Walkability and connectivity: unpacking measures of the built environment

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Abstract

The creation and replication of walkability indices uses geographic information systems (GIS) and warrants exploration of assumptions made implicit by different research disciplines. Most methods of measuring walkability variables – residential density, street connectivity, and land-use mix – lack contextual rationale for inclusion in walkability indices. Furthermore, walkability indices used in contemporary literature themselves are in conflict not only with each other, but also with human spatial behavior. This thesis first compares three walkability indices to make explicit the various ontologies that result as a consequence of choices and calculation of walkability variables. The second article then explores ontological distinctions between connectivity measures and their subsequent effects on methodology and interpretation. Given non-linear patterns of human mobility in activity spaces, this last part explores granular scales of connectivity measures that can better represent the built environment.

Keywords: walkability; connectivity; built environment; methodology; ontology

Acknowledgements and Dedication

This thesis is dedicated to my beloved grandpa, my nanu, who passed away before the completion of this degree. Although far from me, he always supported me through every academic undertaking and believed in me throughout. He was an avid walker, the fastest in our family, even in the last of his days.

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Chapter 1.

Introduction

A report published by Smart Growth BC studied the relationship between objective and subjective walkability, and health outcomes in 16 communities from British Columbia and concluded that the built environment did indeed have a significant impact on some health outcomes and physical activities (Tomalty & Haider, 2009). This was the first report that had explored the effects of the built environment on health for British Columbian residents across various municipalities. Indeed, walkability has been studied by diverse academic disciplines and government departments especially with the rise of research on the health effects of urban sprawl (L. Frank, Engelke, & Schmid, 2003; Frumkin, Frank, & Jackson, 2004). This research has given wind to much exploration of the factors of the built environment that can facilitate healthier communities, such as land-use mix (Christian et al., 2011; L. N. Oliver, Schuurman, & Hall, 2007; Ozbil, Peponis, & Stone, 2011), connectivity (Berrigan, Pickle, & Dill, 2010; Tal & Handy, 2012), residential density, access to transportation (Buck et al., 2011; Glazier et al., 2014), proximity to parks (Abildso, Zizzi, Abildso, Steele, & Gordon, 2007), and more subjective or perceived facilitators such as presence of sidewalks, safety, aesthetics (Feuillet et al., 2015; Neckerman et al., 2009; Zhu & Lee, 2008), and many more.

In the last decade, researchers have noted various limitations of ‘objective’ walkability methodology. Some have pointed out the uncertainty in defining the most relevant or geographically representative neighbourhood of a pedestrian (Boone-Heinonen, Popkin, Song, & Gordon-Larsen, 2010; Ding & Gebel, 2012; A. V. Moudon et al., 2006; Spielman, Yoo, & Linkletter, 2013), showing the range of ‘neighbourhood’ definitions that can operate walkability indices. Those who have explored specific definitions of neighbourhood areas have asked at which spatial unit the built environment can most accurately represent the daily activity spaces and better explain physical activity levels, whether it be buffers (James et al., 2014; L. N. Oliver et al., 2007) or administrative boundaries (Berke, Gottlieb, Moudon, & Larson, 2007; Diez Roux & Mair, 2010). Other researchers have commented on the specific calculations of walkability variables and their risk of miscalculation or misuse (Hajna, Dasgupta, Joseph,

& Ross, 2014; Knight & Marshall, 2015; Song, Merlin, & Rodriguez, 2013), or the pre-conceived assumptions upon which walkability indices are built (Andrews, Hall, Evans, & Colls, 2012; Yang, Shoff, & Noah, 2013) bringing attention to the subjectivity of researchers in objective walkability.

The necessity of geographic information systems (GIS) in quantifying the built environment makes various geographic problems inevitable and requires interdisciplinary conversation on solutions. GIS is growing as the common language that walkability researchers from various disciplines communicate in, and data interoperability is a crucial component of objectively measured GIS-based walkability studies. Indeed, several studies concerning themselves with the built environment are limited by not only the definitions of the variables (Brownson, Hoehner, Day, Forsyth, & Sallis, 2009), but also the ways in which these definitions are recorded in the data itself. Schuurman and Leszczynski (2006) use land use data as an example of how two dataset for the same area but from different sources can create interoperability issues if the classifications are mismatched; their analysis would each result in different scores. Ellis et al (2016) show how a variety of connectivity measures result in different connectivity scores, and indeed say very different things about the same street network. However, data interoperability is not the only issue in GIS.

Walkability is a quantification of the ability of the built environment to support physical activity. In so doing, it seeks to explain a relationship between the built environment and human behaviour, an erratic unbounded and nonlinear human capacity. However, the current norm of human research occurs at the policy-relevant spatial unit. This scale, although most necessary for policy-makers and planners, is not able to fully capture the extent to which the built environment influences human behaviour. In fact, many geographers and planners have called for a more human scaled study design that better accounts for the trajectories, spatial and temporal, that humans move through rather than politically drawn units, such as census boundaries or neighbourhood boundaries used by policy analysts and city planners (Kwan, 2009, 2016; Peponis, 2016).

The usage of geographic information systems in the creation of walkability indices warrants recognition of the ontology – or design and language of creation and formulation – of these indices. Definitions of GIS variables and the term ‘walkability’ itself, while initially classified by each discipline that played a role in their creation, now permeate disciplinary boundaries as they seek interoperability. Indeed, the crux of the first part of this thesis is that the definitions of walkability and each of the variables that are included in composite indices have a significant influence on the methodology used to quantify the variables. The smallest difference in numerator or denominator in these variable calculations can result in a value that can grossly misrepresent or lead to alternate interpretations.

This is most obvious in connectivity measures since they are often confused with proximity or accessibility measures (Tal & Handy, 2012). The complexity of the street network is thus filtered into a singular measure of connectivity that becomes representative of several functions that are fulfilled by the street network. In this way, the street network acts as a grid upon which activity spaces are configured and through which travel occurs. As a measurement of the planar street network, connectivity represents the dimension upon which other walkability variables exist. For this reason, the second part of this thesis understands the effects of ontological differences on results and interpretation solely in connectivity measures.

This thesis is organized into four chapters. The first provides a brief introduction to the literature that informs this work as well as an outline of the thesis; the second makes the implicit assumptions of walkability indices explicit by unpacking the definitions and methods of calculating the walkability variables; the third explores the ontological differences in connectivity measures by measuring and comparing them in a single study area; and, the final chapter briefly concludes by outlining the contributions to walkability and the built environment literature.

Chapter 2.

What is walkability and how do we measure it: unpacking assumptions of major indices

2.1. Abstract

The use of geographic information systems in the creation and replication of walkability indices warrants exploration of assumptions made by different research disciplines that are made implicit. This article makes these ontological assumptions more explicit by examining multiple definitions of walkability and how these, in turn, shape the methodologies included in the calculation of walkability scores. This article compares three walkability indices in Vancouver, Canada based on methods used by each index and the resulting variations in walkability scores. Although there were common walkability scores across some central neighbourhoods, differences in scores were notable in neighbourhoods with moderate to low walkability and were most stark when classified differently than their original classifications. Most calculations of walkability variables – residential density, street connectivity, and land-use mix – lack contextual rationale for inclusion in walkability indices. Many of the walkability indices used in contemporary literature are in conflict not only with each other, but also with human spatial behavior. This article calls for greater detail, explanation, and skepticism when constructing methodologies and interpreting the resulting walkability indices. We argue that, as geographers, it is important to explore the impact of variable selection and methodologies on walkability indices in the interests of exposing methodological inconsistencies and implicit assumptions.

2.2. Keywords

built environment; walkability; methodology; ontology; geographic information systems

2.3. Introduction

A rapid growth in obesity and related diseases over the last few decades (World Health Organization, 2017) has led to the consideration of the effects of the built environment on health among public health and urban planning researchers. While public health researchers have aimed to understand the correlation between the built environment and physical activity, as an accessible mediator of health outcomes, urban planners have aimed to understand the effects of the design and configuration of the built environment to increase pedestrian flow and accessibility. Studies on walkability have proliferated beyond just public health concerns to exploring correlations with urban economic viability, and housing marketability.

The methods utilized to measure walkability for these diverse purposes involve the creation or replication of composite walkability indices that can compute the collective effects of various aspects of the built environment using GIS. These aspects, or index variables, range from considering the mix of land-uses and multiplicity of routes to the spectrum of human perception and behaviour. Indeed, studies have shown that measures of singular aspects of the built environment are not as robust as indices when exploring these correlations (L D Frank et al., 2010; Eva Leslie, Cerin, DuToit, Owen, & Bauman, 2007). However, as we will show in this article, the language or ontology of defining and measuring variables in an index bring potential for disparate results and subsequent misinterpretations.

To explore the ontologies of walkability indices, this article has three objectives. First, to provide a summary of what walkability is by reviewing definitions offered in contemporary literature, and of the various methods that have resulted from these definitions. Second, to describe the variation in outcome that results from application of these methods to a study area, namely Vancouver, Canada. Third, to outline some of the ontological assumptions made by current walkability indices and ways they can be addressed.

2.4. Background

2.4.1. Why care about definitions?

The usage of geographic information systems in the creation of walkability indices warrants recognition of the ontology – or design and language of creation and formulation – of these indices. Definitions of GIS variables and the term ‘walkability’ itself, while initially classified by each discipline that played a role in their creation, now permeate disciplinary boundaries as they seek interoperability. The saturation of ontology across disciplines is a natural step towards interoperability in classification, and is thus a part and parcel of the creation of boundary objects that seek to bridge perspectives from different groups of researchers (Harvey & Chrisman, 1998). However, boundary objects are ontologically invented and reinvented as research goals and dynamics evolve with the introduction of new research claims and discoveries, even though they seek a protocol of operationalization. Particularly for GIS-based walkability databases, mediation of ontology between groups is contextually lost in variable data (Schuurman & Leszczynski, 2006).

Indeed, walkability variable databases are then forced into black boxes that conceal contextual information from researchers by making the foundation of these indices and their supporting variables implicit. Instead of explicitly stating assumptions at the semantic level of the variable data, it is stated at the disciplinary level of the researcher (Andrews et al., 2012), thereby offering an avenue of tacit knowledge sharing (Collins, 2001). However, this level of knowledge is ineffective in disseminating contextual information about the data, and remains black boxed. Understanding the foundations of walkability and its GIS application requires the implicit to be made explicit. For example, to make permutations of Frank et als walkability model relevant rather than fitted, implicit assumptions within the data must be made explicit.

Whether walkability is defined as a feature, function, mediator, or proxy plays a significant role in the creation of its composite measures: the selection and measurement unit of variables, the statistical analyses conducted, and the interpretation of observed associations between place and health. These choices are the building blocks upon which an ontological framework of walkability is defined and through which the researcher's assumptions are expressed. Ultimately, what we describe as the walkability of a neighbourhood is shaped by the built environment. This is an important distinction between cause and effect that helps us understand the variables chosen and the methods used to calculate walkability (Coffee, Howard, Paquet, Hugo, & Daniel, 2013).

2.4.2. What is walkability?

To answer this question, we begin by exploring the conception of the term. The resulting architecture of urban sprawl has created environmental barriers to the most readily accessible of all types of physical activity: walking and bicycling (Frank, Engelke, & Schmid, 2003). In their analytical work on the relationship between the built environment and physical activity, Frank et al combined aspects of urban design and public health. Soon thereafter, Frumkin et al related urban sprawl to public health issues, bringing together the disciplines of social epidemiology with urban planning (Frumkin et al., 2004). Together, these two books summarized the health and built environment research of the late 1990s and early 2000s, while facilitating further inquiry into the effects of various features of the built environment on an array of health issues, such as cardiometabolic risk, coronary heart disease, and obesity.

Although their research was an integral part of the literature on the relationship between public health and the built environment, it is important to note that it wasn't a novel finding until their conception of the term, 'walkability'. The pioneering investigators of walkability offered conceptual definitions unique to their disciplines and developed methods of measuring it in the built environment (L D Frank, Schmid, Sallis, Chapman, & Saelens, 2005; E Leslie et al., 2007; A. V. Moudon et al., 2006; Saelens, Sallis, & Frank, 2003; Sallis, 2009). Alongside Frumkin et al's broader connection of the urban form – all the natural or built aspects of the city, affected by planning and city governance mechanisms – to public health outcomes, experienced or pathological (Frumkin et al., 2004), Frank et al contextualized the effects of one specific aspect of the urban form, the built environment, on public health (Frank et al., 2003).

While the current definitions of walkability all point to the conduciveness of the built environment to walking, these are all vague in their construct of who the pedestrian or walker is and their needs (Lo, 2009), and often cater to ingrained methodologies of quantifying the built environment (Coffee et al., 2013). As a result, many researchers have distinguished between the kinds of physical activity that they are considering in their walkability research: walking for transport, or walking for leisure and/or recreation (Brownson et al., 2009). These different needs for walking are represented in indices by way of variable weights: connectivity between work and home would be weighted higher in consideration of transport purposes, whereas, proximity to parks and trails would be weighted higher for leisure or recreational purposes. It is in these distinctions that we see that definitions of walkability are indeed important and reflect the selection and weighting of variables (Table 1).

Table 1. Examples of definitions of walkability used to select variables for indices in current literature.

