to each other in space. To address it, Weng et al. (2019) used the spatial regression:

$$Y = \rho \boldsymbol{W_Y} Y + \boldsymbol{X}\beta + \varepsilon \;\Rightarrow\; Y = (I - \rho \boldsymbol{W_Y})^{-\mathbf{1}} \boldsymbol{X}\beta + (I - \rho \boldsymbol{W_Y})^{-\mathbf{1}} \varepsilon \qquad (2)$$

where $\boldsymbol{W_Y}$ is the spatial matrix that captures the topological information and ρ is the spatial autoregressive coefficient. Compared to the basic linear regression, (2) can explore the spatial interactions between two zones.

Another limitation of (1) is that it assumes that ε has a mean of zero and is independent of $\boldsymbol{X}$**.** There is an estimation bias if ε is correlated with X, i.e., $Y = \boldsymbol{X}\beta + \varepsilon(\boldsymbol{X})$. For example, Sehatzadeh et al. (2011) examined how walking frequency was associated with car ownership and dog ownership, with all these variables being correlated with the environment attributes. In this case, the two-stage least square regression (Hong and Chen, 2014) is used to tackle the potential bias:

The first stage: $$\boldsymbol{X} = \theta \boldsymbol{Z} + \sigma \qquad (3)$$

The second stage: $$Y = \widehat{\boldsymbol{X}}\beta + \varepsilon(\boldsymbol{X}) = \hat{\theta} \boldsymbol{Z}\beta + \varepsilon(\boldsymbol{X}) \qquad (4)$$

Regressing on the instrument variable $\boldsymbol{Z}$, which is independent of the error $\varepsilon(\boldsymbol{X})$, $\boldsymbol{X}$ becomes the dependent variable in the first stage. The predicted value from the first stage $\widehat{\boldsymbol{X}}$ replaces the original value of $\boldsymbol{X}$ in the second stage, such that the error term is not correlated with the independent variable. The two-stage regression is useful in the case where the error and independent variables are correlated.

Discrete output. Discrete choice model (DCM) based on the utility theory is an effective approach used to address categorical dependent variables, e.g., mode choice (Weinberger and

Sweet, 2012; Park et al., 2014), walking route choice (Guo and Ferreira, 2008; Guo, 2009), and destination choice (Clifton et al., 2016a, 2016b). The utility of choice i is:

$$U_i = \beta x_i + \varepsilon_i \tag{5}$$

With the logit model assuming ε_i an independent and identical Gumbel distribution, the probability of i will be:

$$P_i = \frac{e^{\beta X_i}}{\sum_j e^{\beta X_j}} \tag{6}$$

Using maximum likelihood estimation (MLE), β can be calibrated to specify the model.

The logit model (5)-(6) assumes the same parameters for all individuals, which omits the effect of individual heterogeneity. As an extension, the mixed logit (ML) model (Halat et al., 2015; Aziz et al., 2018) can capture the heterogeneity effect by a mixing distribution of β_n with a probability density function f, i.e.,

$$U_{ni} = \beta_n x_{ni} + \varepsilon_{ni} \text{ , } \beta_n \backsim f(\beta) \tag{7}$$

The probability for individual n to choose i hence becomes:

$$P_{ni} = \int \frac{e^{\beta_n X_{ni}}}{\sum_j e^{\beta_n X_{nj}}} f(\beta) d\beta \tag{8}$$

Note that the ML model will degenerate to (6) with $f(\beta) = 1$.

For ordinal output, the ordered logit model can be applied Wasfi et al. (2016) used it to study the relationship between the frequency of walking, low, moderate, or high, and the neighbourhood walkability.

