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Urban Walkability Measures: Data Quality, Cautions, and Associations with Active and Public Transportation Across Canada

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Graduate Program in Geography

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Abstract

Geographical Information Systems (GIS) has emerged as a primary tool to study the built environment (BE) and its correlates. Accurate results employing GIS-based methods, however, depend on high-quality data sets and agreement on the appropriate nature and scale of areal units. Exploratory groundtruthing exercises illuminated possible issues of data accuracy. GIS-derived walkability measures for intersection density and land use mix were calculated for 2011 using Census of Canada data to determine whether commercially- or municipally-sourced urban data sets were better suited for BE studies. Road network data were ‘cleaned’ to remove unwalkable sections of road and to repair instances of intersection overrepresentation. Results suggested that municipal land use data and commercial road network data were ideal and both sources of data have benefits and limitations that should be discussed prior to any large research analysis. The second major analysis in this thesis utilized DMTI road and land use data and journey-to-work transportation data for three Canadian census years – 2001, 2006, 2011 – for thirty-three Canadian Census Metropolitan Areas (CMAs) to determine if a Canada-wide association between walkability and active and public transportation (AT/PT) exists. Using a Spearman’s Rank correlation matrix, walkability was positively associated with AT, PT, and AT/PT ($r = 0.324 - 0.459$; $p < 0.01$) and negatively associated with median household income and age of development ($r = 0.124 - 0.222$; $p < 0.01$) for all three census years. Study findings can be used to inform urban transportation and public planning policies dependent on multi-modal transit networks.

Keywords

Urban, Walkability, GIS, journey to work, neighbourhood, active transport, public transport.

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1 Chapter 1 - Introduction

1.1 Introduction

This dissertation focuses on the Canadian urban built environment (BE) and its effects on urban walkability and multimodal transportation. It utilizes Geographic Information Systems (GIS) to examine neighbourhood walkability in cities across Canada and how it associates with the utilization of active and public transportation (AT/PT), with respect to the journey-to-work census data. Issues surrounding data types and associated data accuracy are also discussed within the larger realms of urban geography and built environment studies while suggesting best practices to prepare large datasets for analysis. This chapter begins by providing a brief contextual background and overall organization to the thesis. It briefly introduces some modern approaches to urban planning and design in terms of fostering increased alternative transportation options and concludes with a description of how this thesis integrates into the broader disciplines of urban planning, design, and transportation.

1.2 Contextual Background

Although urban geography became a separate field of study in Canada in the 1950s (Gilliland and Gauthier, 2006), it has only been since the 1990s that academics and policymakers started giving increasing attention to issues of alternative transportation modes in urban settings. This has been brought about, in part, due to changing societal preferences regarding the environment and associated urban forms (Bunce, 2004). In Canada, and as local and provincial policies shift evermore towards denser designs of urban space, efforts to encourage multimodal transportation options have moved to the forefront of urban health and planning discourse. These ideological shifts can be attributed to key urbanist movements born out of the United States, most notably New Urbanism, Smart Growth, and Transit-Oriented Design (TOD).

While New Urbanism tends to focus on the design and integration of land uses within a neighbourhood, Smart Growth takes on a more comprehensive, region-based approach. However, it can be argued that Smart Growth is more applicable to the

American context. Many urban conurbations contain multiple, small municipalities. Highly-fragmented urban political realms can breed competition and inequality; Smart Growth's regional approach seeks to eliminate some inherent inequality by increasing local government collaboration in the design of urban areas.

Of particular interest to the Urbanist movement is the influence of the BE on AT/PT usage. This might be attributed to the influence of TOD. TOD is a concept focused on mixed-use urban forms, which seek to increase potential rider/usership for multimodal transportation options. TOD underpinnings tend to focus on land use mix and population density (Fisher, 1994). Focusing built density and land use mixtures around key transit hubs or corridors through greater building heights and multi-use zoning bylaws not only increases potential ridership, but capitalizes into greater land values which foster higher and better uses, thus catalyzing more efficient use of municipal lands (Bartholomew & Ewing, 2011; Cervero & Duncan, 2002; Hess & Almeida, 2007; Knapp, Ding, & Hopkins, 2001). Expanded to a municipal or regional level, it becomes clear how TOD can have a substantial impact on the viability of a city's or region's multimodal transportation options. In fact, current survey-based literature shows that demand exists for these types of urban forms (Belden Russonello, & Stewart, 2003; Belsen Russonello, & Stewart, 2004; Handy et al., 2008) and demand is likely to increase (Myers & Gearin, 2002; Nelson, 2006). Thus, focusing development in this nature could have monumental effects on the viability of municipalities and their associated assessments and property revenues (Bartholomew & Ewing, 2011).

It is no surprise then that popular urban measures used to quantify the BE include measures of land use mix and population density. Often combined within an index referred to as a 'walkability index', urban data is quantified to a predetermined areal unit and compared against data pertaining to transport and/or health metrics to identify potential associations (Frank et al., 2006). These types of studies are known in travel behaviour as aggregate or ecological studies and have become popular over the last decade in North America due, in part, to municipal open data initiatives and the availability of commercial data sources. Data proliferation, however, does bring its own potential drawbacks. Data is often not created equally, thus comparing multiple

municipalities through multiple or different datasets might identify data errors. Further, the raw data itself can be inaccurate and might require a level of groundtruthing or stewardship before beginning any complex analysis.

1.3 Research Questions

The above context was drawn from background literature reviews and established the foundation for the following research questions:

1. Are municipally-sourced road and land use datasets more reliable than larger datasets, sourced from commercially-available means?
2. Are there statistically-significant correlations between neighbourhood-level walkability and the use of AT/PT within Canadian Census Metropolitan Areas (CMAs)?

This study follows a methodology similar to many recent BE and urban walkability studies (Manaugh & El-Geneidy, 2011; Mecredy, Janssen, & Pickett, 2012). Data sourced for a specific study area is input through a GIS to create walkability values which are compared to relevant health or transport data, generally at an areal unit level. However, the underlying intentions of this study are two-fold. Through the direct comparison of two types of data – municipal-source versus commercial-source – this study seeks to identify which, if either, data set is more accurate when utilized in BE studies. Further, studies tend to focus on specific urban areas or cities. This thesis intends to aggregate the data country-wide to analyze a larger dataset, free of contextual limitations that might impact specific CMAs (i.e. physical constraints such as water bodies and mountain ranges). This thesis builds upon previous works by removing these contextual limitations and considering Canada’s CMAs as a larger, united entity rather than subdivided microcosms of urban fabric.

1.4 Study Objectives

Considering these intentions, the research findings presented within this thesis are guided by the following, six objectives:

1. To examine the literature and establish a brief timeline for the progression of walkability and transportation geography.

2. To establish an understanding of best practices and study findings within areas of urban walkability and the built environment.
3. To determine the viability of large, commercial datasets and their overall benefits and limitations.
4. To suggest best practices for data cleaning and the mitigation of data inaccuracy prior to analysis.
5. To determine if any associations exist between urban walkability and journey-to-work transport data across Canadian CMAs.
6. To establish policy implications for urban and transportation planning efforts in municipalities across Canada.