Definitions	**Variables**
the ability of the urban form to impact travel and activity patterns of pedestrians (Frank et al., 2010)	intersection density, net residential density, retail floor area ratio, land-use mix
"the extent to which characteristics of the built environment and land use may or may not be conducive to residents in the area walking for either leisure, exercise or recreation, to access services, or to travel to work" (Leslie et al., 2007, p. 113)	dwelling density, connectivity, land use accessibility and diversity of uses, net area retail
"a neighbourhood's capacity to support lifestyle physical activity" (Carr, Dunsiger, & Marcus, 2011, p. 1144)	proximity to closest amenity in 13 categories: grocery stores, coffee shops, restaurants, bars, movie theatres, schools, parks, libraries, book stores, fitness centres, drug stores, hardware stores, clothing/music stores
"[v]arious elements of the built environment...widely-viewed as 'walk supportive'" (Coffee et al., 2013, p. 163)	dwelling density, intersection density, land-use mix, net retail area
man-made elements of the environment that positively influence physical activity (Duncan et al., 2014)	intersection density, land-use mix, count of and proximity to recreational open space, residential density, traffic density, average speed limit, sidewalk completeness

Frank et al proposed the first composite walkability index that includes land use mix, connectivity, and residential density within a buffer around a residence (Frank et al., 2005). This definition of walkability describes it as a *function*: a product of all built environment attributes that act as predictors of health. In this way, walkability stands alone, separate from the built environment, but offers a health-oriented representation of it and other types of urban form that might predict physical activity. On the other hand, Leslie et al propose an alternate definition of walkability as a characteristic of the built environment that supports the act of walking (Leslie et al., 2007, p. 113). As a *feature* of the built environment, this definition of walkability represents a quality or characteristic of the built environment that acts as a predictor of health. In so defining walkability, it removes the concept from being used as an absolute representation of the built environment.

These essential, yet under examined ontological distinctions inform the variables that are included in indices (Table 1), the methodology used to calculate the index score per area, as well as the ontology of interpretation utilized by walkability researchers to explain the resulting index scores. This conceptual distinction has informed the direction of the relationship between walkability and physical activity as either a mediator or a proxy (Ann Forsyth, 2015) of the built environment since these indices cannot be proposed as absolute representations.

2.4.3. Definitions create methods

Walkability indices have been created to understand the extent to which the built environment encourages physical activity (Leslie et al., 2007) for various demographics (Villanueva et al., 2014; Zhu & Lee, 2008) and health benefits (Sundquist, Eriksson, Mezuk, & Ohlsson, 2015). Interdisciplinary exploration into walkability has led to a growth not only in the variety of walkability variables, but also in the definitions that are utilized to create methodologies. The way these variables are defined have an impact on the way they are measured. These biases become apparent when variable definitions are passed on from study to study without proper exploration of the applicability of these variables to the context being studied.

Transportation studies conceived of the built environment factors that contribute to walkability, namely, connectivity and proximity (Saelens et al., 2003). Connectivity can be characterized by intersection density, block size, sidewalk continuity or completeness, access to public transportation and neighbourhood planning that allows for gridded streets over cul-de-sacs that don't allow for route directness. Proximity can be characterized by residential density, retail floor area ratio, land-use mix, population density and access to parks and recreational facilities. Table 2 provides an overview of the most prominent walkability variables and their variations. Where studies further differ is on their spatial scale, the limitations of their quantification of some variables, and their sub-variable choices, as we will explore later in this article.

Table 2. A compendium of walkability variables and their definitions and methodological variations in the analysis of objectively measured, or spatially analyzed, walkability indices.

Category	Variables	Definitions	Methods and Variations
Connectivity	**Intersection density**	The number of unique street connections with more than three legs at each intersection per unit area square kilometer in their analysis (E Leslie et al., 2007) A ratio of intersections to total unit area (L D Frank et al., 2010)	Intersections of bicycle and footpaths with streets (Arvidsson, Kawakami, Ohlsson, & Sundquist, 2012)
		Offers a concise definition of an intersection to bring clarity to their international dataset (M. A. Adams et al., 2014)	The total number of intersections with or without traffic lights rather than a ratio (de Sa & Ardern, 2014) .
	Block size	No definition offered	Block size along with two kinds of intersection measures to determine connectivity (Grasser, Dyck, Titze, & Stronegger, 2013).
	Sidewalk continuity/completeness	Sidewalk completeness or existence is measured by the existence of sidewalks on none, one or both sides of the street (Duncan et al., 2014).	A literature review showed a small collection of methods for measuring the availability and accessibility of sidewalks in objective walkability models, including a more common measure of the ratio of sidewalk to road lengths (Brownson et al., 2009) .
	Access to public transportation	No definition offered	The distance to the nearest public transportation service (Feuillet et al., 2015)
			The density of public transportation services in a specified spatial unit (M. A. Adams et al., 2014)
			A kernel density of public transit stops within 1km (Buck et al., 2011)
			The total number of stops within a buffer around the residence (Carr, Dunsiger, & Marcus, 2010)

Category	Variables	Definitions	Methods and Variations
	Route directness	The ratio of the actual to straight distance travelled between two points (Chin, Van Niel, Giles-Corti, & Knuiman, 2008)	An indicator of connectivity (Chin et al., 2008)
		The actual distance travelled as one that followed a street network and calculated the ratio as a median (Duncan, Aldstadt, Whalen, Melly, & Gortmaker, 2011) .	Connectivity measured by intersection density was offered as an indicator of route directness (Boone-Heinonen, Evenson, Song, & Gordon-Larsen, 2010; Frank, Kerr, Sallis, Miles, & Chapman, 2008).
Proximity	**Land-use mix**	Land-use mix has been characterized as "[t]he level of integration within a given area of different types of uses for physical space..." (Saelens et al., 2003, p. 81) . However, some studies have calculated land use mix using three classifications (residential, office, commercial), while others have utilized five (residential, retail, entertainment, office and institutional). Even so, the chosen three or five classifications of land use vary among themselves: while Frank uses the above mentioned five (Frank et al., 2010) , Leslie replaces the 'office' classification for an 'other' (E Leslie et al., 2007). Few have offered definitions for each of these classifications, which can vary at each level of research.	Leslie et al provided a broader political background to the calculation of land use itself (E Leslie et al., 2007, p. 116) and have used the land use and zoning datasets to avoid skewing the land-use mix scores in favor of large vacant lots waiting for development. Furthermore, methods of measuring land-use mix commonly circulate between employing variations of the Herfindahl-Hirschman index (Arvidsson et al., 2012; Eriksson, Arvidsson, Gebel, Ohlsson, & Sundquist, 2012) or the Entropy index (L D Frank et al., 2005; Reyer, Fina, Siedentop, & Schlicht, 2014).
	Residential density	This variable is defined as the raw count of dwellings per unit area zoned for residential use (Saelens et al., 2003) .	The simplest of all the walkability variables, this one hasn't shown much variation in measurement or translation.

Category	Variables	Definitions	Methods and Variations
	Access to parks	Some have defined this as access to parks and some have defined this as proximity to parks, both simply measures of proximity.	In their study of equity in access to parks, Cutts et al discuss the appropriate distance buffer to use when measuring proximity to parks (Cutts, Darby, Boone, & Brewis, 2009) . They further argue that access to parks isn't simply about proximity, but also entails the distribution of park area relevant to population distribution per neighbourhood.
	Access to recreational facilities	In their literature review, Brownson et al found access to recreational facilities to be differentiated between accessibility, or distance to facilities, and intensity, or the count or proportional count of facilities per area (Brownson et al., 2009) .	Interestingly, Brownson et al also include park area in their definition of recreational facilities.
	Retail floor area ratio (FAR)	Retail floor area ratio is a way of describing the density of retail area within the total amount of zoned retail area (E Leslie et al., 2007) . It is a way of determining how accessible retail areas are to the pedestrian.	The variation in this variable occurs when studies don't have access to their municipal government's FAR datasets and must extrapolate that information from land use and zoning data. As mentioned before, each government has it's own way of determining land use classifications and use different definitions for these.
	Population density	Very simply, population density is the ratio of people to the land unit area (Lovasi, Neckerman, Quinn, Weiss, & Rundle, 2009) .	It is possible to measure this as a density within a density weighted by the amount of land area captured within the buffer (Boone-Heinonen, Evenson, et al., 2010).

Rather than study these variables individually for correlation to physical activity, Frank et al proposed a collective assessment of the correlation of these variables to physical activity and other health issues (Frank et al., 2010, p. 925) . These variables have been used in some of the most widely cited indices and walkability studies, including the Physical Activity in Localities and Community Environments (PLACE) study based out of Australia (E Leslie et al., 2007; Eva Leslie et al., 2007), the International Physical Activity and Environment Network (IPEN) study analyzing 12 countries (M. A. Adams et al., 2014), the Belgian Environment Physical Activity Scan (BEPAS) study (Van Dyck et al., 2010), the Frank Walkability Index (Frank et al., 2010), and the multiple contextualized walkability audits and indices created by city governments and planning or health advocates (Charreire et al., 2012; Dygryn, Mitas, & Stelzer, 2010; Millington et al., 2009; Reis, Hino, Ricardo Rech, Kerr, & Curi Hallal, 2013; Yin, 2013). Many of these studies have argued that most American walkability indices have not only the luxury of relying on high quality or relevant data that is often difficult to come across in relatively resource-constrained countries (Charreire et al., 2012; Hanibuchi, Kawachi, Nakaya, Hirai, & Kondo, 2011), but also rely on constructs of the built environment that are particular to an American style of urban planning and living (Reis et al., 2013).

2.5. Methods

2.5.1. Study area

The City of Vancouver, Canada, shown in Figure 1, was chosen as the study area as the built environment is most intimately known to the researchers and can thus be considered within its context. With a population of 603,502 and an area that covers 115 km^2, the City is a growing center for research and practice in urban sustainability and aims to be the greenest city in the world by 2020. The 22 neighbourhoods that cover this partly urban, partly suburban City of Vancouver were utilized as the areal unit for this comparative study. Although Vancouver is categorically an urban city, the typology varies in each neighbourhood, and it is with this variation in typology in mind that Vancouver was chosen as the study area. Data for application of the indices was collected from the City's publicly available Open Data Catalogue (Vancouver, 2017), municipal boundaries created by DMTI Spatial, and public transit data from Translink's General Transit Feed Specification (GTFS) Data (Translink, 2017).

Figure 1. **The City of Vancouver neighbourhoods displayed by area. The total land area of the spatial unit plays an important role in all variables that add up to the final walkability score. While Kensington-Cedar Cottage, Renfrew Collingwood and Hastings-Sunrise cover a higher land area, they also normalize the intersection or residential counts in density calculations. In order to account for varying land areas, different methods are utilized to calculate land-use mix, for example.**

2.5.2. Choice of indices

One of the three objectives of this article is to illustrate variability in measures of walkability that exist in current academic literature. To do this, three indices were chosen to reflect the variety in methodology currently utilized in walkability literature: a walkability index by Frank et al, published in the American Journal of Preventive Medicine in 2005; a walkability index by Sundquist et al, published in Social Science and Medicine in 2011; and, a moveability index by Buck et al, also published in Health and Place in 2011. Table 3 shows this variety of perspectives in greater detail by exploring the definitions and selections of variables of each of these three indices. Furthermore, by deconstructing one of the permutations of Frank et al’s original walkability index, and there are others (M. A. Adams et al., 2014; Christian et al., 2011; Coffee et al., 2013;

Koohsari et al., 2016; L. Oliver, Schuurman, Hall, & Hayes, 2011), this article is able to explore ontological differences in the creation and application of walkability indices.

Table 3. **The variety of spatial and health epistemologies offered by the three walkability indices chosen for this article, including the variables and methods used for the final walkability scores.**

	Frank et al (2005)	**Sundquist et al (2011)**	**Buck et al (2011)**
Academic discipline	Planning, public health, psychology, medicine	Health care research, geoinformatics	Public health, medicine, sports sciences
Spatial scale	Area 1km around participants' homes	Neighbourhoods created from administrative areas	School catchment area
Formal study	Strategies for Metropolitan Atlanta's Regional Transportation and Air Quality (SMARTRAQ)	Swedish Neighborhood and Physical Activity Study	Identification and prevention of Dietary- and lifestyle-induced health EFfects in Children and infantS study (IDEFCS)
GIS application	Euclidean and network buffers	Built on the index created by Frank et al (2006)	Kernel density estimation (KDE)
Statistical analysis	Logistic regression	Multilevel linear regression, intraclass correlation	Multilevel logistic and multilevel lognormal regression models
Connection to health	Physical activity		
Perceived/self-reported	Accelerometer	IPAQ	Reported by parents using a 4-question questionnaire
Walking purpose	Unspecified	Active transportation, leisure	Travel, leisure
Demographic	General (specific age – 20 to 70)	General – unspecified	Children
Area of study	Atlanta, USA	Stockholm, Sweden	Delmenhorst, Germany
Street connectivity	Number of intersections per square kilometer	Number of intersections with 3 or more legs per square kilometer	KDE (bandwidth = 1 km) of sidewalks, bikeways, intersections, public transit stations
Residential density	Number of residential units per residential acre	Number of residential units per square kilometer	Called 'destination density': KDE (bandwidth = 1 km) of sports facilities, playgrounds, and parks/greenspaces
Land-use mix	Entropy score (3 categories: residential, commercial, and office development)	HHI score (categories: retail/service, entertainment/physical activity, institutional/health care, office/workplace, dwellings)	Called 'level of urbanization': residential density, and land use mix (calculated using an entropy index of 6 categories: residential, commercial, industrial, agricultural, recreational, and miscellaneous)
Equation	W = (6 * z-score LUM) + (z-score RD) + (z-score SC)	W = (z-score LUM) + (z-score RD) + (1.5 * z-score SC)	M = 1/3(SC + DD + LU)

2.5.3. Street connectivity

To create the appropriate street connectivity measure for the indices, data was required for each individual street leg and intersection for the City of Vancouver. Street network data was extracted from the ‘Streets package’ of the Open Data Catalogue. Intersections were manually calculated using the public streets dataset whereby the unsplit street centerlines allowed for the addition of data on the number of street legs meeting at each intersection.

The kernel density estimation (KDE) utilized to reconstruct Buck et al’s moveability index was recreated using their specifications (2011, p. 1193), that is, with a 2m by 2m cell size, and a bandwidth of 1km. Resulting mean values of the kernel density maps were recorded for each neighbourhood area. The regular street network was substituted for a KDE of sidewalks since this data wasn’t available, even though it has greater benefits over the regular street network for walkability analyses.