In the case the dependent variable is a count, e.g., the number of walking trips per week (Bödeker et al., 2018), Poisson regression is often used, which assumes the dependent variable is a Poisson distribution, and the logarithm of the expectation can be regressed by the following linear combination:

$$log\, E(Y|x) = log\, \lambda = \beta x \tag{9}$$

Correspondingly, the probability can be written as:

$$P(Y=y|x)=\frac{\lambda^y}{y!}e^{-\lambda}=\frac{(e^{\beta x})^y}{y!}e^{-e^{\beta x}} \tag{10}$$

One limitation of Poisson regression is that the conditional standard deviation σ is fixed and equal to the conditional mean λ. It is likely to under- or over-estimate the dispersion of the sample. On top of (9), the negative binomial regression may be used by introducing another parameter τ:

$$E(Y|x)=\tau\lambda=\tau e^{\beta x} \quad \Rightarrow \quad P(Y=y|x,\tau)=\frac{(\tau e^{\beta x})^y}{y!}e^{-\tau e^{\beta x}} \tag{11}$$

where τ follows Gamma distribution (θ,θ) with $E(\tau)=1$ and $D(\tau)=\frac{1}{\theta}$. Then the probability becomes:

$$P(Y=y|x)=\frac{\Gamma(\theta+y)\theta^{\theta}(\tau\lambda)^y}{\Gamma(y+1)\Gamma(\theta)(\tau\lambda+\theta)^{\theta+y}} \tag{12}$$

Compared to the Poisson regression, the negative binomial regression has a higher degree of freedom, making it more flexible and precise to characterize the dataset.

In walkability analyses, the dependent variable may involve a large proportion of zero counts, i.e., no walking trip (Cruise et al., 2017; Huang et al., 2019). The zero counts comprise two cases, namely certain zero and uncertain zero. Excessive counts of zero can bring severe prediction errors to the analysis results. To address this, the zero-inflated negative binomial (ZINB) regression model is designed to characterize such over-dispersed data. For each observation, the ZINB model consists of two processes: (I) a binary model is generated separately for the certain zero with the probability π; (II) the negative binomial distribution $g(x)$ is generated to predict the remaining uncertain zero. That is:

$$y_i \sim \begin{cases} 0, & \text{with the probability } \pi_i \\ g(y_i), & \text{with the probability } 1-\pi_i \end{cases} \tag{13}$$

Note that process (II) can also generate zero, so the probability of $Y=y_i$ given x can be written as:

$$P(Y=y_i|x)=\begin{cases} \pi_i+(1-\pi_i)g(y_i=0), & if\ \ y_i=0 \\ (1-\pi_i)g(y_i), & if\ \ y_i>0 \end{cases} \tag{14}$$

The ZINB model serves as an extension and degenerates to (12) if $\pi = 0$. It is necessary to conduct summary statistics to check if the dataset is over-dispersed before applying the ZINB model.

Additionally, hierarchical analyses were reported in the literature, such as multi-level linear regression (Owen et al., 2007; Clark et al., 2014), decision tree analysis (Keyvanfar et al., 2018), and analytical hierarchy process (Ruiz-Padillo et al., 2018; Golan et al., 2019). These approaches first arrange the items into various layers which are then analysed and interpreted, respectively.

3.3.2 Unsupervised learning

Unlike supervised learning dealing with labelled data, unsupervised learning is a group of approaches that investigate the dataset with no pre-existing label or tag. It is to study the similarities and dissimilarities across the dataset. For this purpose, two main approaches have been developed, namely principal component analysis (PCA) and clustering method.

PCA is a shrinkage method that reduces the dimensionality of datasets and increases interpretability while minimizing information loss. This approach first identifies the latent variables based on measured variations and then condenses correlated items into a smaller set of new independent variables. PCA has been widely adopted (Christiansen et al., 2014; Park et al., 2015; Lindelöw et al., 2014, 2017) to extract variables that represent pedestrian behavioural responses and facilitate further exploration.

Clustering is to group the items such that components in the same cluster are more closely related to each other than to those in different clusters. Jeffrey et al. (2019) employed clustering analysis to explore 230 train stations in Melbourne and cluster them into three groups, i.e., the most, intermediate, and least walkable stations. They showed which stations were fit for transit-oriented development (TOD). Borner et al. (2018) conducted the latent profile analysis (LPA), a probabilistic model for clustering, to identify specific groups of pedestrians based on their accumulation of physical activities across different locations.

3.3.3 Summary remarks

Instead of a comprehensive review, Section 3.3 focuses on the viable approaches that establish the associations between supply-side walking attributes and their demand-side effects. These descriptive models serve as methodological foundations to facilitate the development of prescriptive analytics to enhance walkability performance.