1.5 Geographical Perspectives

This study uses two geographical perspectives to investigate how the BE influences multimodal transportation usage. The first is the spatial component. Through the application of a GIS-based methodology and employment of areal units as a proxy for the neighbourhood area, differences in the spatiality of urban walkability can be visualized and studied in greater depth. Additionally, spatial discrepancies in AT/PT utilization can be studied at a neighbourhood level across a 10-year temporal horizon (2001 to 2011).

The second is a theoretical component grounded in synoptic planning theory. Synoptic planning theory, as described by Lane (2005), includes the establishment of goals and targets; the quantification of, and predication on the environment; and, the concern to identify and consider many alternative policy options (Lane, 2005). Synoptic planning employs a top-down approach, while participatory planning considers a more unified approach that balances top-down policy with community development approaches that take into account the voices of residents, community groups, and other special interest groups. In this vein, the marriage of synoptic and participatory planning informs this study by not only allowing for the quantification of the urban realm and AT/PT usage, but by giving added credence to policy implications that can be directly applied to Canadian urban planning discourse.

1.6 Organization of Thesis

This thesis is organized into five chapters, inclusive of this introduction. This chapter establishes a brief background of BE and transport studies through an overview of relevant philosophical approaches to 21st century urban planning and design. The research questions and study objectives are also highlighted. The next chapter (Chapter 2) gives a more in-depth review of the literature. It establishes key historical benchmarks for urban geography, common methodologies and trends in the fields of BE and urban transportation while noting gaps in the literature for current and future study consideration.

The first manuscript (Chapter 3) focuses on data types, ‘cleaning’, accuracy, and cautions. It compares disaggregated walkability metrics of intersection density and land use mix derived from two different types of Canadian GIS data – municipal (local) versus commercial (global) – to determine if the two tend to differ significantly from one another; what elements within the data create this disparity; how they can be rectified; and, which form of data is best applied to studies of the BE and walkability. The second manuscript (Chapter 4) utilizes three sets of commercially-sourced data for all Canadian CMAs from Desktop Mapping Technologies Inc. (DMTI) and journey-to-work AT/PT travel data spanning three census years (2001, 2006, and 2011) to compare against GIS-derived BE walkability index to AT/PT utilization at a neighbourhood level.

The main topics being examined by this thesis – data quality, cautions, and associations of BE and AT/PT – are quite broad and complex with many potential impacts to academic research and planning and transportation policy. Thus, the final chapter (Chapter 5) discusses the above issues with a greater depth before distilling them into succinct arguments which lead to important methodological and policy contributions posited by the two manuscripts. The aim is to establish procedures for best practices for data collection and preparation prior to any analysis, and then use the results to inform theoretical and applied urban planning and transportation policies within landscapes of ever-changing Canadian urbanity.

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2 Chapter 2 – Literature Review

2.1 Introduction

Since the 1990s, academics and policymakers have been giving increased attention to issues of alternative transportation modes in urban settings. This has been brought about due, in part, to changing societal preferences regarding the environment. As local and provincial policies in Canada shift evermore towards denser urban forms, efforts to encourage multimodal transportation have moved to the forefront of health and planning discussions. Of interest is the influence of the built environment on active and public transportation usage. Determining what built environment elements influence residents' transportation and neighbourhood choices is paramount to planning for current, and future allocations of active and public transportation amenities.

The goal of this chapter is to further introduce the concepts of built environment, travel behaviour, and key findings in the literature; modern philosophies of urban planning, such as New Urbanism and TOD will be further examined; the Modifiable Areal Unit Problem (MAUP) will also be introduced as a key form of spatial bias pertaining to the use of areal units to delineate data aggregation. This chapter also seeks to locate the current research within the existing discourse by identifying the gaps which it intends to address.

2.2 History

Prior to the 1950s, the geographical research was almost entirely focused in the physical realm; urban geography publications were decidedly sparse. It was not until the mid-1950s when urban geography gained exposure within the broader geographical framework. Much of the early urban geographical research focused on the urban environment as a singular aspect of a much larger, more complex web of influences; however, only a few studies gained prominence in the field of urban morphology. It was not until the mid-1960s that urban morphology became established in geographical studies (Gilliland & Gauthier, 2006).

Urban morphology was the precursor for the introduction of the built environment as an area of focus. The general notion is that the built environment is the portion of the physical environment – hardscape and softscape – constructed by human activity (Saelens & Handy, 2008) and includes every element from street furniture up to large skyscrapers and residential complexes.

Originally, despite a large number of urban researchers, very few were focused directly on these built environment dimensions rather than regional densities and structures. Over the past three decades, however, there have been a large number of important, Canadian built environment studies that have addressed a variety of its elements. Studies on such topics include, but are not limited to, office building morphogenesis (Gad & Holdsworth, 1984, 1985, 1987a, b, 1988); the evolution of different forms of housing stock (Dennis, 1994; Evenden, 1997; Gilliland & Olson, 1998); urban-suburban fringe residential landscapes (Harris, 1996, 2000); ‘micro-morphology’ of individual households (Gilliland, 2000); and, transportation reactions to evolving street networks (Gilliland, 1999, 2002).

2.3 Forms of Urban Development

2.3.1 Urban Sprawl

At approximately the same time, an ideological struggle was developing at the heart of urban planning discourse. Increased suburban development commenced at the beginning of the post-WWII era in North America. This type of urban growth erupted in response to social and economic pressures of a growing middle class, larger families, and the establishment of the automobile as the main form of personal transportation. These factors made low-density, segregated urban forms not only feasible, but preferred, and set in motion the next seventy years in North American expansion (Arbury, 2005; Newman, 1992). This type of development is generally referred to as urban sprawl and is highlighted by low-density development, leap-frog development, segregation of land uses, automobile-dependence, and a lack of activity centers with no centralized planning or land-use control (Burchell, 1997a; Burchell, 1997b; Burchell & Mukherji, 2003; Burchell *et al.*, 1998a; Burchell *et al.*, 1998b; Burchell *et al.*, 2000). Downs (1998a,

1998b, 1999) notes that not all suburban development is sprawl; rather, it is a particular type and might be exacerbated in some contexts by highly-fragmented political systems, especially in the United States (Downs, 1999). Highly-fragmented urban politics can increase inter-municipal competition and cause a disjointed form of development due to a lack of regional planning mechanism to streamline regional growth and development (Tindal & Tindal, 2006).

2.3.2 Alternative Forms of Development

In response, movements to curb outward growth pressures developed. The two most popular approaches were New Urbanism and Smart Growth, both of which include principles espoused by the concept of Transit-Oriented Design (TOD). The seeds of these urban development forms can be traced back to the growth management policies in the 1960s, 1970s, and 1980s (Burchell *et al.*, 2000; Gillham, 2002), and other antecedents such as housing reforms and anti-exclusionary zoning policies (Burchell *et al.*, 2000). All three concepts share similar criteria and can be defined as medium-to-high density development forms that emphasize human scale attributes, public realm domination and active street frontages, multimodal transportation opportunities, and brownfield redevelopment/adaptive reuse within highly connected, mixed-use communities (Litman, 2009). Figure 1 visualizes the evolution of street networks through two centuries of urban form. It illustrates the shift back towards a more linear, interconnected pattern of roads rather than the proliferation of crescents, cul-de-sacs, and disconnected ways seen in the mid-to-late 20th century (Wheeler, 2003).