2.5.4. Residential density

The number of residential units was obtained from the 2006 census data, ‘Census local area profiles 2006’ (Vancouver, 2017). The residential units for each neighbourhood were divided by either the residential area in acres, or the total neighbourhood area in square kilometers to obtain either the net residential density, or the gross residential density, respectively. Instead of including residential density as a separated measure, Buck et al calculated residential density and land-use mix into a comprehensive measure of the level of urbanization in the spatial scale of their study.

Furthermore, this density measure was replaceable by population density for calculations of the ‘level of urbanization’ measure used in the proposed moveability index (2011, pp. 1192–1193). In our reconstruction of this measure in Vancouver, we used population density. The original ‘destination density’ measure includes sports facilities, public playgrounds, and parks or greenspaces; however, our reconstruction was only able to find reliable and complete data on public parks and greenspaces for our study area. For example, municipal fields and community centers that could be counted as either public playgrounds or sports facilities were few and far apart and data interoperability with this categorization was severely low.

2.5.5. Land-use mix

Three land-use mix index variations were recreated for this comparative analysis: a 3-category entropy score, a 6-category entropy score and a 5-category HHI score. The entropy score is a relative measure of land use types in an area where a higher entropy score indicates a higher land use mix (Song et al., 2013) The Herfindahl-Hirschman Index scores the opposite of the entropy index with higher scores indicating lower land use mix. The HHI equation is as simple as the entropy score and measures land use mix symmetrically with attention to the number of land use types in an area and the size of each land use type in the area.

The dataset used for this variable was obtained from the ‘Zoning districts and labels’ dataset from the Open Data Catalogue (Vancouver, 2017) along with explanations of all zoning labels (Vancouver, 2016). Of the three scores, the 5-category HHI score proved the most difficult to find compatibility with the available data. While commercial, residential and office land uses were moderately compatible due to overlap in subcategories, the category of ‘entertainment or physical activity’ was extracted from the parks dataset.

One of the HHI categories – institutional or health care – was excluded from the HHI index calculation because of low data interoperability. Although the City of Vancouver has several institutional and health care facilities, these weren’t categorized as such, but rather included in a zoning category that can be zoned based on need. Figure 2 shows the output of the three land-use calculations.

2.5.6. Calculating the indices

The scores from the respective variables for each index were converted into z-scores, multiplied by their assigned weights, if any, and finally, added to equal the final score for each neighbourhood. They are shown below, first, in their original walkability classification (Figure 3), and second, in a quartile walkability classification that allows for comparison between indices (Figure 4).

For each index, there were three spatial specifications, among others, that were normalized for their reconstruction as part of this comparative study. First, even though the *spatial unit* used in some indices was different – for example, square footage in

Frank's walkability index, and square kilometers in the other two indices – the calculation of a z-score normalized these differences into a score that can be compared across indices. Second, although each index calculated their scores on a different *spatial scale* – i.e. Frank's index was calculated for individual locations, Sundquist's index for neighbourhood or administrative unit, and Buck's for neighbourhood or catchment area – all three indices were calculated for the 22 neighbourhood spatial units in Vancouver for this comparative study. Third, while the *classification* of the final walkability scores were different in all three studies – i.e. Frank et al classified by quartiles, Sundquist et al classified by deciles, and Buck et al were classified as high or low – these classifications were compared using their original classifications in Figure 3, and using a quartile classification in Figure 4.

2.6. Results

2.6.1. Walkability variables

Between the walkability indices calculated by Frank and Sundquist, no matter how similar the methodology to measure each variable and the classification system in place, the slightest change in spatial unit or land-use categorization can shift the resulting variable score. This is more obvious in Figure 2, where the simplest change in the number of categories used to measure the entropy score for Frank and Sundquist has resulted in different scores for the same area, for example, West End, Downtown and Strathcona in the north and Killarney in the south-east neighbourhoods. This differentiation in classification is also noted for the methods to calculate residential density, where Buck adds residential density to land use mix to calculate his categorization of the walkability variable, 'level of urbanization'. Furthermore, because of his utilization of the HHI score, the resulting land-use mix score is greatly different from the other two indices. Take for example, Downtown, Mount Pleasant or Shaughnessy in the north and central neighbourhoods.

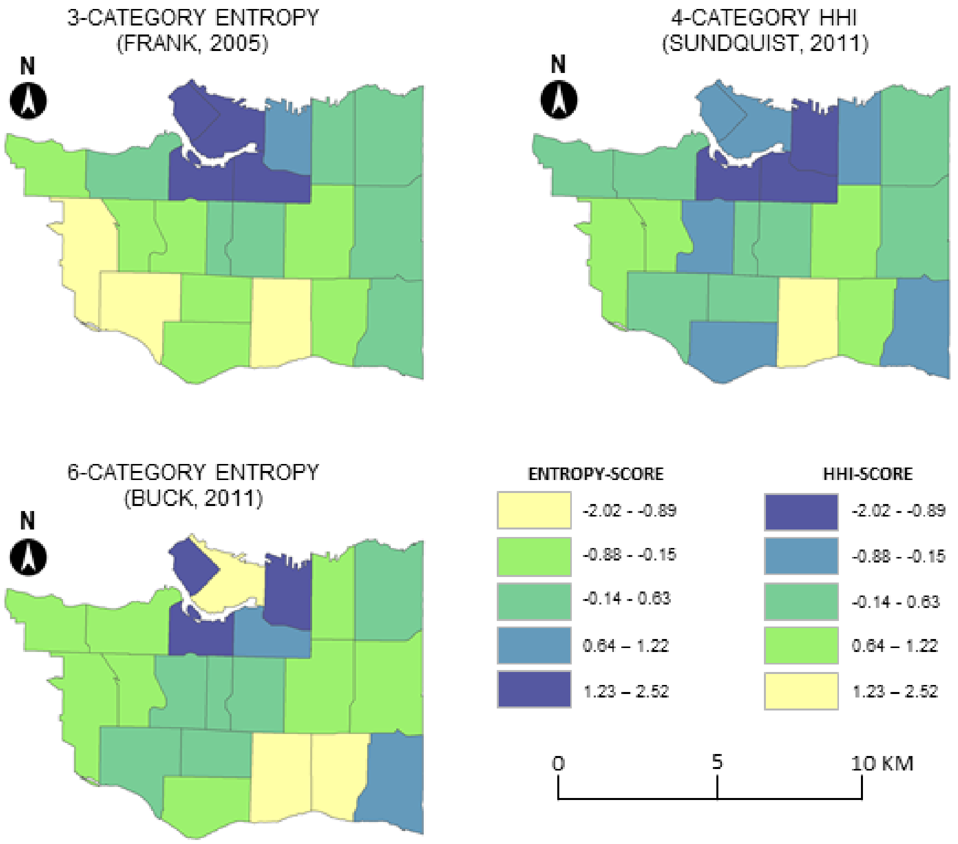


Figure 2. **The first two entropy scores on the left report a lower entropy score for neighbourhoods with lower land-use mix. The HHI score on the top right reports a lower HHI score for neighbourhoods with higher land-use mix. Visually, they are similar in understanding the northern-central neighbourhoods to have a higher land-use mix, however some disagreements are apparent for neighbourhoods showing lower land-use mix scores.**

Table 4 reviews the descriptive statistics for each of the three variables for each index. Since the final walkability scores were all normalized by z-scores, the mean was always 0, but the standard deviations varied. The normalized walkability scores varied for neighbourhoods, but the non-normalized mean variable scores, listed in Table 4 below, varied as well. The different methodologies are also most obvious in the unit of measurement across variables – for example, residential density was measured by the number of houses per residential acre, houses per square kilometer, and residents per square kilometer. Of note as well is the weighting scheme utilized for the three indices. While Buck has utilized equal weighting for the three variable categories, Sundquist weights the street connectivity variable 1.5 times more than the others, and Frank weights land-use mix 6 times more than the others.

Table 4. Variable and final walkability score mean and standard deviation comparisons showing not only differences in resulting calculations, but also differences in units used in these calculations.

Variable		Frank et al (2005)	Sundquist et al (2011)	Buck et al (2011)
Street connectivity	Mean	133.88 int/km^2	105.53 int/km^2	19.53 street km/km^2
	Standard deviation	29.97 int/km^2	22.47 int/km^2	2.56 street km/km^2
Residential density	Mean	24.35 houses/res. acre	2764.02 houses/km^2	5786.71 residents/km^2
	Standard deviation	39.06 houses/res. acre	3043.95 houses/km^2	4378.93 residents/km^2
Land-use mix	Mean	0.52 entropy score	4849.46 HHI score	0.58 entropy score
	Standard deviation	0.24 entropy score	2238.57 HHI score	0.17 entropy score
Walkability score	Standard deviation	7.25	2.31	0.70

2.6.2. Walkability Indices

Two of the three indices presented in both Figure 3 and 4 are in accord that the north-central neighbourhoods around the Vancouver Downtown Core are more walkable than the outer, peripheral neighbourhoods. The south-western neighbourhoods – West Point Grey, Dunbar-Southlands, Kerrisdale – receive the lowest walkability scores across all three walkability indices. The slightest difference in walkability can be observed even in moderately walkable neighbourhoods as they shift between the second and third quartiles of walkability. The difference in score frequency classification used by each of the walkability indices is stark in some neighbourhoods – for example, Strathcona, Sunset, and Victoria-Fraserview all show either extremely high or extremely low scores when classified according to their original studies (Figure 3) and also in quartiles (Figure 4).

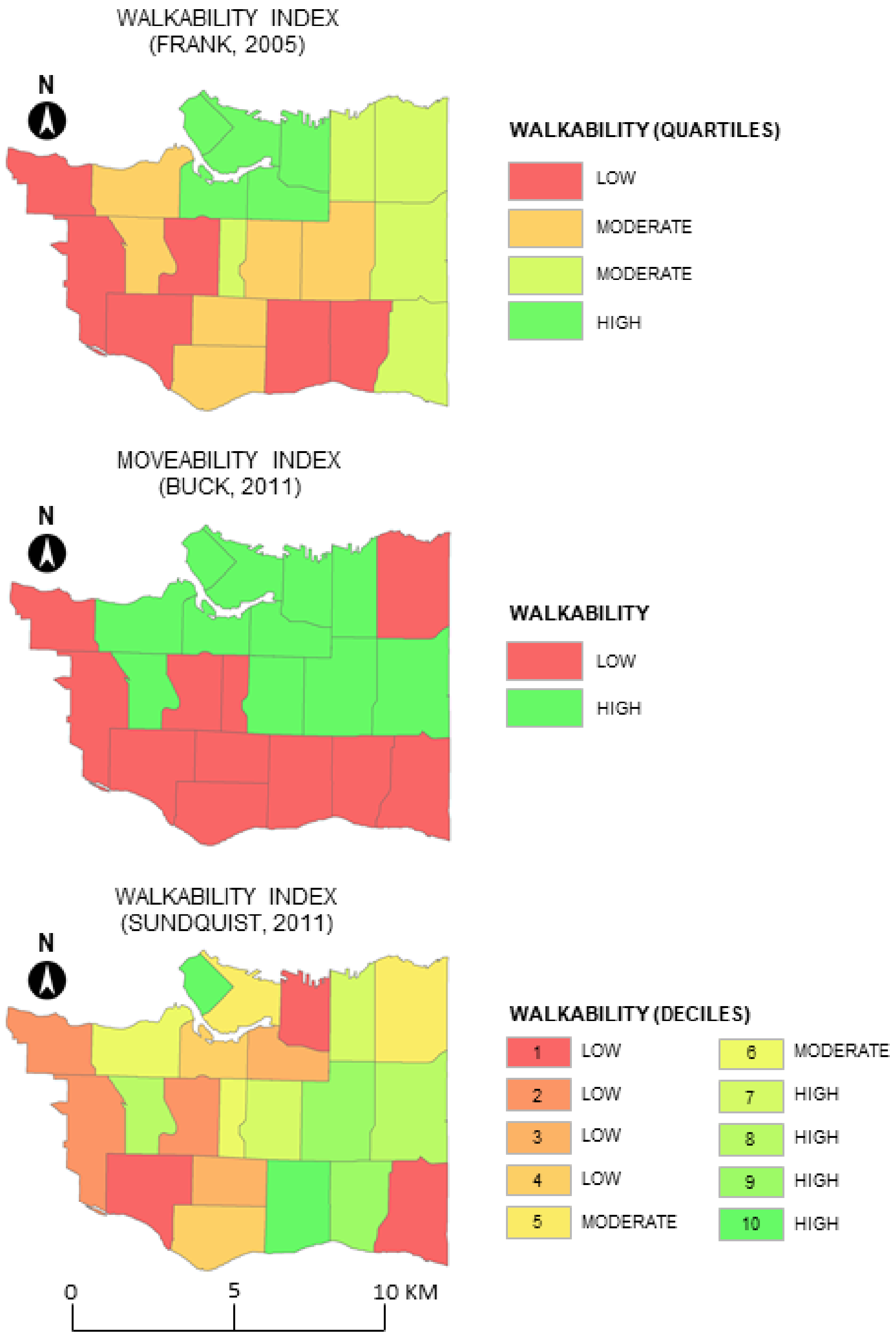


Figure 3. **The walkability scores with their original classifications. The downtown core in the north shows walkability scores that agree between Frank and Buck, but disagree with Sundquist. Not only are the results fundamentally in conflict with each other, their classifications also paint a different picture of walkability for each of these neighbourhoods. For example, a simplification of high or low walkability in Buck, although representative of the researcher's objectives, paint a black and white picture of how the built environment either promotes walkability or not at all.**