4 Prescriptive perspectives

Realizing the joint effects from both the supply and demand sides, this section investigates the benefits generated from walkability enhancement and prescriptive approaches taken by different stakeholder groups for conceiving and developing strategies to enhance walkability. We first list four types of walkability benefits, then specify stakeholders including non-governmental organizations (NGOs) representing special pedestrian groups, government, and the private sector in the planning process, and summarize useful prescriptive analytics for walkability improvement.

4.1 Benefits of enhanced walkability

Enhanced walkability will not only have impacts on individual behavioural preferences as in Section 3.1, but also can bring about various benefits to the system or society, as summarized in four aspects below.

4.1.1 Health or well-being

Studies have investigated the impacts of the built environment on health, such as the body mass index (BMI), cardiovascular disease, diabetes, and so on (e.g., Sallis et al., 2012; Alfonzo et al., 2014; Braun et al., 2016). It is often conjectured that a walkable neighbourhood can increase physical activities, leading to better health or well-being.

4.1.2 Environmental benefit

As a green transport mode, Frank et al. (2006) stated that improved walkability could divert people from driving to walking, thereby reducing vehicle mile travelled (VMT), emissions, and air pollution.

4.1.3 Economic value

Walkability is considered to be a factor that would influence real-estate prices. However, it remains unclear whether real-estate prices are directly related to walkability, as walkability is often highly correlated with other factors, such as mixed land use and open space density that may also affect real-estate prices (Boyle et al., 2014; Yang et al., 2018).

4.1.4 Social impact

Walking can strengthen social cohesion through enhancing face-to-face interactions (van den Berg et al., 2017) and familiarity (Battista and Manaugh, 2018, 2019), which, in return, help the government gain support and start a virtuous circle to develop a more walkable community to encourage walking.

4.1.5 Summary remarks

All these benefits from enhanced walkability greatly motivate policymakers, typically the government, to strive for a more walkable neighbourhood. Despite the conjecture that a higher level of walkability would generate greater benefits, we should point out that the causality behind deserves more rigorous in-depth analysis. For example, self-selection bias may exist when studying health issues from walkability. Physically active residents are likely to prefer a more walkable area and have a healthier lifestyle. Such bias should be carefully addressed (Mokhtarian and Cao, 2008). Similarly, Talen and Koschinsky (2013) criticized that the correlation between walkability and social benefits was weak, and Boyle et al. (2014) found insignificant relationships with real-estate prices after controlling for heteroscedasticity and neighbourhood effects.

4.2 Stakeholder groups

A walkable environment certainly benefits pedestrians. However, enhancing walkability involves a trade-off between cost and benefit to different stakeholders. Through identifying three stakeholders, (I) NGOs representing pedestrians with special needs, (II) government, and (III) the private sector, we summarize their roles in walkability planning.

4.2.1 Special pedestrian groups

Most studies consider pedestrians in general as one group without distinguishing their characteristics. However, pedestrians with distinct backgrounds may have diverse concerns about the walking environment, and hence may respond differently. As Barnes et al. (2016) pointed out, pedestrian walking patterns may vary with age, especially among children and the elderly. For example, children deserve special attention, as they need to be accompanied by peers or adults to complete their trips (Barnett et al., 2019). Besides, studies on children between 10-13 showed that there existed child-specific characteristics in their routes, modes, and destination choices (Moran et al., 2015, 2018; Williams et al., 2018).

There are also studies on the walking behaviour of the elderly (Cunningham et al., 2005; Loo and Lam, 2012; Ståhl et al., 2013). With limited mobility or a slow walking pace, they need special design in the walking environment. Yun (2019) reviewed environmental factors that were related to their walking behaviours. Similarly, people with disabilities also require special attention, especially for facilities to overcome elevation or slope. Schreuer et al. (2019) discussed the daily activities of people with various levels of disabilities, including physical and mental. Prescott et al. (2020) characterized the factors affecting their walking or wheeling in a community.

Importantly, special walkability planning should be incorporated to accommodate concerns from various pedestrian groups for universal access. NGOs, representative of certain special groups, play a critical role in the planning process. Not only should they perform a variety of service and humanitarian functions to special pedestrian groups, but also bring their concerns to and work with policymakers for enhancing enhancement.