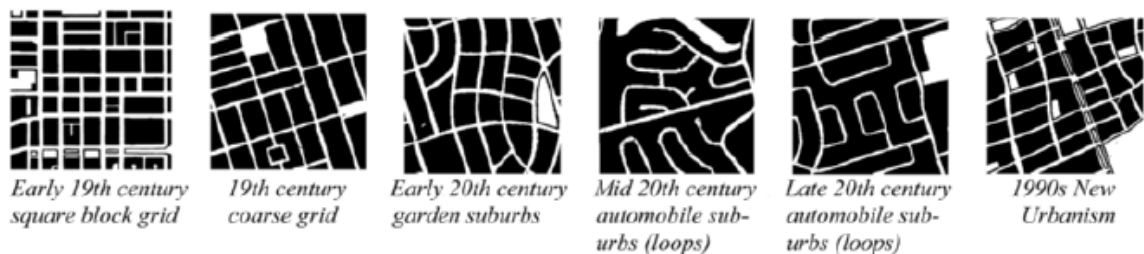


Figure 1: Evolution of street network topologies in Toronto, ON (Wheeler, 2003)

However, while all three terms can, in some instances, be used interchangeably (Grant, 2009), there appear to be some subtle differences. Smart Growth tends to be a

regional structure, especially in highly-fragmented urban areas and possesses a greater political, collaborative component (Litman, 2009), while TOD is flexible; its principles can be applied broadly (i.e. regional) or to individual developments to facilitate greater transit usage.

2.3.2.1 Impacts on Canadian Policy

These alternative urban concepts have become so influential that Canadian urban areas have begun to implement similar policies (Filion, 2002, 2003). Toronto, Canada's largest urban region has consistently had one of the highest urban densities in North America. Intensification has been a part of planning practices in Toronto for the past couple of decades (Bunce, 2004). Toronto's new Official Plan focuses on urban intensification and brownfield redevelopment as key drivers to attract private investment and skilled labour to the downtown. These initiatives were intended to bolster the economic success of the region for the next thirty years (Bunce, 2004).

Other Canadian urban areas including the Greater Vancouver Regional District (GVRD), Calgary CMA, and Markham have all adopted forms of Smart Growth policy (Grant, 2009). The City of London has not only established a form of Smart Growth policy called Placemaking (City of London, 2007), but their new Official Plan draft – the London Plan – is, in a sense, a city-wide form of TOD, where strict infill and intensification policies are directed around proposed rapid transit corridors that dissect the city north-south and east-west and are interwoven with a denser network of multimodal pathways and transport options (City of London, 2015).

2.4 Built Environment and Walkability

While urban planning and city development ideologies have been shifting towards denser, multimodal, environmentally-conscious forms, a particular type of built environment study has also been gaining visibility across multidisciplinary lines. This particular form of analysis has sought to quantify the built environment in an attempt to determine the degree to which it influences or associates with a variety of dependent outcomes. Over the last decade, built environment quantification has slowly evolved into the study of urban and neighbourhood walkability, and the number of studies utilizing

this approach has grown drastically and proliferated from geographical and planning realms into a multitude of health disciplines.

Built environment studies of this nature employ indices to quantify the perceived walkability of a neighbourhood or neighbourhoods. The walkability index most commonly utilized in these studies is often attributed to Frank, Andresen, and Schmid (2004) and is hereafter referred to as ‘Frank’s Index’. This particular walkability index is often calculated to predetermined areal units using Geographic Information Systems (GIS) and generally employs three or four metrics including connectivity or intersection density; land use mix, presented as an entropy index; population density; and, commercial floor area ratio (FAR). If a three-metric walkability index is employed, it is FAR that is normally excluded, possibly due to a lack of FAR data for a study area. This exclusion does not necessarily have a detrimental effect on the overall robustness of the index. Abridged walkability indices with three variables often correlate strongly with those employing four (Mayne et al., 2013) and are widely used. Raw values for each metric and areal unit are converted to z-scores, where they are summed to return a walkability value for each areal unit. These walkability values create an independent set of values to compare against any number of dependent variables. Examples of dependent variables differ by academic discipline but have begun to examine more health and transportation outcomes including Body Mass Index (BMI), utilitarian walking, leisure walking, physical activity, cycling, and automobile usage.

2.5 Built Environment and Transportation

It is also this quantification of the built environment and growing accessibility to Geographic Information System (GIS) data that has allowed for the increased integration of built environment and travel behaviour studies. Travel behaviour studies that employ real world data generally fall into two categories: Disaggregated (Individual level) and Aggregated (Ecological or Area-level).

2.5.1 Disaggregate and Individual-Level Studies

Disaggregate, or individual-level studies focus on travel behaviour at an individual or a household level. These studies may use areal units to differentiate data; however, the

areal unit is not the focus of the analysis. Disaggregate studies focus on the individual or household, rather than a population within an areal unit. Travel data is generally collected using qualitative methods including surveys, questionnaires, and activity or travel diaries to document how an individual or a household travels for work or leisure over a given period of time (Handy, 1996a). Disaggregate studies will generally also employ multivariate statistics to study the relationship. This can become overwhelming if larger urban areas, or multiple areal units are being studied using this framework. However, if executed correctly, disaggregate studies are quite helpful for alluding to causal relationships (Handy, 1996a).

2.5.2 Aggregate or Ecological Studies

Aggregate, or Ecological studies are essentially the opposite of disaggregate or individual-level; they focus their analysis on a grouped population at an areal unit level, rather than individual or household. The ‘neighbourhood’ is the most commonly employed areal unit, which are derived either by arbitrary means or by using existing built and physical environmental boundaries such as arterial roads, rivers, and parkways; or enumeration areas, including dissemination areas, census tracts, or urban political boundaries. Census data is a common input for aggregate studies because it is readily available through governmental sources and is already aggregated to the desired areal unit, although, it is worth noting that travel data can be collected at a disaggregate, or individual, level, aggregated, and then used if appropriate census data is not available at the required unit level (Handy, 1996b). Through the application of various forms of multivariate and spatial regression modelling, aggregated built environment and travel pattern data can be analyzed quickly at a spatial unit level to determine if statistically significant relationships exist. This is advantageous if large, or numerous, urban areas are being studied simultaneously. Aggregate studies, however, will only allow correlation to be determined. Causation cannot be concluded, only suggested, from aggregate study results.