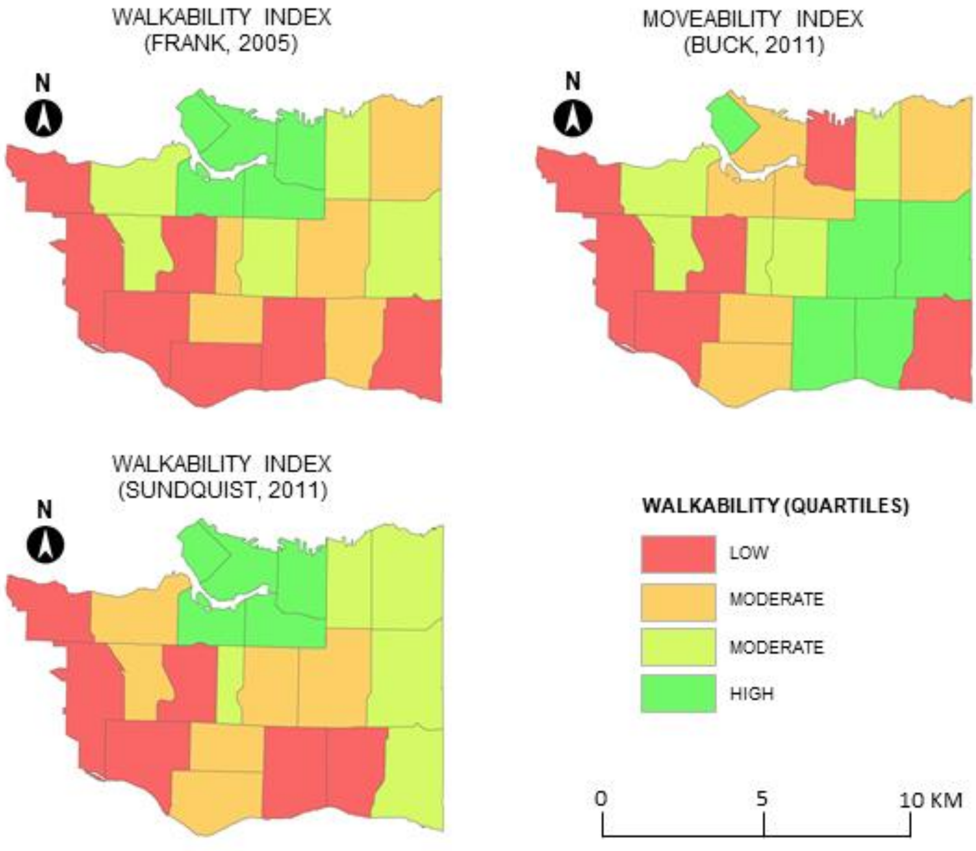


Figure 4. **The walkability scores classified according to quartiles for a simpler comparison of results. Here, the polar dualisms or extremely minute details of neighbourhood walkability can be understood on a more digestible spectrum of low, moderately low, moderately high or high walkability. These classifications can also show trends of whether a neighbourhood is in dire need of attention or can be more easily assisted in boosting walkability. In these classifications also, Frank and Sundquist are more in agreement with their walkability scores than Buck.**

2.7. Discussion

Each of the three indices was deconstructed to explore the selection of variables and their subsequent methodologies for inclusion in the final walkability equation. Table 3 above shows the methods used to measure the walkability variables for each of the three indices along with their final score equations. Of note in the first equation by Frank et al is the choice of net residential density, rather than gross residential density, which measures residential units only on residentially zoned land rather than dispersion over the entire neighbourhood. This affects the final residential density score by only accounting for the specific land-use designation of the land area rather than the entire land area (Schuurman & Leszczynski, 2006).

Where Frank et al accounted for all intersections, Sundquist only accounts for those intersections with 3 or more legs, thereby only accounting for streets that are most connected to other streets. If this distinction isn't made, then T-junctions or dead-ends that don't necessarily represent high connectivity can get included in the calculation, thus skewing the resulting interpretations that could be made of either. Furthermore, the Herfindahl-Hirschman Index (HHI) included in Sundquist et al's equation accounts for 5 rather than 3 categories of land-use mix. Land use mix calculations are often plagued by modifiable areal unit problem (MAUP), and while entropy and HHI scores can be interchangeable, entropy scores are recommended for a higher scale of land-use variation observed (Song et al., 2013). However, since one of the categories of land-use measure was excluded from the HHI calculation, perhaps the HHI score isn't entirely misguided in this case.

2.7.1. Limitations of data non-interoperability

The availability of good quality data is a problem in any quantitative spatial analysis, and data interoperability creates difficulties to align the purpose of the study to the data available. This is often ameliorated by changing the definitions of the variables measured and creating an ontology that is often left theoretically unexplored. These changes in ontology should not be left unexamined in walkability studies, for they risk misunderstanding the relationship between humans and their daily experience of the built environment. For example, street connectivity has been measured using intersection density, block size, sidewalk continuity or length, access to public transit or route directness. However, simply measuring connectivity using the street network can prove difficult because of how the data creator defines a regular two-way street – either using a line for each direction, or drawing on the median. For this study, creating our own streets and intersection data proved to be a more reliable method to obtain the metadata of each street and intersection.

The moveability index created by Buck et al challenged the limitations of simple density measures by exploring measurement of the built environment using kernel density estimation. While the first two indices used simple GIS methods, Buck et al's moveability index explored how GIS can address limitations of measuring the properties and variables within fixed spatial scales that aren't representative of human spatial behavior. Furthermore, definitions of the spatial units themselves are prone to non-interoperability issues, for example, definitions of a 'neighbourhood' (A. V. Moudon et al., 2006; Spielman et al., 2013), and can be observed in synthetically modeled built environments as well (Orenstein, Frenkel, & Jahshan, 2014). More than MAUP, this methodology seems to also address the uncertain geographic context problem (UGCoP) that can often mask the environmental and social contexts of human spatial behavior (Kwan, 2012b).

Indeed, no two cities are the same, yet the variables used to understand the walkability of a built environment are. While walkability indices provide a framework for comparisons between cities – used successfully in various cities internationally (M. A. Adams et al., 2014) – the contextual nuances of each city must also be attended to. Although these studies also provide replicability analyses, they fail to account for this UGCoP so typical in most applications of geographical information systems. For example, pedestrians don't just use sidewalks, but also trails and paths that cut across parks and greenspaces, measures of connectivity that aren't measured in walkability indices. In fact, even multivariate analyses utilized widely in walkability studies may not be able to avoid MAUP at all (Fotheringham & Wong, 1991) since the majority of walkability data is aggregated.

Some studies have shown that measuring sidewalk width and slope instead of directly measuring street connectivity might address wider concerns about walkability (Ann Forsyth, Hearst, Oakes, & Schmitz, 2008). While some indices have utilized sidewalk data (Chin et al., 2008; Tal & Handy, 2012), these are usually not easily obtained from municipal open data catalogues and must either be manually drawn, siphoned from Google Maps or Open Street Maps, or requested from the municipal government. Therefore, reapplication of an index in another city might prove difficult and sidewalk data is often replaced by street network data to measure connectivity. This is not always the most reliable because it doesn't truly represent availability of sidewalks in neighbourhoods, a data interoperability issue that can be further explored.

2.7.2. What are the assumptions?

Although left unexamined in most walkability studies, we bring attention to these for the purposes of future walkability studies that seek to understand the relationship between the built environment and human behaviour. The assumptions apply at the level of the whole index, the individual variables within the index, and the weighting of the index as well. The first assumption, and most important one, is that walkability assumes an ontological homogeneity. In other words, the way walkability is defined and measured is the same for various contexts. For example, the same calculation can be used for assessing potential physical activity as well as real estate marketability (Walk Score). This assumption is made when the definition of walkability upon which the walkability index in use is left unexamined and unquestioned in reproductions.

The second assumption, and which follows from the first, is that the ontology of each variable included in the walkability index is consistent. Even the same variable used in a fairly homogenous area such as communities within Greater Metro Vancouver define and populate the same variable differently. For example, Frank defined street connectivity as intersections per kilometer, whereas Sundquist defined street connectivity as intersections with three or more legs per kilometer. This slight variation in ontology populates the variable fields differently and holds the potential to skew further aggregate measures that build on this variable. In other words, the classification of the variable is assumed to be standardized – independent of environmental or socio-economic context upon which they are built (Bowker & Star, 2000).

This comparative study found several inconsistencies and difficulties in measuring land-use mix using simple zoning districts. Although zoning districts are often used instead of land-use designations, these could be representative of the current land-use of a location or represent what the location has been zoned for. As noted earlier, the land-use designation of ‘CD-1’ was often used for locations with specific zoning needs and these designations are widespread across Vancouver (Vancouver, 2016). These ontological differences have been explored in greater detail elsewhere (Schuurman & Leszczynski, 2006), and we agree that greater exploration of metadata that provides context to these categorizations of land use and their purpose would bring greater clarity to walkability studies heavily reliant on land-use mix as a variable.

Minute differences in definitions of variables and their subsequent methods result in different walkability scores, as is made apparent in this comparative study. Including and/or excluding variables can result in a walkability score that can neglect the context or composition of an area. For example, using street connectivity as measured by intersections with 3 or more legs per km^2 compared to measuring all intersections per km^2 can notably alter the final walkability score (compare Frank to Sundquist in Table 3 and Table 4).

2.7.3. Addressing assumptions

To make walkability indices truly representative and reproducible, this implicit assumption is replicated in subsequent permutations of the index. Furthermore, the weighting of the original index, if reproduced, assumes contextual similarity and semantic homogeneity, which is likely not true. However, the second assumption can become a strength when it is used as an adaptive mechanism to make walkability indices more responsive to the local context. The weighting and variable ontologies can be changed to better suit the local socio-political and environmental context.

Over the last few years several comparative studies on methodologies used to measure individual variables of the built environment have emerged. Some of these comparative studies consider the methodological nuances of land-use measures (Christian et al., 2011; Hajna et al., 2014), including measures not used in this comparative study (Song et al., 2013), and connectivity (Knight & Marshall, 2015; Ozbil et al., 2011; Peponis, Bafna, & Zhang, 2008). These studies have also proposed variations and urged future research to be more cognizant of the methodological quirks that distort results in a certain direction. Furthermore, several protocols to guide GIS researchers have also been developed (M. Adams, Chapman, Sallis, & Frank, 2012; A Forsyth, 2007). These steps are important contributions to understanding the affordances of the built environment. While we concur, we add that careful clarification and statement of the purposes of variable usage in walkability analyses be appended to these explorations of the built environment.

This study was limited by the availability of high quality spatial data. Although this is common in most GIS studies, it should not be a methodological restriction for walkability studies. We also found that definitions and methods utilized in walkability indices were not explicated with sufficient details. In other words, the assumptions contained in the indices should be made transparent. At the present, walkability indices are largely black boxes. This research has done much to reveal the methodological steps used to calculate the indices and, in so doing, has illustrated that many are fundamentally in conflict. This points to the need for more research combined with greater skepticism about the results of such indices.

2.8. Conclusion

This article investigated how walkability has been defined across several disciplines seeking to understand the built environment and its effect on health and human spatial behavior. We explore several indices that have been developed and modified for further use in walkability research. We then examine how these definitions have shaped the methods used to calculate walkability in cities. Not only do differences in definitions shape methods, differences in methods also create different walkability scores. Lastly, we propose uncovering implicit assumptions that hinder interpretation and methodological clarity in walkability indices and propose ways to address these assumptions.

We explored this variation in walkability scores in 22 neighbourhoods in the City of Vancouver, Canada using three distinct indices. While most indices reported a similar trend in walkability scores for many neighbourhoods, there were stark differences in scores in some areas. However, differences were observed even in those neighbourhoods with moderate walkability. Most importantly, although the three methodologies examined in this study were replicated from their original study area and study purpose, they still utilize widely accepted measures of residential density, land-use mix and street connectivity. Our purpose in replicating them was to observe how slight variations can result in significant differences in walkability scores. This ontological variation in walkability studies should be further explored for individual variables and be accounted for in future interpretation.

This discovery and demonstration of differences in methodology and results associated with three leading walkability indices is an important first step in appreciating that indices are not the truth about the built environment, but reflections of priorities held by the researchers who develop them. As geographers, it is important that we recognize and explore these inconsistencies so that we can contribute to this important discussion in the fields of urban planning and public health.

Chapter 3.

The role of connectivity in walkability studies

3.1. Abstract

Connectivity is one of the most important correlates of the built environment that are studied when exploring human behaviour. Several measures of connectivity currently exist in literature, each proposed by different disciplines and perspectives on the built environment. This study first distinguishes connectivity from other similar street network measures, proximity and accessibility, and then explores the ontological differences between six measures of connectivity. This study also finds the effects of the modifiable areal unit problem in connectivity measurements, and explores value in granular measurement of connectivity and whether this may provide context to aggregate measures of connectivity. The findings of this study are of relevance to all researchers that use connectivity as a metric of the built environment and urges researchers to measure at human and policy-relevant scales to better ground study results.

3.2. Keywords

built environment, connectivity, scale, street network

3.3. Introduction

Walkability indices originated after years of research on both the arrangement of land use designation and the configuration of the street network, that have contributed to physical activity and subsequent health outcomes. These indices were created in order to bridge the perspectives of both land-use planners and transportation planners with public health analysts (Lawrence D Frank, Andresen, & Schmid, 2004; Frumkin et al., 2004). Walkability is measured as a result of land-use mix, street connectivity, population density, and floor-area-ratio, where each of these variables are weighted and combined in an additive index (L D Frank et al., 2010) and spatially represented using geographical information systems (GIS) (Kwan, 2012a; E Leslie et al., 2007). Currently, various definitions of walkability are utilized in built environment and health studies, and these definitions in turn have a notable effect on the methods utilized to measure this phenomenon (Shashank & Schuurman, nba).