4.2.2 Government

As the primary decision-maker, government conceives and develops policies and projects to enhance walkability. Enhancing walkability fosters a greener and more walkable city, provides a comfortable environment for citizens, and increases their well-being. In return, this helps the government gain support and recognition from the residents, starting a virtuous circle.

Walkability planning should be an integral part of land use planning because pedestrians have different preferences of supply-side walking environment for their trips to different activities or destinations (Millward et al., 2013). Guo and Ferreira (2008) applied DCM to pedestrian route choice and found significant differences in the weighted coefficients of attributes between work and non-work trips. Chan et al. (2019) compared the walking patterns for different types of trips including: work/school, leisure/recreation, and household responsibility; such factors should be duly considered following the type of land use to enhance walkability.

However, enhancing walkability inevitably will require government expenditure, which requires cost-benefit analysis (CBA) for justification in the planning process. While estimating the benefit of walkability is non-trivial and essential, estimating the cost of walking infrastructure improvement is routine for civil works. CBA will facilitate the government to decide which part of and to what extent the walking facilities, as summarized in Section 2.1, should be investigated. Decisions by the government are not limited to the constructions of walking infrastructures, but also planning policies and incentives that can encourage more walking, e.g., the Hong Kong government proposes 'Fitness Walking' scheme [4] where they offer useful walking information including proper fitness posture, calorie calculator, recommended walking tracks, etc.

4.2.3 Private sector

The private sector is another stakeholder since walkability can affect commercial values such as real-estate prices and rental fees. A pleasant walking experience will attract more walking trips, a higher pedestrian flow, and hence a larger customer base, which will increase the

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[4] https://www.lcsd.gov.hk/en/sportforall/common/pdf/fitness_en.pdf

property value of retail shops. On the contrary, in residential areas, this may induce overcrowding, which may bring discomfort to residents and hence lower the housing prices. Besides, rather than simply as the recipient of walkability outcomes, the private sector is also a main player in the planning process. They can actively participate and work with the government to develop various options for a walkable neighbourhood that benefits all stakeholders.

4.2.4 Summary remarks

The roles of pedestrian groups and government as stakeholders in walkability planning have been well examined by the literature, while studies looking into the roles of the private sector are limited, perhaps due to lack of adequate data or successful case studies. Enhancing neighbourhood walkability is beneficial to each stakeholder group: pedestrians (health or well-being), government (environmental benefits and social impacts), and the private sector (economic values). Therefore, it is worth investigating how stakeholders may collaborate to bring about a more walkable community. For example, developing footbridges linking neighbouring commercial buildings with shopping arcades, paid and maintained by the private sector and approved or encouraged by the government via certain land-use policies, will improve the walkability in this cluster of commercial buildings, bring convenience to pedestrians, increase the pedestrian traffic among the shopping arcades and hence their rental values, reaping win-win-win benefits to all those involved.

4.3 Prescriptive approach

This section summarizes approaches developed to prescribe optimal decisions or policy interventions by providing predicted outcomes to stakeholders about their decisions. Three types of prescriptive approaches are commonly adopted, namely intuitive, case-based, and model-based approaches.

4.3.1 Intuitive approach

The intuitive approach, aka qualitative approach, is a common way of decision-making based on intuition or empirical experience. It provides an intuitive basis that is consistent with our expectations in the planning process and hence easy to conduct.

In the early decades with limited data, many policy interventions were developed based on the intuitive approach. For instance, the SPACE assessment framework by Pikora et al. (2003) was developed according to a Delphi study, which was a decision-making process using the results from questionnaires sent to a panel of experts. Ståhl et al., (2008) came up with policy interventions to enhance walkability in the outdoor environment through enquiring the elderly and involving them in the cooperative planning process. The followed-up study (Ståhl et al., 2013) showed that the overall appreciation of that walking environment was indeed improved.

This is a popular approach since it represents the opinions and concerns directly from stakeholders. Integrating their intuitions or opinions makes the policy more widely recognized and accepted. Including intuition or stakeholder opinion plays a significant role in the decision process; however, by intuition alone, the process may bring serious errors due to insufficient consideration, oversight, prejudices, and lack of openness and sufficient representation in opinion collection.