2.6 Key Findings

Built environment studies operationalizing areal units to analyze aggregated transportation tendencies have been employed broadly. Larsen, Gilliland & Hess (2012) studied children's travel behaviour between school and home locations using 100-metre corridor buffers in London, Ontario. They discovered that the percentage of single detached homes, street tree density, and land use mix were all positively associated with active travel in children ($p < 0.05$), while distance between home and school was negatively associated with active travel at the same alpha (< 0.05) (Larsen, Gilliland & Hess, 2012).

Mitra and Buliung (2012) focused their study on Toronto, Canada. Using 200, 400, 800, and 1,000-metre circular buffers around student's homes, the research determined that average block density, number of signalized intersections, walking density, and presence of schools were positively associated with active transport in children, while travel distance was negatively associated ($p < 0.01$) (Mitra & Buliung, 2012).

In the United States, Frank et al. (2010) created a four-variable walkability index to study journey-to-work and travel patterns in King County, Washington and Baltimore-Washington DC regions. Census data was stratified based on income level and showed that high-income earners were 4-6% more likely to walk to work if located in a highly-walkable neighbourhood, while low-income earners were 4-7% more likely to walk to work if in a highly-walkable neighbourhood (Frank et al., 2010).

Internationally, Lin and Chang (2010) studied active travel to and from school in Taiwan at a Li level, which is a similar proxy for neighbourhood size to the DA. They concluded that different variables were significant when comparing travel to, and from school. Tree and shade densities along with sidewalk coverage were positively correlated with active travel to school, while intersection density and block size were negatively associated ($p < 0.05$). With respect to active travel from school, however, built density was positively associated, while road width was negatively associated ($p < 0.05$) (Lin & Chang, 2010).

Van Dyck et al. (2010) studied walkability in twenty-four neighbourhoods in Ghent, Belgium. Walkability was calculated and accelerometer data aggregated at the statistical sector level using a GIS. It was found that highly-walkable neighbourhoods correlated highly with greater accelerometer minutes ($p < 0.001$), transportational walking, recreational walking, and less motorized transport ($p < 0.05$) (Van Dyck et al., 2010).

Distance, or proximity to a destination, does not only affect active travel in children or walking; it also affects recreational cycling as well. Cervero et al. (2009) studied recreational walking and cycling in Colombia by operationalizing 500 and 1,000-metre circular buffers as proxies for neighbourhood and extended neighbourhood boundaries. They discovered that proximity to cycleways, along with street density and connectivity, were all positively associated with increased leisure cycling (Cervero et al., 2009).

As noted earlier, Frank's index has been utilized in urban geographical and health research in increasing frequency since the early 2000s. This is no different in travel behaviour where numerous studies have applied Frank's index in its complete, or an abbreviated format and have published similar results. Badland et al. (2012) and Frank et al. (2007) both concluded that the entire index was positively associated with leisure and utilitarian walking (Badland et al., 2012; Frank et al., 2007). However, other studies have noted that only one or two variables are positively, and significantly, associated with active travel. In these instances, land use mix and intersection density were positively-associated with active travel (Beenackers et al., 2012; Cerin et al., 2013; Dalton et al., 2011; Saelens et al., 2012).

In contrast, Christian et al. (2013) utilized the Frank index to study self-reported walking in Australia using 1.6-kilometre network buffers around participant's homes. The authors concluded no significant relationships between walking and any variable of the Frank index. They did, however, note that residential density, land use mix, and street connectivity did exhibit positive, but insignificant associations with walking (Christian et al., 2013).

Additionally, Kerr et al. (2010) utilized 1-mile street network buffers as neighbourhood proxies to study walking duration in San Diego County. They concluded a negative association between Frank's index and walking duration in men and no significant association in women (Kerr et al., 2010).

2.7 Impacts and Issues of GIS Data

It is clear that GIS-based methodologies have become very common in built environment studies due greatly to the proliferation of data. Not only do municipal governments tend to create their own proprietary GIS datasets for dissemination and analysis, but commercial companies that specialize in GIS technologies and desktop mapping have begun to aggregate and make accessible larger datasets, provincial or federal in scale, that allow for direct comparison of municipalities using data created with identical or similar methods.

However, all data is not created equal. Often, sourced road network data contains segments that are not realistically walkable. These tend to be access ramps and freeways because they do not include infrastructure attributed to walking (i.e. sidewalks and/or pathways). Road networks have an additional consideration. If a road segment contains a median or is divided in another manner, it might be represented as multiple roadways. This becomes a problem when computing intersection density. An intersection of two divided roads, for instance, might be overrepresented by a factor of 4 or greater, depending to what degree the road is divided.

2.7.1 Modifiable Areal Unit Problem (MAUP)

The MAUP is a common spatial bias that is inherent to any study that employs an areal unit as its focus for data aggregation. The MAUP can have potentially large effects that fall into two different forms – scalar and zonal. Scalar effects refer to any bias perpetuated by the size of the areal unit employed for a particular analysis, while zonal effects refer to the orientation of areal units over a landscape of study. Scalar and zonal effects of the MAUP are discussed in greater detail in Chapters 3 and 4.

2.8 Gaps in the Literature

Findings from the majority of published studies suggest a strong relationship between built environment and associated travel behaviour (Handy, 1996a). However, these analyses tend to focus on singular urban entities and do not compare multiple cities or metropolitan areas at a state-, province-, or country-scale. There should be merit in aggregating the data from multiple urban areas within the same political context to determine if global trends exist or if commonly-analyzed cities are unique in their characteristics.

Additionally, temporal effects and changes should be considered. Analyzing associations between the built environment and urban transportation for a single study year affords a snapshot but fails to consider change over time and if a particular urban area is trending towards greater walkability and/or multimodal transportation usage or vice-versa.

The scope of this study compares two types of Canadian data to determine which is better for a global study of the built environment. Data is compared for one study year (2011) at two different areal unit levels – Census Tract (CT) and Dissemination Area (DA) – to mitigate any scalar effects of the MAUP. Then, commercially-sourced data is employed to study all Canadian CMAs and draw global correlations between Canadian BE walkability at the neighbourhood level and journey-to-work AT/PT patterns and trends across three census years (2001, 2006, and 2011).

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3 Chapter 3 – Paper 1

Data Quality in Urban Walkability Measures: A Cautionary Tale

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3.1 Abstract

Understanding the built environment is paramount to our understanding of the urban realm and its effects on residents. One method used to study the urban realm is the quantification of the built environment using Geographic Information Systems (GIS). This is most commonly performed through the creation of a walkability index; an index which generally used three or four measures characterizing the built environment, including intersection density, land use mix, population density, and commercial floor area ratio. However, the accuracy of the index is dependent on the quality of the data. This study focuses on six Canadian cities and utilizes both commercially-sourced and municipally-sourced datasets to determine how they compare in terms of intersection density land use mix and whether, statistically, one form of data is more adequate for large-scale built environment studies. Using a combination of orthophotography and groundtruthing with Google Maps™ and Streetview™, a primary comparison of road network data determined that raw data from both sources is inadequate and needed addressing. Road networks were ‘cleaned’ to remove unwalkable sections and repair instances of intersection overrepresentation. Upon analysis, the two types of data vary substantially and in many instances are significantly different [intersection densities ($p < 0.1$) and land use proportions ($p < 0.05$)]. Municipal land use data is deemed to be more accurate because of its spatial resolution and consistent stewardship. Commercial land use data tended to severely underrepresent commercial lands within each of the study cities. Contrarily, commercial road network data often included private circulation systems such as townhouse/condominium complexes, private drives, and commercial circulation systems, which were excluded from municipal data, and thus, were deemed more accurate for intersection density calculations. Researchers should be cognizant of the type of data they employ and its inherent benefits and limits. No two municipal datasets are created equal, which makes commercial data attractive for comparative studies, but it must undergo a prescribed degree of scrutiny prior to the commencement of any rigorous built environment analysis.