Of particular importance is the higher weighting of the connectivity variable than other variables, with subsequent research building on the original walkability index (Ellis et al., 2016). With this in mind, measures of connectivity have a greater potential of altering the resulting walkability score of an area and must be chosen and quantified with care. Several studies on the relationship between the built environment and health have explored street connectivity as a predictor of health behaviours and outcomes (Berrigan et al., 2010; Dill, 2004; Lundberg & Weber, 2014; Tal & Handy, 2012). Some have also studied the difference between utilizing pedestrian networks versus street centerlines in walkability analyses (Chin et al., 2008; Ellis et al., 2016; Tal & Handy, 2012). The street network acts as a grid upon which activity spaces are configured and through which travel occurs. As a measurement of the planar street network, connectivity represents the dimension upon which other walkability variables exist. We consider connectivity in this article because we believe that it dimensionalizes simple walkability measures by taking into account that greater connectivity means more can be accomplished through walking when it enhances transportation. Furthermore, we seek to question whether measuring street connectivity at different scales can bring a notable difference.

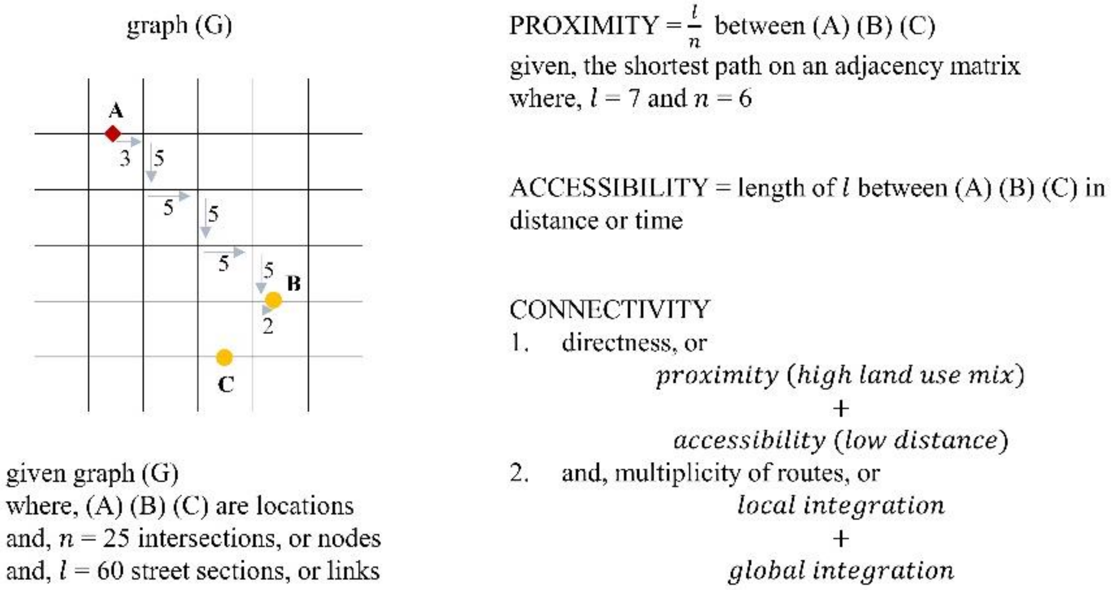
With advances in transportation research and application of mathematical models to active transportation research, studies have begun exploring the consequences of space syntax on walkability research (Baran, Rodríguez, & Khattak, 2008; Koohsari et al., 2016; Özbil, Peponis, & Stone, 2008). Measures of space syntax can be most useful in delineating distributions of pedestrian movement in areas and add to a contextual understanding of the configuration of sections within the overall street structure (Bafna, 2003; Özbil et al., 2008). Most walkability analyses utilize neighbourhoods or buffers as spatial units, studying the potential for human behaviour within boundaries that encapsulate smaller policy-relevant areas within a larger city or regional boundary. However, the methods used to calculate connectivity within these boundaries do not account for the provision of context or purpose by granular observations for larger spatial units. Not measuring walkability at a more granular scale holds the potential to misrepresent the street network as a discretized and broken graph, rather than a continuous structure that is broken in studies according to political man-made boundaries (Gil, 2017).

We follow the suggestion of Peponis et al (2008) in their work on street configuration in proposing that walkability must account for global integration of the street network, rather than solely calculating the local integration of the street network. Indeed, human behaviour occurs at a local scale, and yet this scale is not bound by political or man-made delineations, but crosses it in daily activity spaces. These delineations of human activity spaces overlap, and so when walkability or connectivity is calculated globally, it can also shed light on the local aspects of the built environment.

The purpose of this article is twofold: first, to explore the ontological distinctions in connectivity measures and how these very distinctions inform methodology and interpretation; and second, to compare ontologies and scales of connectivity as representations of the built environment. We concur that the distinctions in definitions and methodology provide diverse scores of connectivity for the same area, and we hope to shed light on issues pertaining to the ‘modifiable areal unit problem’ (MAUP) that might derail the purpose of measuring connectivity. We run these measures of connectivity in the City of Vancouver using neighbourhoods as the spatial unit.

3.3.1. Defining Connectivity

To better understand the dimensions of connectivity, we must first distinguish it from other attributes or functions of the street network. The street network has been studied for the role it plays in proximity, accessibility and connectivity. Proximity is the closeness of facilities within an area, often understood as a function of the mix of land uses (Handy, Boarnet, Ewing, & Killingsworth, 2002) as well as the support offered by the topology of the street network. In much the same way, accessibility is also understood as a function of both the land-use mix and street network, however with a particular focus on the potential, or ‘opportunity’ of activity available to them (Geurs & van Wee, 2004). Curiously, both attributes of the built environment require observations of land-use mix and the street network in order to quantify them. Furthermore, they rely on each other as well, since proximity to potential activity must be understood where the potential activity is quantified, and vice versa. Their distinct ontologies can be better compared in Figure 5.



given graph (G)
where, (A) (B) (C) are locations
and, $n = 25$ intersections, or nodes
and, $l = 60$ street sections, or links

PROXIMITY $= \frac{l}{n}$ between (A) (B) (C)
given, the shortest path on an adjacency matrix
where, $l = 7$ and $n = 6$

ACCESSIBILITY = length of l between (A) (B) (C) in distance or time

CONNECTIVITY
1. directness, or
$$proximity\ (high\ land\ use\ mix) + accessibility\ (low\ distance)$$
2. and, multiplicity of routes, or
$$local\ integration + global\ integration$$

Figure 5. The relationship between proximity, accessibility, and connectivity is interdependent. Without an understanding of proximity and accessibility, connectivity is of no significance to street topology.

Connectivity, while aloof from observations of land-use mix, is best contextualized when potential activity and the proximity to this activity can be observed and quantified for an area. Connectivity can be understood as “the directness and multiplicity of routes through the network” (Tal & Handy, 2012, p. 49). Most walkability indices only provide methods to measure connectivity, as either the directness (E Leslie et al., 2007), the number of intersections (L D Frank et al., 2005), and the ability of the pedestrian network to provide connections (A. Moudon, Hess, Snyder, & Stanilov, 1997), rather than also provide definitions or the implications of measuring connectivity particular to their studies. Studies have collected and categorized all of the connectivity measures used in urban planning, urban design and health research (Berrigan et al., 2010; Brownson et al., 2009; Dill, 2004), and provide insight into the features (attributes) and functions (provisions) of connectivity (Shashank & Schuurman, under review).

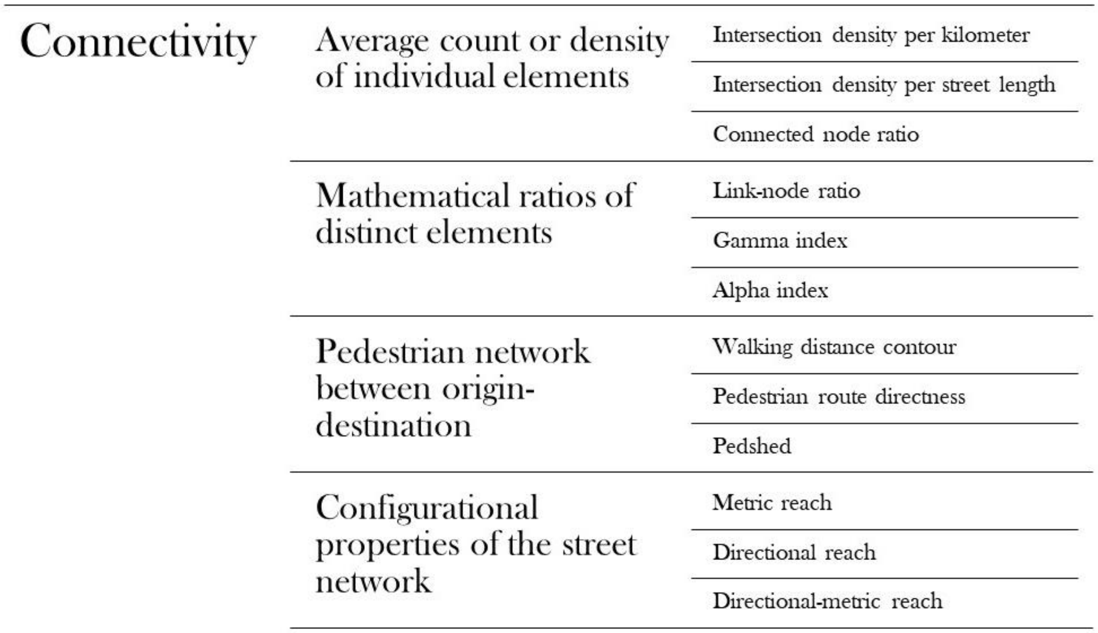
Ozbil et al (2011, pp. 126–127) have offered a categorization of these measures, and to theirs we have added our own modifications. While these categories offer a succinct description of the contextual foundations of these measures, we found a lack of clarity in the explanation of method, which made it difficult for subsequent researchers to implement the ideas. Our modifications are primarily methodological, and they are an important extension of this categorization (Figure 6):

1. Measures of the average count or density of a distinct element present in the street network. While Ozbil et al suggest that this category distinguishes between typologically distinct neighbourhoods of different planning eras, researchers find that these typological distinctions can be observed in other measures as well (Baran et al., 2008; Knight & Marshall, 2015). These measures are densities of intersections and counts of streets converging at intersections.

2. Measures of the distinct elements of the street network as mathematical ratios that represent the relationships between these elements themselves. Although Ozbil et al combine these measures with those from the first category, we draw a distinction here: the first category considers densities, i.e. intersections per kilometer, intersections per street kilometer; whereas, the second category only considers ratios and is not concerned with area, but rather the existence and relationship between various elements of the street network, i.e. link node ratio.

3. Measures of the pedestrian network between locations or from a point. Indeed, these are similar to those specified by Ozbil et al. However, we acknowledge that these measures are also ratios and build upon the second category but within the confines of an area between locations or radiating outwards from, or inwards to, a point.

4. Measures of the structure of the street network as a whole and its subsections by observing the configuration of the various street elements. While these are mathematically rigorous in their utilization of graph theory, they are built from a unique understanding of urban morphology: space syntax. These measures seek to understand the relationship not only between elements of the street network, but also how their configuration affects social life.



Connectivity	Average count or density of individual elements	Intersection density per kilometer
		Intersection density per street length
		Connected node ratio
	Mathematical ratios of distinct elements	Link-node ratio
		Gamma index
		Alpha index
	Pedestrian network between origin-destination	Walking distance contour
		Pedestrian route directness
		Pedshed
	Configurational properties of the street network	Metric reach
		Directional reach
		Directional-metric reach

Figure 6. **The measures of connectivity when categorized methodologically and ontologically build on the categories provided by Ozbil et al (2011).**

3.4. Methods

This article measures connectivity from the first two categories listed in the previous section, i.e. average count or density of individual elements, and mathematical ratios of distinct elements. The third category is not measured because of its requirements of a specific points as origin and destination which weren’t appropriate for comparison in our study, and are also better understood as measures of accessibility rather than connectivity (Barthelemy, 2011, p. 9). As ratios or areas of reach between two specific points, they are not necessarily representative of the connectivity of the street network as a whole. The fourth category is not measured either, since it can be represented by its simpler ratio measures of the second category which require less data and are highly operational compared to measures of the fourth category (Jiang & Claramunt, 2002).

3.4.1. Average count or density of individual elements

1. Number of intersections with 3+ unique streets per kilometer
2. Number of intersections with 3+ unique streets per km of street length network
3. Ratio of four-way intersections to all intersections

Of all the measures of connectivity, perhaps the most well utilized, also widely critiqued, is intersection density. Simply, it is a measure of the density of intersections in an area. While this measure of connectivity has grown in understanding and depth over decades of research in transportation planning, its methodology has also varied in walkability studies, and is often misunderstood in purpose or scope. We measured intersection density using three different methodologies: the number of intersections per square kilometer, the number of intersections per kilometer of street length network, and the ratio of four-way intersections to all intersections.

Simple intersection density, or the number of intersections per square kilometer, was included in early walkability analyses as a measure of street connectivity for a one kilometer network buffer around participants' homes (L D Frank et al., 2005). Roemmich et al (2007) measured intersection density as a ratio of intersections to the street length network within a Euclidean buffer area. In so doing, the study reduced the degree to which solely measures of intersections, or the nodes that provide route options, themselves could provide a value of connectivity. The last measure, also called connected node ratio, or the ratio of four-way intersections to all intersections, is a measure of the connectedness between two points, or two nodes. Although it doesn't measure the street length between the nodes, it compares nodes understood to be better facilitators of street connections than those with limited overall access, such as dead ends or cul-de-sac nodes. Each of these measures were computed for intersections with three or more intersecting streets (Lawrence D Frank et al., 2004; E Leslie et al., 2007).