4.3.2 Case-based approach

With diverse data available and successful case examples, policymakers can apply the case-based approach to tackle new problems by adapting previously successful solutions to similar or past problems. In the forms of cross-sectional and longitudinal analyses, this approach can produce policies to augment the approach based on intuition.

Cross-sectional analyses have been widely applied in walkability studies (Adlakha et al., 2016; Christiansen et al., 2016; Moran et al., 2018; Barnett et al., 2019). The comparisons of cases among different areas with high/low walkability and/or socio-economic status provide useful insights for policy interventions. By making analogy or association with similar cases, the planning process can be more comprehensive and avoid the omission of important considerations.

Longitudinal analyses are useful to learn about how cases evolve. For instance, to study the outcomes of walkability on health, Braun et al. (2016) applied the fixed effect (FE) model, which was adjusted for time-varying covariates, and random effect (RE) models, which were adjusted for both time-varying and time-invariant characteristics. Marquet et al. (2017) applied the difference in differences (DiD) method to study not only cross-sectional but also longitudinal impacts of walkability on residents in Barcelona. Badland et al. (2017) conducted longitudinal studies to testify the outcomes of 14 walking policies in Australia. In the transportation context, however, these studies were not strictly longitudinal in nature since the residents, as well as the environment, would inevitably change over time. Nevertheless, studies over periods or before and after specific policy implementation can offer insights to guide future planning. Besides, Hauer (1997) reviewed feasible approaches for conducting before-and-after studies.

4.3.3 Model-based approach

The model-based approach uses a quantitative framework to provide more accurate estimates of the planning outcomes under different circumstances. The guide book by Kuzmyak et al. (2014) recommended the facility-based models considering the facility volume in the supply-side environment and the choice-based models concerning the four-step transport planning perspective for estimating walking for planning and project development. By modelling pedestrian behaviours under specific conditions, model-based approaches can simulate the results of certain policy interventions and accordingly generate the optimal model outputs for walkability planning.

Clifton et al. (2016a) were among the first to use a model-based approach to analyse destination choice of pedestrians. Figuring out the determinants of their choices offers inference for enhancing walkability. Clifton et al. (2016b) introduced an enhanced four-step pedestrian framework to model walking activities by simulating the walking patterns under different planning scenarios and evaluating the effectiveness of the policies to be implemented. Erath et al. (2017) proposed a pedestrian accessibility tool (PAT) based on link accessibility. By calibrating the model with RP experiments, the PAT depicts the performance of the current network and that of a future plan on walkability changes.

Taking into account the interactions between policy decisions and pedestrian behaviour responses, the model-based approach is a useful planning tool to identify fit-for-purpose policies or improvement schemes, while balancing benefits and costs. In the context of transport planning, this type of model-based approach is often referred to as the network design problem (NDP), which can be formulated as a bi-level mathematical program. Even though the development of NDP formulations for vehicular or motorized traffic has been around for a long while (e.g., Lo and Szeto, 2009; Lo et al., 2013), its formulation and application for pedestrian traffic is rare. In an NDP formulation, the lower-level captures the equilibrium travel choice of travellers, whereas the upper-level determines the optimal planning decisions, such as the infrastructure improvement scheme, so as to optimize an objective function, such as minimizing the overall travel disutility. Such an approach can be readily extended for pedestrian traffic or for the optimal joint planning between vehicular and pedestrian infrastructure.

4.3.4 Summary remarks

Most existing prescriptive approaches for walkability enhancement are based on the intuitive and case-based approaches; few are based on the model-based approach, even though it is much more rigorous. With more advanced descriptive models developed and calibrated with data, the model-based approach is promising if it is suitably designed and integrated into the transport planning process. Actually, while the transportation network design problem is common for vehicular traffic and accordingly formulated, it has yet to be the case for pedestrian traffic. The review sees the big gap of incorporating walkability planning as part of formal transport planning, which can be formulated as a bi-level optimization problem, in which the upper-level is to maximize certain walkability performance measures or benefits and the lower-level represents pedestrian behavioural responses in a multi-modal transportation network, inclusive of both walking and other mode choices.