Keywords: Urban, Walkability, GIS, data, areal unit, built environment, land use mix, intersection density

3.2 Introduction

Understanding the built environment is paramount to our understanding of the urban realm and effects on its residents. Developing a deeper knowledge of urban environments affords academics and policymakers the ability to more thoroughly and accurately inform modern urban planning and transportation policies, many of which have slowly shifted towards denser forms grounded in New Urbanism and Smart Growth principles. One consistent method used to study the urban realm is the quantification of the built environment. In recent years, the number of built environment studies has increased substantially, and thus, the number of methods used to quantify its features has also expanded. One of the most popular avenues is through the calculation of walkability measures. Walkability measures are commonly aggregated into chosen areal units and allow for researchers to quantify the built environment in a manner that affords relative ease of computational analysis and tends to include values pertaining to land use mix, intersection and population densities, and commercial floor area ratios (FAR).

Issues around the computation of built environment metrics have also arisen. The Modifiable Areal Unit Problem (MAUP) is commonplace in this form of analysis. Many studies incorporate entire municipalities, which tend to be large in area. Employing areal units such as census tracts or dissemination areas as proxies can create representational discrepancies in the data. Another common issue relates to data quality. Any secondary data compiled for computational analysis must be accurate or any generated results cannot be deemed reasonably acceptable.

An emerging trend in built environment studies is the acquisition and employment of commercial data sets. That is, data sets created and released for sale by commercial organizations. These sets of data can be focused to specific municipalities or can span entire countries and are commonly-used because of their accessibility and areal coverage. A number of recent Canadian studies have employed commercial data instead of municipal data as an effective way of compiling and analyzing urban data (Glazier et al., 2014; Gropp, Pickett, & Janssen, 2012; Hobin et al., 2012; Jacques & El-Geneidy, 2014; Manaugh & El-Geneidy, 2011; Manaugh & Kreider, 2013). However, questions of consistency arose during a comparative groundtruthing exercise using commercial and

municipal data in London, Ontario. The purpose of this study is to explore the nature of both forms of data, determine statistical difference, and provide cautionary notes for future research ventures.

This study seeks to quantify the built environment in six Canadian cities using commonly-employed walkability indicators applied to two distinctly different data sets from two different sources: 1) a commercially-available provider; and 2) municipally-sourced, locally-created data. These two sources of data are not created using the same means, thus, analyses using these different sources might yield different results. This study seeks to determine whether a statistically-significant difference exists, which can be used to inform future research methodologies looking to employ externally-sourced built environment data. It is extremely important to understand the accuracy and inherent limitations of data so its results can accurately inform policies related to the development and management of the built environment.

3.3 Built Environment and Walkability: A Brief Overview of the Literature

Prior to the 1950s, geographical research was almost entirely focused in the physical realm and it was not until the mid-1950s when urban geography gained exposure within the broader geographical framework. Important studies including Kerr and Spelt (1965) and Bourne (1967) established urban morphology as a major facet within Canadian geographical research (see Gilliland & Gauthier, 2006). Canadian scholars note that, despite a large number of urban researchers, very few were focused directly on morphological dimensions rather than regional densities and structures. Scholars such as Larry Bourne published numerous, popular works (e.g. Bourne, 1967,1971; Bourne et al., 1973) that helped establish an overall understanding of urban morphology without explicitly dealing with elements such as lots, streets and buildings (Gilliland & Gauthier, 2006).

Over the past three decades, however, there have been a large number of important, Canadian built environment studies on topics such as office building morphogenesis (Gad & Holdsworth, 1984, 1985, 1987); the evolution of different forms

of housing stock (Dennis, 1994; Evenden, 1997; Gilliland & Olson, 1998); urban-suburban fringe residential landscapes (Harris, 1996, 2000); ‘micro-morphology’ of individual households (Gilliland, 2000); and, transportation reactions to evolving street networks (Gilliland, 1999, 2002). Since its genesis in Canada, studies of the built environment have found relevance in such fields as urban and transportation planning, and a variety of health and medical fields such as epidemiology.

The general notion is that the built environment is the portion of the physical environment constructed by human activity (Saelens & Handy, 2008). Health, Geography, and Planning researchers tend to recognize that the built environment is a human-constructed network of elements including, but not exclusive to, roads, walkways, parks, and buildings that facilitate human habitation and interaction; however, some definitional idiosyncrasies do exist. Geographers and planners alike tend to focus on key aspects of the human-scale built environment such as land use, street network, and street design, while health researchers might lean towards proximity to amenities and provision of parks and PA facilities, while also studying neighbourhood walkability at a slightly larger scale.

This dichotomy is not without its own limitations and researchers have noted major concerns pertaining to the built environment and its measurement. Researchers tend to draw from the methods established by Frank et al. (2006) by utilizing a walkability index. Walkability indexes regularly aggregate three or four individual metrics – intersection density, land use mix (LUM), population density, and commercial floor area ratio (FAR) – into a single index, which can be studied easily against dependent variables. Policymakers, however, have had problems correctly interpreting which of the included walkability metrics is positively associated with greater walkability and incorrect assumptions have prevailed (Clark, Scott, & Yiannakoulias, 2014). This has allowed numerous other measures of walkability to proliferate the literature and can cause inconsistent conclusions.

Connectivity, otherwise known as street connectivity or intersection density, is one of the most widely-vaunted metrics used to measure the built environment. It can be

measured numerous different ways either as a density value or connectivity factor and represents the degree to which a study area's road network is interconnected. Road networks can include such infrastructure as public roads, private roads, and rear lanes. Areas with higher connectivity tend to focus on older neighbourhoods developed as a grid or quasi-grid network; they offer more avenues for vehicle and pedestrian travel; and, they have been linked with positive health outcomes such as lower BMIs and greater active transport (Mayne et al., 2013). Connectivity is also commonly used within the literature because it directly quantifies the movement networks within specified areas. Connectivity is generally described as the count of 3+ leg intersections divided by the total land area within an areal unit (see Figure 2). This relationship is represented as follows: Connectivity (expressed per land unit) = count of 3+ leg intersections / areal unit.