3.4.2. Mathematical ratios of distinct elements

4. Beta index - Ratio of links (streets) to nodes (intersections)

5. Alpha index – ratio of the number of actual circuits to the maximum number of circuits
6. Gamma index – ratio of the number of links in the network to the maximum possible number of links between nodes

The beta (β), alpha (α), and gamma (γ) indices are ratio measures of the discrete elements of networks and one of the fundamental types of structural analyses that come from applications of graph theory in transportation geography (Taaffe, Gauthier, & O'Kelly, 1996). The foundations of these three indices is built on graph theory and a lucidity towards street topology which allows these measures to lend insight to the structural relationships between discrete elements of street networks. The street network here is abstracted as a planar graph where no two streets, or links, can intersect except by intersections, or nodes. Circuits can then be understood as loops that start and end at the same node. While spinal networks represent minimal connectivity where the number of intersections is greater than the number of streets, delta networks represent maximal connectivity where the number of streets are greater than the number of intersections. Grid networks are at the midpoint of the spectrum of minimally and maximally connected street networks.

Link-node ratio, also called the beta index (β), is the ratio of streets to intersections, mathematically written as,

$$\beta = \frac{links}{nodes}. \qquad 1$$

While intersection density can be measured as the number of intersections per street length (refer to measure #2 in previous section), link-node ratio is the inverse and measures the number of streets per intersections. As the number of streets increase, the β index value also increases and ranges from 0 to 3 for planar graphs (Kansky, 1963). While intersection density deduces the connectivity of the network by measuring the frequency of intersections in an area, the link-node ratio is able to obtain connectivity by assuming that a node with fewer streets converging at it will result in lower β index values as compared to a node with more streets converging at it. Given these parameters, the β index would still result in a consistent value for two graphs that are isomorphic, i.e. have the same number of streets that are either straight or winding.

The alpha index (α) is a ratio of the actual circuits to the maximum possible circuits in the network, mathematically written as,

$$\alpha = \frac{links - nodes + 1}{2\,(nodes) - 5}\ , \qquad 2$$

and is calculated as an α value between 0 and 1. For highly connected networks, the α value will be closer to 1, and for poorly connected networks, the α value will be closer to 0 (Barthelemy, 2011). Since it can also be represented as a percentage of maximum possible connectivity in a street network, it is independent of the number of intersections in a network (Kansky, 1963). It is able to account for the purpose of intersections not just as a frequency but rather as part of a larger graph of network connectivity.

The gamma index (γ) builds further on the link-node ratio and is a ratio of the number of streets in the network to the maximum possible number of streets between intersections. It can be mathematically written as,

$$\gamma = \frac{links}{3\ \times (nodes - 2)}\ . \qquad 3$$

By measuring the number of *streets* against the maximum possible number of *streets* between intersections, it differs itself from both the β and α indices. Nonetheless, the γ index provides insight into the configuration of the street network in a way that β and α indices cannot. Since the gamma index produces values between 0 and 1, all values between 1/3 and ½ are significant of spinal networks, values between ½ and 2/3 are significant of grid networks, and values between 2/3 and 1 are significant of delta networks (Taaffe et al., 1996). Like the α index it can be presented as a percentage of possible connectivity.

Each index builds upon the deficiency of its predecessor in the order presented above. The β index provides the frequency of streets and intersections and allows researchers to deduce the relationships that might exist. The α index provides a deeper distinction between highly and poorly connected networks. Lastly, the γ index can speak further to the various configurations of the street network itself. With each index comes a deeper understanding of the topology of each subsect of the whole street network.

3.4.3. Global connectivity

A global connectivity map was created using depthmapX 0.50. This open-source software has the ability to create axial maps and analyze single segments of the street network and calculate connectivity based on adjacency (Segment Analysis). The resulting scores are given to each single street segment and inform the number of connections available to each segment. Scores ranged from 1 to 6 for the resulting maps, with higher scores indicating higher connectivity.

3.5. Results

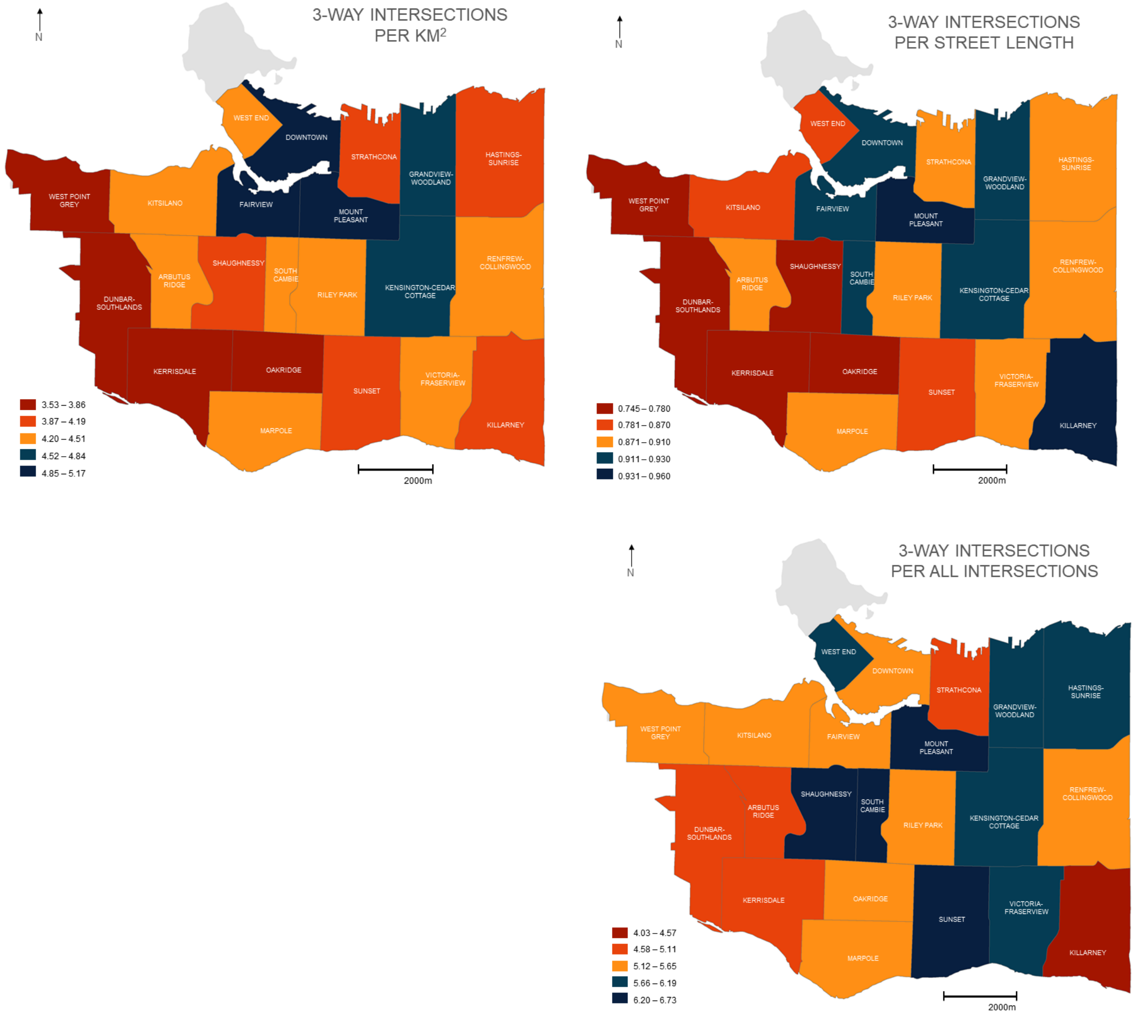
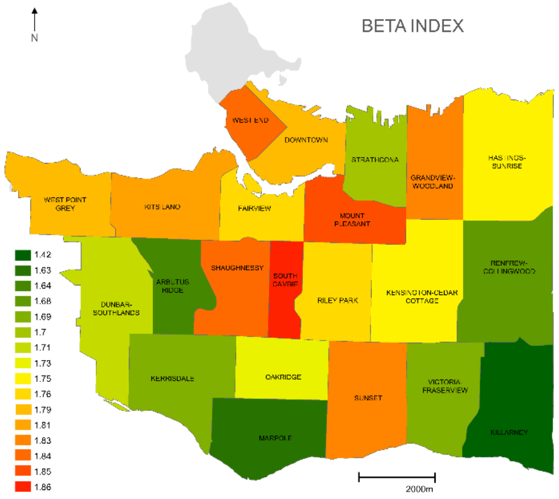


Figure 7. The simplest and most utilized intersection density calculation, three way intersections per squared kilometer mapped per neighbourhood on the top left. An intersection density calculation that solves the issue of ignoring street lengths in connectivity is shown on the top right. The connected node ratio calculates the percentage of intersections in the network that are at the junction of 4 or more streets compared to all intersections that account for dead-ends and cul-de-sacs (shown in map on the bottom left).

The three measures of intersection density show variation in almost all neighbourhoods in Vancouver. The measure of intersections with 3 or more legs that were calculated per kilometer and per street length network showed some similarities in the Western neighbourhoods of Vancouver (Figure 7). However, the third measure of 4-way intersections per all intersections showed entirely different density values for all neighbourhoods but one, i.e. Mount Pleasant. The first measure, i.e. per squared kilometer, is interpreted as number of intersections per kilometer in the neighbourhood. The second can be interpreted as the number of intersections per length of street in the neighbourhood. The third can be interpreted as the number of intersections that connect to 3 or more streets as a percentage of the number of intersections in total.

The beta, gamma and alpha indices showed an entirely different story of connectivity in these neighbourhoods (Figure 8). First, the beta index showed that the entire city consistently had a link node ratio that was greater than the recommended 1.4 (Victoria Transport Policy Institute, 2017). For this reason, the left map in Figure 8 shows the individual values for each neighbourhood so that viewers can distinguish the degree to which the beta values are greater than 1.4. There was a clear distinction between the north-western and the south-eastern neighbourhoods that had a lower link node ratio value compared to the central neighbourhoods. Furthermore, because of the shape of some neighbourhoods, their beta values were high (eg. South Cambie).

The alpha index calculation resulted in more interesting values (Figure 8, center row). Although this distribution of values was not grossly different from the distribution outputted by the beta or gamma index, the values themselves were indicative of the potential for connectivity in each neighbourhood. The values were on the lower end of the possible results (0-1) and suggested that although the network did not represent extremely poor connectivity, it was not well connected either since all alpha index values did not go above 0.5.


BETA INDEX
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STRATHCONA
GRANDVIEW-WOODLAND
HASTINGS-SUNRISE
WEST POINT GREY
KITSILANO
FAIRVIEW
MOUNT PLEASANT
DUNBAR-SOUTHLANDS
ARBUTUS RIDGE
SHAUGHNESSY
SOUTH CAMBIE
RILEY PARK
KENSINGTON-CEDAR COTTAGE
RENFREW-COLLINGWOOD
KERRISDALE
OAKRIDGE
SUNSET
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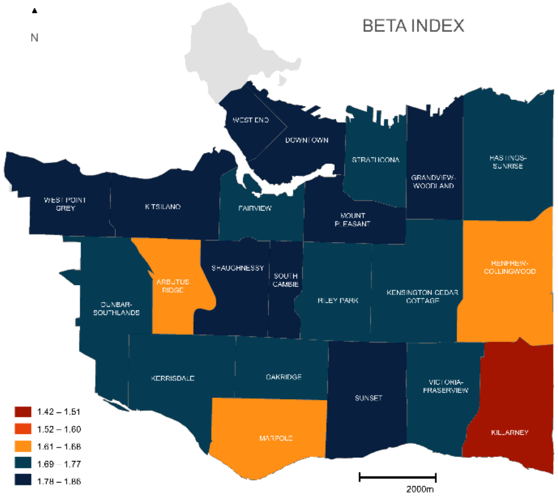
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SUNSET
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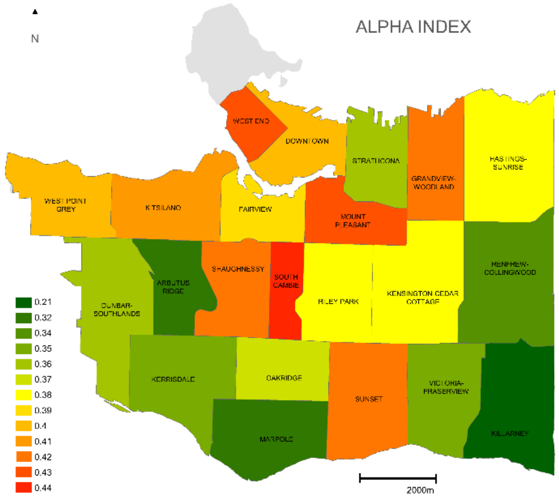
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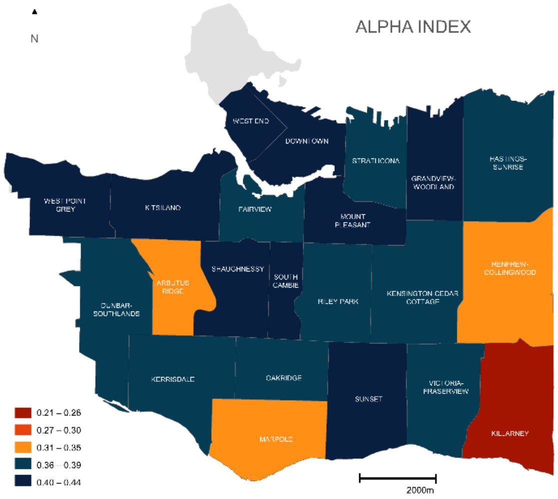
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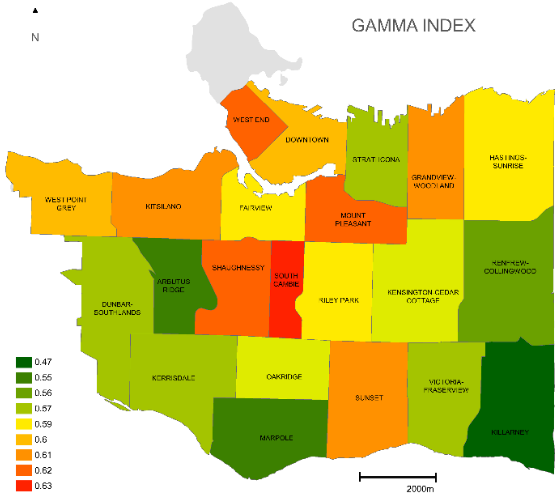
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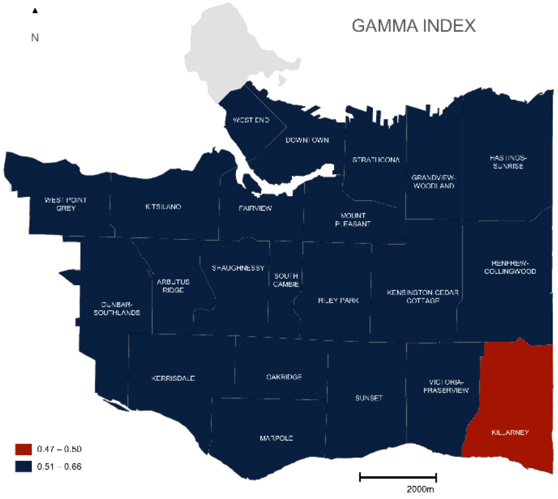
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HASTINGS-SUNRISE
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KITSILANO
FAIRVIEW
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DUNBAR-SOUTHLANDS
ARBUTUS RIDGE
SHAUGHNESSY
SOUTH CAMBIE
RILEY PARK
KENSINGTON CEDAR COTTAGE
RENFREW-COLLINGWOOD
KERRISDALE
OAKRIDGE
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VICTORIA-FRASERVIEW
MARPOLE
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0.47 – 0.50
0.51 – 0.66
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Figure 8. (Preceding page) The beta index values in Vancouver range from 1.42 to 1.86, with all values higher than the recommended 1.4 value. The map on the left shows the individual beta values for each neighbourhood while the map on the right shows the beta values for each neighbourhood sorted into quintiles. The alpha index values range from 0.21 to 0.44 and are indicative of a street network with poor overall connectivity compared to the potential connectivity of infinite graphs. The gamma index values range from 0.47 to 0.63, with the majority of values indicating a gridded street network, more apparent in the bottom right map. The bottom left map shows the individual gamma values for each neighbourhood to show the degree to which the neighbourhoods are gridded.