5 Concluding remark and future research directions

This paper reviewed and summarized the walkability literature in three aspects: (I) attributes of the walking environment and facilities, and their measurements and assessments, which can be considered as supply-side analyses in transport planning; (II) behavioural responses and approaches to model their associations with the built environment, which can be considered as demand-side analyses; and (III) the prescriptive perspectives by stakeholders for walkability improvements by considering both supply-side and demand-side effects with specific aims and proper tools. We note that significant progress has been achieved on walkability studies in the recent past, which lays a solid foundation for extensions and supports the planning for a walkable city in practice. In what follows, we expose some key challenges yet to be tackled and identify potential research directions.

5.1 Further investigation of walking facility attributes

Walking facility attributes, as reviewed in Section 2.1, are essential supply-side elements for walkability planning. Although their importance has been recognized, our taxonomy in Figure 2 indicates several research gaps in the studies of some specific attributes.

Firstly, elevated facilities that separate pedestrians from vehicular traffic flow deserve further study. For example, footbridges can protect pedestrians and lower the risk of traffic accidents while improving the efficiency of both vehicular and walking trips. The integration of footbridges that jointly connect the adjacent junctions can also increase network connectivity and establish an accessible neighbourhood. Secondly, indoor coverage is worth investigating since it brings comfort to walking while mitigating the negative impacts of certain uncontrollable factors, e.g., heavy rain and ultraviolet radiation. Thirdly, it is important to study how the use of emerging technologies and smart facilities, such as E-map apps, 3D models for indoor navigation, and sensors to provide real-time information, would enhance walkability, making the walk trips more convenient and enjoyable. Fourthly, facilities subject to opening hours, such as restaurants and shopping booths, can affect the walking demand and route choices during different times of a day. Gathering such dynamic walking patterns, i.e., morning/evening and peak/off-peak periods, will facilitate better walkability planning.

5.2 Making use of emerging technologies and methods for measurement

The measurement approaches categorized in Section 2.2 are useful to characterize the walking environment. Devising new measuring approaches with the use of emerging technologies, such as portable devices for tracking and drones for remote sensing, with convenience and accuracy deserves further study. There is also a need to develop AI image recognition algorithm to characterize facility attributes from videos, such as road width, slope, traffic and pedestrian volume, etc.

5.3 Developing comprehensive assessment of walking environment

Through capturing certain physical attributes of the infrastructure that are considered to have potential impacts on pedestrian behaviours, walkability indices have been developed to reflect the quality of walkability of an area. As mentioned in Section 2.3.3, by using walking facility attributes alone, however, such assessments tend to overlook or oversimplify pedestrian behavioural responses, which are at the crux of walkability analyses. Future studies may develop composite walkability indicators by jointly considering both the physical infrastructure and topological information from the supply side and pedestrian behaviours from the demand side. With the ability to accurately reflect the level of walkability, a comprehensive indicator is of great importance for planning improvement schemes.

5.4 Effective collection and utilization of pedestrian behaviour data

RP and SP are two survey types commonly used to estimate pedestrian behaviours, with their characteristics summarized in Section 3.2, respectively. SP surveys can capture behavioural responses to a future project under planning, while RP surveys capture actual pedestrian behavioural responses or choices under the current situation. The difference between RP and SP survey data is well recognized, yet there is limited published work on combining SP and RP data in a coherent, consistent, and rigorous manner (Bhat and Castelar, 2002; Hensher, 2008). To overcome this limitation, future studies can focus more on data enrichment, i.e., the process of merging RP and SP data while ensuring their consistency.

In addition, with more data sources available, pedestrian choice modelling in the future should make use of big data, e.g., proximity data from Wi-Fi routers, telecom base stations, or Bluetooth receivers and location data from GPS devices (van Oijen et al., 2020). Big data greatly reduce the costs of data collection but miss the specificity of the counts and may contain a lot of noise. Integrating big data and complementary well-structured data from basic surveys will be very useful to improve the explanatory power of behavioural modelling.