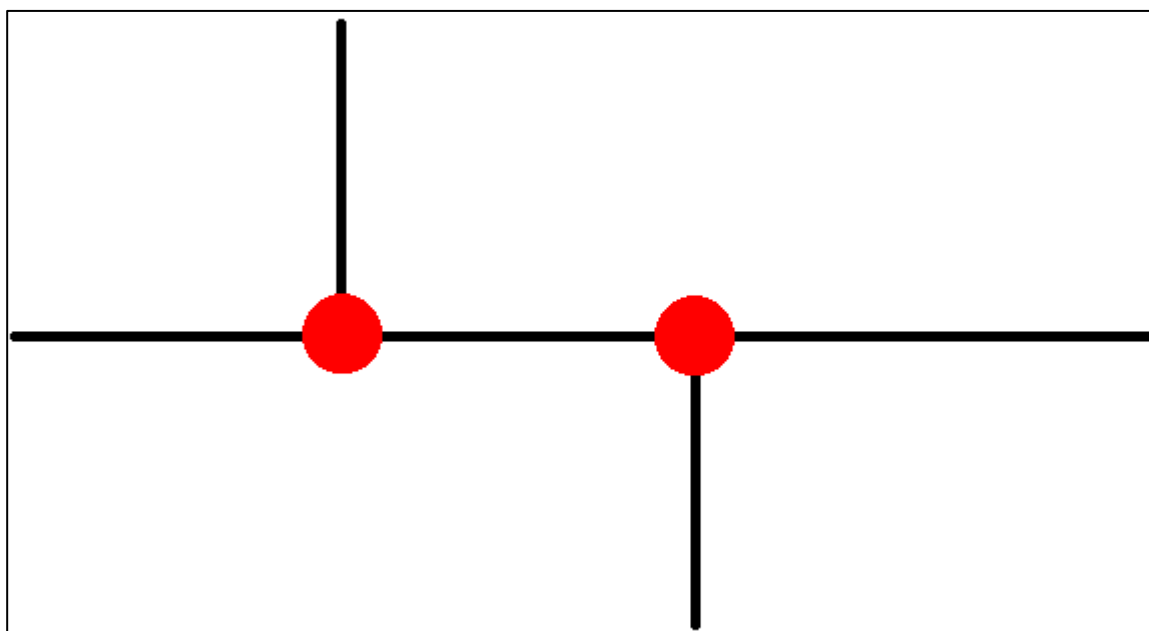


Figure 2: Graphic representation of two 3-leg intersections (Not to Scale)

The measure of connectivity varies greatly across the breadth of the literature. While many researchers adhere strictly to the street connectivity measure shown in Figure 2 to quantify the road network within their chosen study scope, researchers will also employ similar measures. Alpha and gamma indices are expressed as connectivity

factors based on formulas that take into account an areal unit's count of street segments and nodes, which represent 3+-leg intersections (Berrigan, Pickle & Dill, 2010; Grafova, 2008; Grafova et al., 2008; Leal et al., 2012; Scott, Dubowitz & Cohen, 2009). Street density is a metric that looks at the number of individual street segments within a study area and displays it as a density value (e.g. km²) (Cervero et al., 2009; Leal et al., 2012; Lin and Yu, 2010; McDonald et al., 2012; Michael et al., 2013; Rodriguez et al., 2012; Sarmiento et al., 2010; Scott, Dubowitz and Cohen, 2009; Sedatzadeh, Noland & Weiner, 2011; Shin, Kweon & Shin; 2011; Titze et al., 2010). The connected node ratio is a common descriptor that computes a connectivity factor based on the ratio between street segments and the number of 3+-leg intersections (Berrigan, Pickle & Dill, 2010; Laxer & Janssen; 2013; Leal et al., 2012; Mecredy, Pickett & Janssen, 2011). Similarly, the link/node ratio seeks to do the same as the connected node ratio, but includes other nodes (e.g. cul-de-sacs and dead-end streets) (Berrigan, Pickle & Dill, 2010; Boone-Heinonen et al., 2010; Cervero et al., 2009; Gomez et al., 2010; Hou et al., 2010). All of these connectivity metrics act as proxies for determining the degree to which a road network is interconnected.

Another widely-articulated measure of the built environment is Land Use Mix (LUM), sometimes referred to as land use density or land use intensity. LUM metrics quantify an area's land use diversity. This is done predominantly through an entropy index, but has also been approached through land use proportions, amenity counts, and recreational use densities. LUM is an important built environment measure because it affords researchers and policymakers a proxy for how close various amenities are to residents of study neighbourhoods. Areas with lower levels of land use mixing tend to be newer, suburban forms of development. They can be a product of single-use zoning policies, which encourage automobile-dependence and lower levels of utilitarian and recreational physical activity because amenities are located outside of walking distances. LUM is often calculated as an entropy index. The entropy index, represented as a value between 0 and 1, describes the degree to which land uses are heterogeneous across a chosen study boundary; higher values are indicative of greater levels of land use mixing. A 6-variable entropy index is represented below:

$$\text{Land use mix} = -A/(\ln(N));$$

where; area =

- $A = (b1/a) * \ln(b1/a) + (b2/a) * \ln(b2/a) + (b3/a) * \ln(b3/a) + (b4/a) * \ln(b4/a) + (b5/a) * \ln(b5/a) + (b6/a) * \ln(b6/a)$
- a = total square feet of land for all six land uses present in buffer

b1-b6 measure areas of land use for:

- b1= single-family residential
- b2= multifamily residential
- b3= retail
- b4= office
- b5= education
- b6= entertainment
- N= number of six land uses with area > 0 (Brown et al, 2009; Frank, Andresen, & Schmid (2004).

Although the index is argued to be an objective measure of land use mix, the number and types of designations used to quantify the land use mix within a study area is subjective. Commonly-employed indices include between five and seven discrete, but varied, land use designations. This in itself creates an opportunity for discontinuity of results since there is no specific guideline for the required number of types of land use designations used within the entropy index.

To supplement this particular measure, other measures seeking to quantify land use mixtures have permeated the literature. Retail uses have been counted within areal units to demonstrate commercial land use concentrations (Eid et al., 2008). Per capita retail densities are a similar metric, but expressed as a density per unit of population (Yang et al., 2012). Percent, or proportion, of residential land use expresses each areal unit as a percentage, based on how much is represented by a residential land use designation (Laxer & Janssen, 2013; Lee & Moudon, 2008; Rutt & Coleman, 2005). Measures of land use mix can also be subjective. NEWS and PEDS environmental audits

train observers to quantify a study area's amenities based on specific criteria (Lee et al., 2012; Grow et al., 2008).

The Modifiable Areal Unit Problem (MAUP) is another inconsistency that undoubtedly arises when attempting to measure the built environment. Areal units can be census districts and can range in size from city blocks to electoral ridings, or larger. A number of studies also use buffers as areal units. Buffers can be calculated as straight-line distances or as transportation distances along movement networks and can range in size from 200 metres to as large as five kilometres. This poses a major problem for consistent built environment research. When summarizing the literature, Brownson et al. (2009) found 18 different areal units have been employed within built environment research. Thus, it is worth suggesting that inconsistencies might exist within results derived at different scales. The MAUP can influence results based on two distinct effects – scalar and zonal. Scalar effects occur based on the level of spatial resolution [e.g. employment of a dissemination area (DA) vs. census tract (CT)] (see Figure 3). Zonal effects are dependent on the orientation of the areal units, where two different orientations of DAs, for instance, might return different results (Clark & Scott, 2014). There is general agreement in the literature that these effects can significantly influence results and researchers should be cognizant of their chosen geographical scales and possible issues that might arise.