The gamma index results were able to address the layout of the street network and reported values that were fairly accurate (Figure 8, bottom row). The distribution of these values was not greatly different from the beta and alpha indices, and the resulting values showed the existence of spinal and grid networks in Vancouver neighbourhoods. Neighbourhoods with values between 0.5 and 0.66 – all but one – were representative of grid networks. The only neighbourhood that had a value lower than 0.5 – 0.47 – showed the existence of some spinal networks, which proved fairly accurate after comparison to the street network configuration. Furthermore, the variation in the degree of griddedness of the street network should be noted in all neighbourhoods (bottom left map, figure 8). Much like the spatial distribution of the alpha index values, the gamma index suggests that central neighbourhoods were more highly gridded and closer to delta networks than the outer western and eastern neighbourhoods.

3.6. Discussion

The simplest of measures, intersection density, resulted in varying scores for the same area. Table 5 shows the intersection density values for each neighbourhood. What this variation shows is a difference in research objective with each change in denominator, shown in Figure 9. Intersections per squared kilometer can be used as a proxy to measure the density of nodes within an area, signified by the blue boundary in Figure 9. Intersections per street length can indeed tell us more about the length of the streets and thus the length of connection from one intersection to another, but as other intersection density measures, remains within a short range of values (3.53-5.17) for this study area. This can point us to the fact that the street network in this study area is homogenous, shown in Figure 10 (left map), and will thus show lower variety in connectivity. Given that the configuration of the street network can tell us more about connectivity than intersection density measures, turning to the measures of graph theory can indeed explain this short range.

Table 5. Intersection density and graph theory values for every neighbourhood in Vancouver for each of the six connectivity calculations utilized.

3-way intersections	Km^2	Street length	All intersections	Beta	Alpha	Gamma
Arbutus Ridge	67.57	4.4	0.865	1.64	0.55	0.32
Downtown	87.6	4.78	0.907	1.79	0.60	0.4
Dunbar-Southlands	44.77	3.53	0.844	1.71	0.57	0.36
Fairview	88.52	4.76	0.896	1.76	0.59	0.39
Grandview-Woodland	78.71	4.7	0.929	1.83	0.61	0.42
Hastings-Sunrise	59.87	4.3	0.915	1.75	0.59	0.38
Kensington-Cedar Cottage	74.76	4.69	0.928	1.75	0.58	0.38
Kerrisdale	38.89	3.59	0.869	1.69	0.57	0.35
Killarney	60.39	5.02	0.745	1.42	0.47	0.21
Kitsilano	68.29	4.07	0.896	1.81	0.61	0.41
Marpole	61.83	4.43	0.878	1.63	0.55	0.32
Mount Pleasant	95.1	5.17	0.938	1.85	0.62	0.43
Oakridge	47.26	3.75	0.892	1.73	0.58	0.37
Renfrew-Collingwood	67.87	4.49	0.9	1.68	0.56	0.34
Riley Park	66.73	4.44	0.892	1.76	0.59	0.38
Shaughnessy	58.93	3.8	0.943	1.84	0.62	0.42
South Cambie	65.14	4.64	0.953	1.86	0.63	0.44
Strathcona	57.29	4.32	0.859	1.70	0.57	0.36
Sunset	55.71	3.86	0.939	1.83	0.61	0.42
Victoria-Fraserview	65.92	4.37	0.919	1.69	0.57	0.35
West End	64.47	4.07	0.914	1.84	0.62	0.43
West Point Grey	44.83	3.61	0.897	1.79	0.60	0.40

If we account for the homogenous nature of the entire street network configuration for the City of Vancouver (Figure 10, left map), we can then say that the shape of the area plays a greater role in intersection density values than previously assumed. As the shape of the area changes, the intersection density of the area increases or decreases, and might not accurately represent the connectivity of the network within the area, but rather the ability of the area to capture a count of intersections. Indeed, geographers who have explored the effects of the modifiable areal unit problem (MAUP) have urged the use of areal units that are more relevant to the behaviour as well as the use of measures that can be more cognizant of the scale and zoning effects of MAUP (Clark & Scott, 2014; Zhang & Kukadia, 2005). To their affirmation of this effect on measures of the built environment, we add that studying the street network can better explain the density values in such homogenously configured areas that are more susceptible to MAUP. To this extent, we compare the Vancouver street network to the configuration of the Surrey street network in Figure 10 (right map).

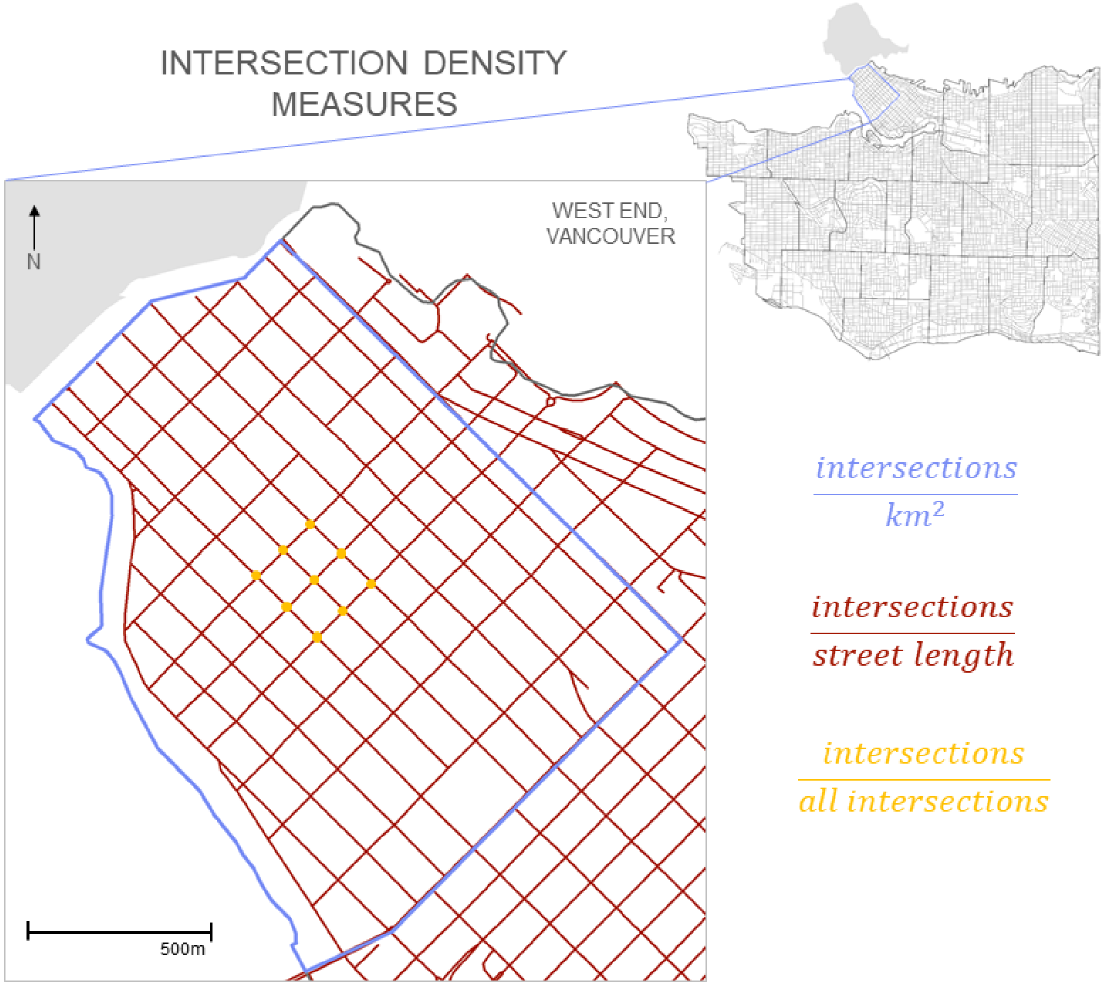

Figure 9. **The calculation for intersection density measures take different denominators in their equations, resulting in various scores of intersection density for the same area and street configuration.**

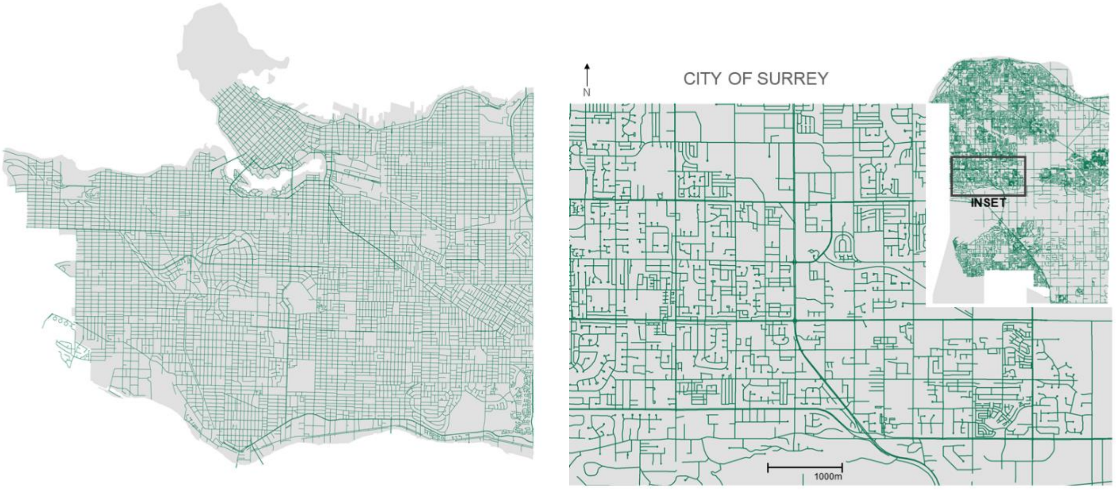

Figure 10. If we observe the street network in Vancouver, we see it is entirely gridded representing a well-planned street network configuration. Compared to the Vancouver street network, the Surrey street network is less gridded and has more cul-de-sacs.

3.6.1. Secondary Analysis of Street Configuration

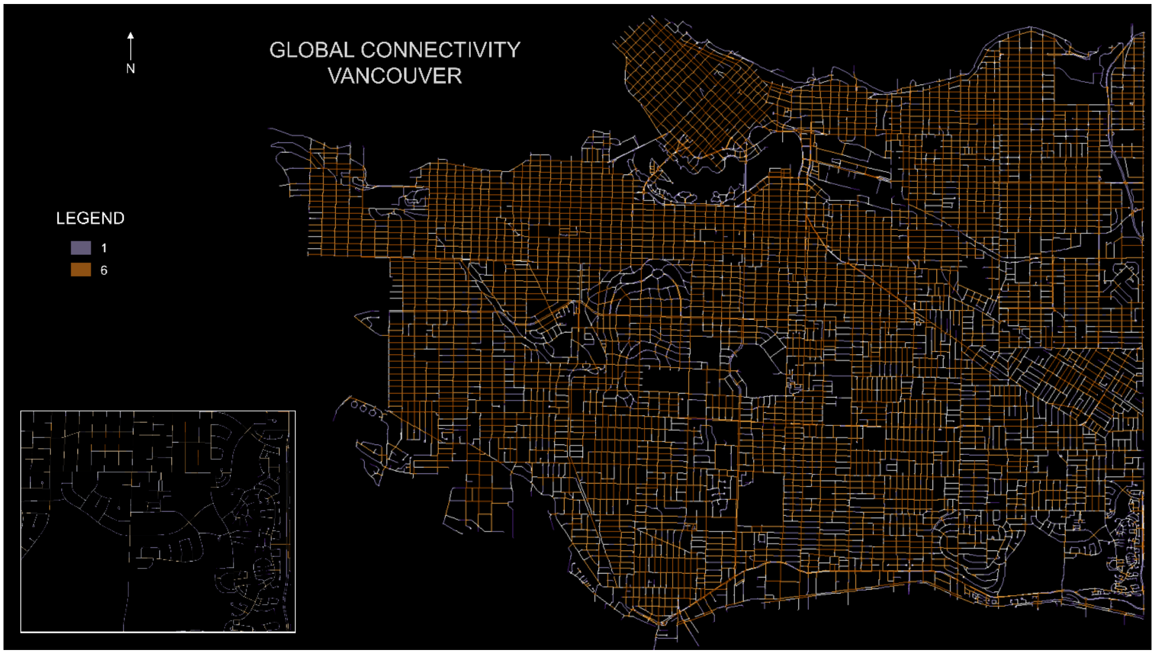

Figure 11. Global connectivity values for each street segment in Vancouver show a higher connectivity value of 6 for most gridded streets and lower connections on windy or spinal streets with cul-de-sacs (inset).