5.5 Developing walkability benefits analysis

Current studies indicate that walkability may be positively associated with several benefits as reviewed in Section 4.1. While substantial efforts have been spent on health and environmental benefits, research on social impacts is limited. In particular, the following aspects about the impacts of walkability deserve further investigation, including changes in socioeconomics, demographics, social cohesion, and support for government proposals. Besides, the problem of self-selection bias exists in the relationship between walkability and its benefits. Specifically, respondents who participate in more (fewer) physical activities may prefer to live in a highly (less) walkable neighbourhood. Future research should provide more insights to explain to what extent the generated benefits can be attributed to the built environment itself versus residents' prior self-selection. Rigorous analyses with sufficient granularity to eliminate self-selection bias can better reveal the relationships and thereby avoid over- or under-estimation of projected benefits in the planning process.

5.6 Refining descriptive models

Section 3.3 reviewed studies that established the relationships between supply-side walking attributes and demand-side effects. With advanced measurement methods aided by drone video and AI image recognition algorithms, detailed walking facility attributes can be captured on a broad scale, which will facilitate supply-side analyses in a more refined way. However, including more features or attributes will inevitably make the resultant models more complicated. Therefore, data feature extraction and how to select influential attributes or variables to balance between prediction accuracy and model complexity are worth studying. Moreover, similar to vehicular congestion, i.e., travel time is related to traffic volume, pedestrian crowdedness effect, i.e., how its utility measure varies with pedestrian volume, can be enhanced to better model the walking choice. Developing more refined descriptive models is necessary since they will be an essential part of prescriptive models to predict the outcomes of walkability enhancement.

5.7 Modelling stakeholders' perspectives

Better walkability is beneficial to all stakeholders in the neighbourhood, as stated in Section 4.1, save for the issue of who will be paying for the expenditures of walking facility improvement, most likely the government. Even then, public expenditure must be properly accounted for and justified. While some studies have examined the benefits of walkability, few have conducted proper benefit-cost analysis, as in an engineering project, to ensure the cost-effectiveness of improvement projects. Studies to quantify the value of walkability improvement constitute an important part to facilitate walkability planning.

Moreover, the fact that all stakeholders are beneficiaries makes it possible for them to develop collaborative partnerships for walkability enhancement. For example, pedestrian NGOs can provide user group data, needs, and preferences, while the private sector can offer financial and technical support (especially for facilities connecting to their commercial canters or shopping arcades), while the government coordinates and encourages the improvement schemes for a more walkable community. Such studies are generally missing, especially in uncovering the perspectives of private sector, which deserves future investigation. A collective and efficient partnership to build win-win or even win-win-win situations is of great importance for both research and practical value.

5.8 Development of prescriptive models

From the prescriptive perspective, walkability enhancement is regarded as a planning problem that looks for optimal decisions under limited resources. However, to solve this problem, other than the intuitive and case-based approaches, it is surprising to find that few are based on a model-based approach as reviewed in Section 4.3. In the transportation context, advanced bi-level formulations for the network design problem (NDP) have been developed for vehicular transport planning, but not for walkability planning. Conceptually, such formulations can be readily extended to include pedestrian traffic either through a multi-modal network approach or an agent-based approach. In an NDP formulation, the lower level captures the pedestrian choice behaviours so that any modification of the network can be reflected in the model; whereas the upper level finds the optimal planning decisions, such as identifying the location or type of infrastructure improvement, so as to maximize an expected objective, e.g., the overall pedestrian walking utility or accessibility of a neighbourhood. This type of prescriptive model will provide an objective basis to facilitate the planning process.

5.9 Incorporating walkability into formal transport planning

Currently, transport planning practice tends to undervalue walking (Litman, 2018), with the emphasis primarily on motorized trips. Such orientation gives rise to vehicle-driven transportation policies and strategies, leaving little room for improving walkability in formal transport planning. This review sees the big gap of incorporating walkability planning as part of formal transport planning. Inclusion of walkability planning needs to consider the entire trips of individuals, from end to end, including any walking trips for access or transfer between segments. This will fundamentally change the predominant trip-based approach, where the walking segments are ignored, and will call for an agent-based and activity-based planning approach. There is a strong need to demonstrate the inclusion of the walking choice in a multi-modal network through an agent-based and activity-based approach. Such an effort is so far missing in the literature and is essential if walking is to be incorporated in formal transport planning.

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