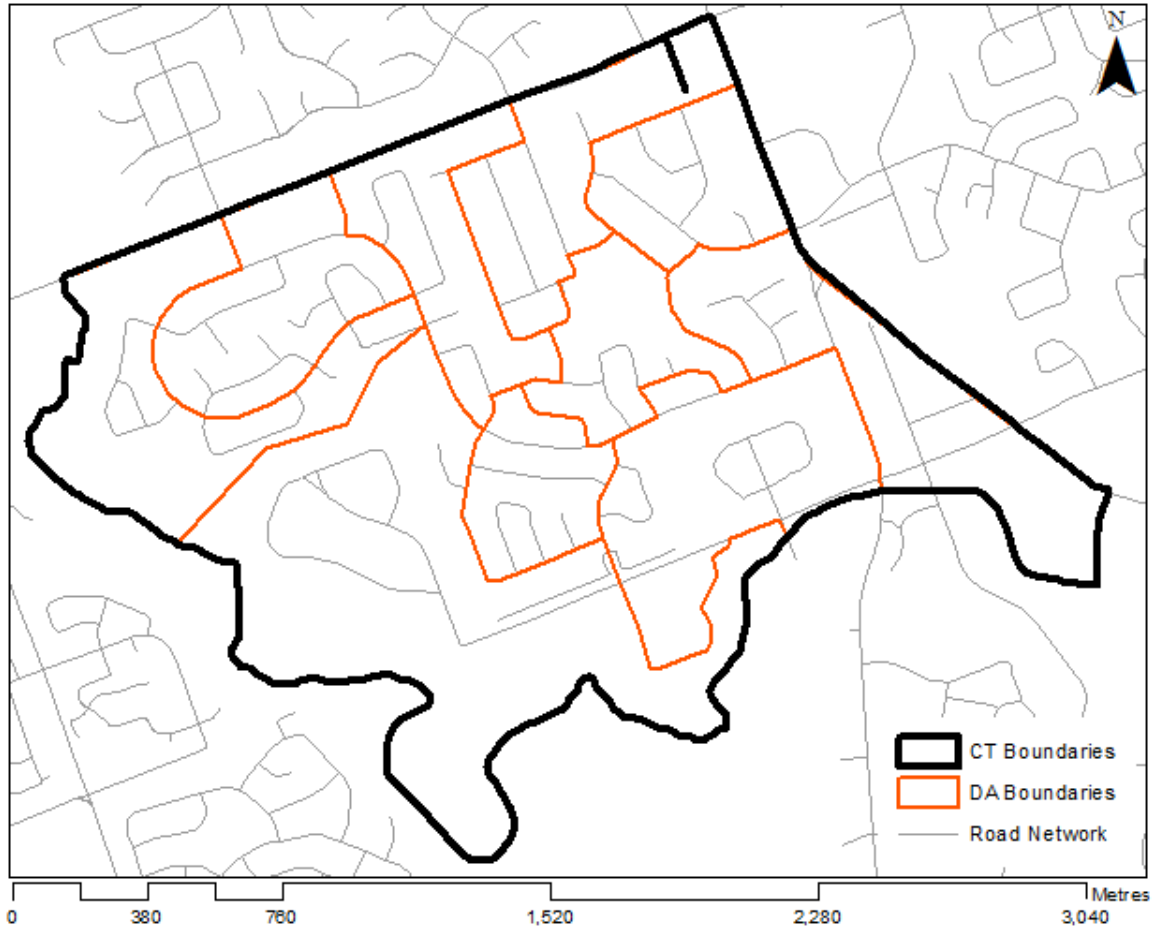


Figure 3: Spatial resolution comparing Census Tract boundaries to Dissemination Area boundaries in London, Ontario

A third important problem revolves around a study's choice of data. Commercially-available datasets such as CanMap RouteLogistics datasets from Desktop Mapping Technologies Inc. (DMTI) and TIGER/Line datasets are widely-used in built environment studies. These types of data are created using a common methodology and are global in nature. The ability to compare municipalities using consistent data is beneficial because it minimizes the potential for unique irregularities in the data's creation. Some researchers, however, employ municipal data, or data created specifically for a study municipality. Municipal data can be of a finer detail and is perceived to be more accurate than global data. The choice of data for a study can greatly influence the type of, and quality of, the derived results. A number of papers have noted that problems exist with respect to calculating intersection densities with commercial data and have

listed solutions to the associated problems. First, when major roads or expressways contain medians, they are represented as multiple lines. As a result, where multiple lines meet at intersections, each single intersection is represented by multiple points rather than a single point. This can drastically overestimate the intersection density in a given areal unit. Second, elements included in commercial data such as access ramps and expressways are not walkable features and should not be included during the calculation of walkability metrics. Some researchers have eliminated these non-walkable features prior to embarking upon further analysis to ensure accuracy of results (Glazier et al., 2008; Gropp, Pickett, & Janssen, 2012; Larsen, El-Geneidy, & Yasmin, 2010).

This research informs the literature in three important facets. First, it seeks to acquire and compare two distinctly different types of data – commercial and municipal – for six Canadian cities in the 2011 census year. Through the application of paired two-tailed t-tests of means and local indicators of spatial autocorrelation (LISA), both data sets will be compared at the dissemination area (DA) and census tract (CT) levels. DA and CT census boundaries are commonly employed in Canadian studies, as proxies for neighbourhood. Analyzing both with the same data sets should allow for this study to speak to any possible effects of the MAUP. Additionally, a study of this nature will allow for the datasets to be compared directly to determine if the two differ statistically and where these significant departures, if any, occur spatially. Second, the research discusses best practices with respect to cleaning raw spatial data, including removal of all non-walkable roadways and correction of intersection over-presentation. Third, the study suggests which datasets are better for BE studies and notes cautionary steps to justify their use in future research. As both data types are created exclusive from one another, they are inherently characterized by unique benefits and limitations, which need to be properly contextualized within any research implications.

3.4 Methodology

Data was gathered through two separate sources. Commercial CanMap RouteLogistics data was acquired from Desktop Mapping Technologies Inc. (DMTI, 2011). Municipal data was accessed directly from the cities of London, Hamilton, Sarnia, Regina, Halifax,

and Vancouver (see Table 1). These particular cities were chosen to vary the geographical location and size of the urban areas.