Because of the small value ranges that were obtained from all connectivity measures, we also created a global connectivity map using depthmapX 0.50. The connectivity map color codes each street segment with the value of true connectivity, that is, the number of streets that are connected to that street segment. The integration map color codes each street segment with its centrality value, the degree to which the segment is of importance to the entire street network. Global connectivity values for Vancouver were high in street network areas that were not windy or spinal with cul-de-sacs (Figure 11). While this was the same in Surrey, the configuration of the street network was not mostly gridded, but in fact a combination of gridded and spinal and therefore showed greater local variation in connectivity values for each street segment (Figure 12). Furthermore, the global connectivity maps, while more granular, were still subject to edge effects since the edges of the street network showed lower connectivity values.

When connectivity is calculated locally it runs into several limitations, some of which have been mentioned above: 1) does the boundary accurately represent actual human mobility; 2) can the boundary area itself be subject to MAUP; and, 3) boundaries can be subject to spatio-temporal changes, which may not be accurate in a year, or even a month. Every local measurement of connectivity exists within a global network, and thus representing this measure more locally loses contextual information of the network configuration. We propose that calculating connectivity more granularly does not entail loss of data, but in fact, brings more clarity to the network properties inherent to the street configuration of the study area.

This study is limited by the use of road centrelines rather than footpaths in connectivity analysis. While several researchers have found that footpaths better represent the extent of pathways that are available to researchers (Ellis et al., 2016; Tal & Handy, 2012), the data can be difficult to obtain. In the case that footpath data can be obtained, we still urge researchers to dimensionalize their connectivity measures by calculating global connectivity on a more granular scale that can explain small or large discrepancies in their aggregate connectivity values. This study was also limited by lack of health data that can potentially validate this argument. As mentioned earlier, one study that did explore several measures of connectivity and validate them with health data urged researchers to be cognizant of MAUP problems that might confound correlations (Ellis et al., 2016).

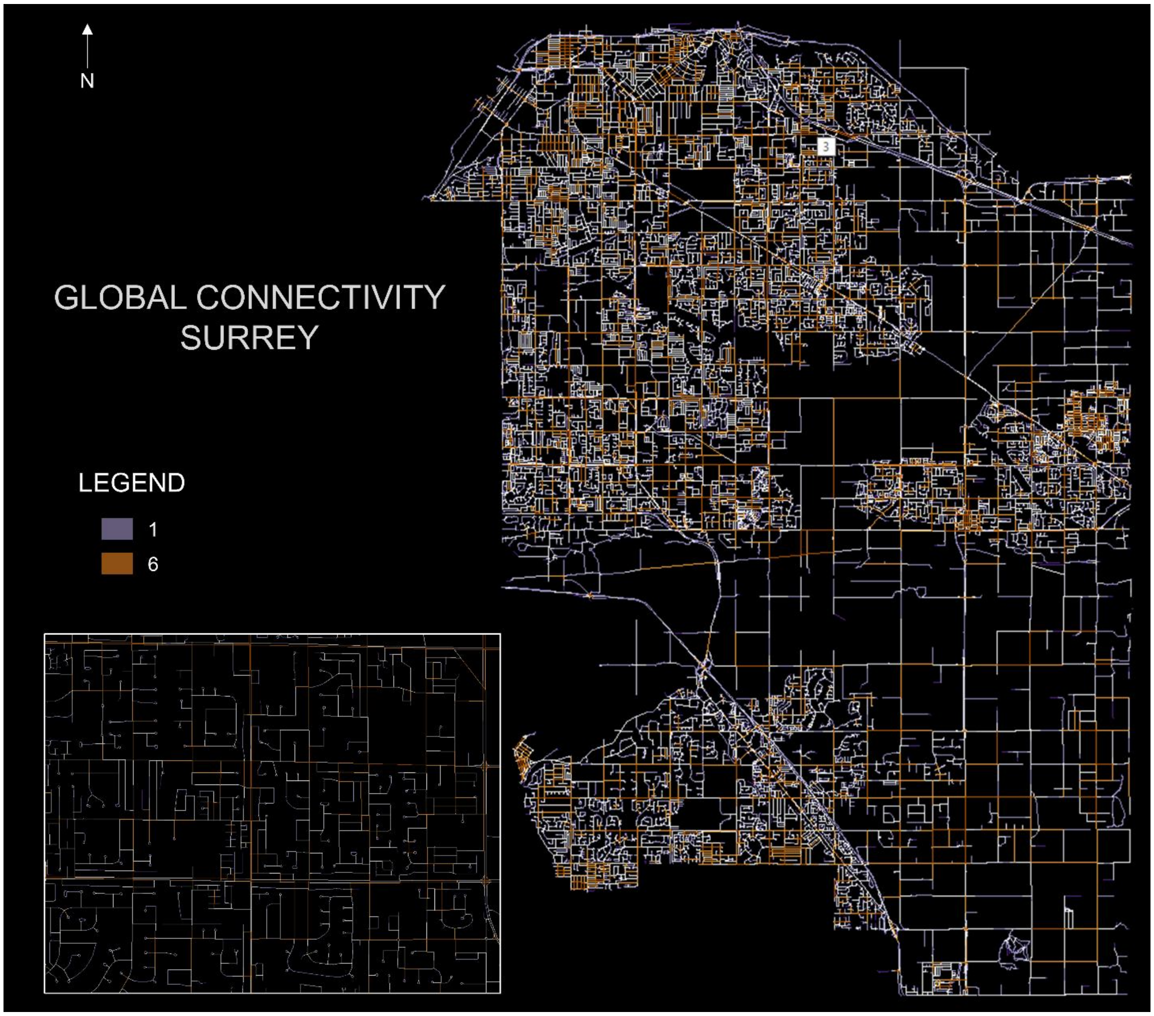

Figure 12. **Global connectivity values for Surrey were similar to those of Vancouver, but because the street network in this area is configured as a combination of spinal and gridded networks, the connectivity showed greater local variation for street segment connectivity values.**

3.7. Conclusion

Given the results of the global connectivity and global integration maps, we urge complementary or further singular analysis of the configuration of the street network toward connectivity measures rather than just intersection density. Indeed, human behaviour occurs at a stochastic scale, and further, this scale does not exist conclusively within a political boundary. These boundaries are more continuous and evolving spatio-temporally. We thus conclude that when calculating connectivity locally, that researchers also calculate connectivity on a more granular street-scale so that it can shed light on the connectivity of each street, which can then be aggregated to a neighbourhood level spatial unit for policy relevant results.

This article brings three core messages to built environment researchers: first, that connectivity must be ontologically distinguished from proximity and accessibility; second, that the categorization and definitions of connectivity measures must be heeded so that researchers can fully utilize the extent to which the resulting values explain the built environment; and finally, that calculating connectivity on a more granular scale can shed light on the global connectivity of street segments that can better explain the effects of the configuration of the street network on intersection density values. This last message can be of significance to researchers who are studying heavily planned cities that result in homogenous built environments where correlations with human behaviour are more difficult to explain. The additional context that comes from studying the street configuration can bring added depth to metrics.

Chapter 4.

Conclusion

This thesis studies the ontological distinctions in individual variables and their composite indices of walkability. By comparing three walkability indices in the City of Vancouver using the same spatial unit, the first part of this thesis shows how differences in variable definitions result in different walkability values for the same neighbourhood. Although this is methodologically obvious, it sheds light on possibilities of interpreting the same neighbourhood as highly walkable, moderately walkable and not walkable resulting from different walkability ontologies. Consistent reporting on variable definitions and addressing of research assumptions can facilitate the process of making ontological difference explicit and acknowledging the metric of the built environment with rigor.

The second part of this thesis follows the approach proposed by the first part and clarifies the ontological origin of connectivity by distinguishing it from proximity and accessibility measures. It then compares 6 measures of connectivity and sheds light on the effects of MAUP on the results and attempts to show how measuring connectivity at a granular scale can help rectify scalar issues affecting connectivity measures. Although this problem has been noted in previous literature, it has never been addressed for a single variable that is so important in walkability and other indices as well, i.e. connectivity.

This thesis adds to the current body of walkability research by more deeply exploring the methodological and ontological issues that come hand in hand with research that involves GIS. In asking whether differences matter, this thesis urges researchers to be more cognizant of the purpose of choosing certain methodologies over others. Of course, data availability is always a limitation, but as more data becomes available at a higher granularity, health and built environment research needs to remain updated with the possible complications that might get hidden in black boxes.

Furthermore, one can also ask whether variables included in walkability indices are ontologically defined by researchers upon inclusion or included because of data availability. In other words, do the methods truly result as a definition of the variable, or do they result because of the way the dataset for the variable was available. Even though variables can be calculated because of the available variable data, it can also be created, in much the way I created street network data in Chapter 2 of this thesis. To this I add that ontological metadata can grossly ameliorate the two sides of this question that researchers struggle with and add clarity to their own interpretations of the data as well. More has been offered on this ontological quest by Schuurman and Leszczynski (2006). This also opens the black box that walkability calculations can sometimes be.

Walkability researchers themselves can begin by defining very clearly by answering ‘What is walkability’ so that their subsequent methods and results can be contextually better understood. The next step would be to define and justify the choice and measurement of built environment variables. Since no two configurations of the built environment are the same, defining and explaining the choice of variables would help readers and users of walkability indices for a particular city or area understand the particularity of the built environment. For example, what about the study area necessitates a higher weighting of land use mix versus connectivity, and so on. In this way, the justification helps provide context that is made accessible. This would also help open those aspects of walkability calculations that remain a black box.

Indeed, there are several walkability indices that are currently in use, some purely algorithmic, others exploring human perceptions of the built environment. Yet others are a combination of the subjective and objective measures. Researchers have compared several of these indices and discussed their relative merits (Brownson et al., 2009; Ellis et al., 2016; Maghelal & Capp, 2011; Sallis, 2009; Tribby, Miller, Brown, Smith, & Werner, 2017). Yet others have developed new ways of using GIS to measure the built environment (Badland et al., 2013; Baran et al., 2008; Feuillet et al., 2015).

Many of the GIS-based walkability indices have built their measures and indices on the original understanding of the walkability index: that land-use mix, residential density and connectivity together provide the basic aspects of the built environment that facilitate physical activity (L D Frank et al., 2005). For this reason, this thesis considers only those objectively measured GIS-based walkability indices that were the core indices upon which others have been built. Indeed, there are others that push the boundaries of what is even considered walkable by researching perceived and observed walkability and comparing these to objective walkability (A. Moudon et al., 1997; Ozbil et al., 2011).

One of the newer studies has been collecting data on the morphology – or changes in urban form – occurring in the United Kingdom, and using the metrics of these to also understand the correlation with changes in health (Sarkar, Webster, & Gallacher, 2015). This is one of the finer examples of using more granular spatio-temporal data to understand the relationship between health and the built environment. While different from walkability, it builds on the socio-ecological model of health to measure the various social, economic, and political variables – not only the 3 representing the built environment – that can represent various scales and temporal segments at which human health is affected by their environment.

Again, this study shows one of the ways in which concepts of measuring the environment that were developed by different disciplines – architecture, landscape architecture, computing science, etc – contribute to our understanding of how the environment affects health. As we expand our understanding and disciplines of researching this complex relationship, it is even more vital that we understand the ontological role of boundary objects and strive to make our language clearer and more concise when we describe the built environment in datasets.

We are at a time in research where many more methods of calculating the ability of the built environment to facilitate walking exist. From the design of street furniture to the more global connectivity of individual streets, more definitions and aspects of the built environment have been included in indices or measures that can describe this facilitative ability of the built environment. And yet, one can ask whether we should still be talking about ‘walkability’.

The original creators of the walkability index created it because research on physical activity at the time was only concerned with vigorous physical activity, but not with low-to-moderate physical activity (Saelens et al., 2003). The simplest physical activity accessible to most people is walking (Owen, Humpel, Leslie, Bauman, & Sallis, 2004). Researchers were considering the difference between unwalkable and walkable built environments and their effects on cardiovascular and other disease and physical activity. The link between the built environment and disease reduction was walking.

Walkability, I argue, is as relevant as it was before, but also requiring clarity of the purpose it is calculated for, and deeper methodological consideration. The methods that have evolved for different purposes have brought much lucidity on this matter, but there is always room for improvement (Andrews et al., 2012). Indeed, walkable built environments hold the ability to improve health and increase likelihood of walking as well, and yet the methods and spatial units used to calculate them must be clarified.

In fact, what is walkability? This thesis would show that it can be understood to be anything by any number of researchers and disciplines. Walkability as a boundary object is commonly understood as aspects of the built environment that facilitate physical activity; but the scale at which it does so, the kind of physical activity and the time at which it does so, can all be defined differently by each researcher. Therefore, walkability cannot be given any one single definition; as a boundary object walkability still brings relevancy to various disciplines researching the built environment.

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