City	Province	Time Zone	2011 Population
Halifax	Nova Scotia	AST	414,400
Hamilton	Ontario	EST	519,949
London	Ontario	EST	366,151
Sarnia	Ontario	EST	72,366
Regina	Saskatchewan	CST	193,100
Vancouver*	British Columbia	PST	603,502

*City of Vancouver boundaries, instead of GVRD

Table 1: Six study cities, listed east-to-west

After a comparative exercise using the London commercial and municipal datasets in tandem, it was discovered that a number of land uses were inaccurately labelled and major intersections were overrepresented in the commercially-sourced data. For example, major arterial roads and expressways, where medians and/or access ramps were present, were represented as multiple roads and thus, where intersections existed, were overrepresented by up to a factor of 4.

To compare the two types of data, CT and DA boundaries for the 2011 census year were acquired. Intersection density and LUM values were calculated for both data sets, in each areal unit, across all six chosen cities to determine if a global data quality issue existed.

3.4.1 Intersection Density

Intersection node files were created in ArcMap 10.2.2 for both 2011 data sets. DA and CT boundaries were used as areal units and were intersected, respectively, with the node files. Intersection densities were calculated for each areal unit by dividing the intersection count by the unit area (km²).

3.4.2 Land Use Mix

Land Use Mix (LUM) was calculated using Frank, Andresen, & Schmid (2004)'s algorithm outlined in Section 3.3 of this Chapter. Prior to analysis, zone code definitions

for the respective cities were acquired and used to categorize municipally-sourced land use files into the following categories, consistent with commercial land use designations: Residential, Commercial, Institutional, Industrial, Park/Recreation, and Open Space. In some cases, categories were grouped to allow for a consistent analysis between commercial and municipal data (i.e. Open Space & Park/Recreation were regrouped into one category). For LUM, DA and CT boundaries were also used as areal units. Area values were computed for each land use type within each areal unit.

3.5 Analysis Method

Paired two-tailed t-tests of means were used to compare the two datasets in each container in each municipality for statistically-significant difference. Alpha thresholds of 0.1, 0.05, and 0.01 were used to determine if a significant relationship existed within each of the 12 comparisons, where a value less than any given threshold would mean that a statistically-significant relationship exists and the commercially-sourced data was significantly different from the respective, municipal data.

Additionally, LISA analyses were used to locate any significant clustering within the intersection density difference values. Difference fields were added to each dataset, where the following syntactical relationship would exist between commercially- and municipally-sourced data:

$$\text{Difference} = [\text{Commercial data metric}] - [\text{Municipal data metric}]$$

Any results with a positive difference value would note that commercial data overrepresented a specific category, relative to municipal data. The corollary would also be true, where a negative value was an underrepresentation by the commercial dataset. Intersection density and a disaggregated measure of LUM (proportion of residential land uses, represented as the percent of total areal unit) were compared via this method, while commercial land use was discussed without associated LISA analyses.

3.5.1 Intersection Density

Commercial road source data perpetuates incorrect intersection density results. This phenomenon is especially present in areal units where major arterial roads or expressways persist. These road types generally contain medians and access ramps. Since commercial datasets represent municipal roads with medians as multiple roads, a major intersection of this nature may be represented with up to ten or more nodes, thus drastically over-representing intersection counts and densities in associated areal units.

Paired two-tailed t-tests of each city's intersection density values illustrate these results. Nine of the 12 intersection density comparisons were statistically significant at the 0.01 alpha level. The three results that did not meet this trend were for Halifax [CT level ($p=0.13$)], and Sarnia [DA ($p=0.49$) & CT ($p=0.41$)] levels. Although, one should note that Sarnia appears to source their base data commercially. This could skew intersection density results.

Further, LISA clustering analyses are significant in all 12 of the datasets. LISA processes were performed on each dataset, looking for significant clustering of difference values, where the municipal intersection densities were subtracted from the DMTI results, expressed below:

$$\text{Difference value} = [\text{DMTI intersection density}] - [\text{Municipal intersection density}]$$

A number of areal units containing expressways and high-order arterial roads are represented by significant high-high clusters, noting areas where commercial data consistently over-represents intersections. This is most evident in London and Hamilton. The 401/402 expressways traverse the southern portion of urbanized London. These areas house statistically significant relationships with respect to both high-high and low-high relationships consistent with intersection overrepresentation.

Additionally, the QEW traverses Hamilton. In a similar fashion, high-high relationships are present in areal units containing the QEW and its associated access ramps. Again, this result is a symptom of the intersection overrepresentation, which needs to be addressed further.

In an attempt to combat the issues with intersection densities, the road network files for both commercial and municipal data were cleaned to better represent urban walkability and intersection provision. First, all expressways were removed. This is an intrinsic fix. There are no sidewalks present on expressways, thus, they are not walkable and would not be included in further steps of the analysis. The commercial road attribute tables were reorganized by road type. All attributes identified as highways and access ramps were removed. This was also performed with more scrutiny at the municipal data. As municipal data creation differs across Canada, extra attention had to be paid to make sure that the same elements were removed for each corresponding municipal dataset.

Second, a process was created and executed to more accurately represent the number of intersections present within respective areal units, thus solving the issue of intersection overrepresentation. Each intersection node was buffered by 15 metres and then subsequently merged and exploded to create individual polygon features for each intersection (see Figures 4 & 5 for examples). A distance of 15 metres was chosen to better represent the connectivity of the street network. In some instances, two roads would converge in close proximity on an intersecting street but would not directly align because of a variety of reasons. These reasons could include physical or environmental constraints and impediments or development and planning preferences. In reality, however, these offset roads segments would do little to deter the flow of traffic. Thus, buffering and merging nodes in close relation to one another acts as an avenue to more accurately portray the realistic connectivity of a street network.

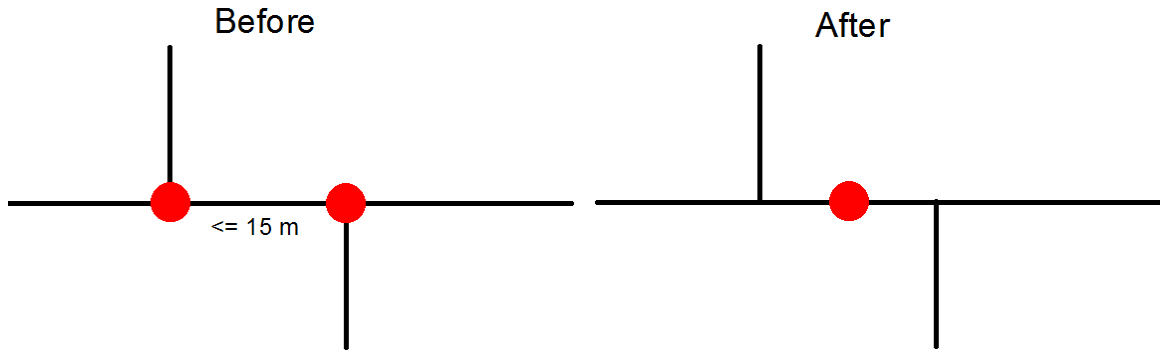


Figure 4: Example of intersection 'cleaning' along a standard municipal road

Once this was performed, the new shapefile was converted from a polygon to a point file, thus representing all nearby intersection as effectively one entity, rather than, in some cases, upwards of ten.

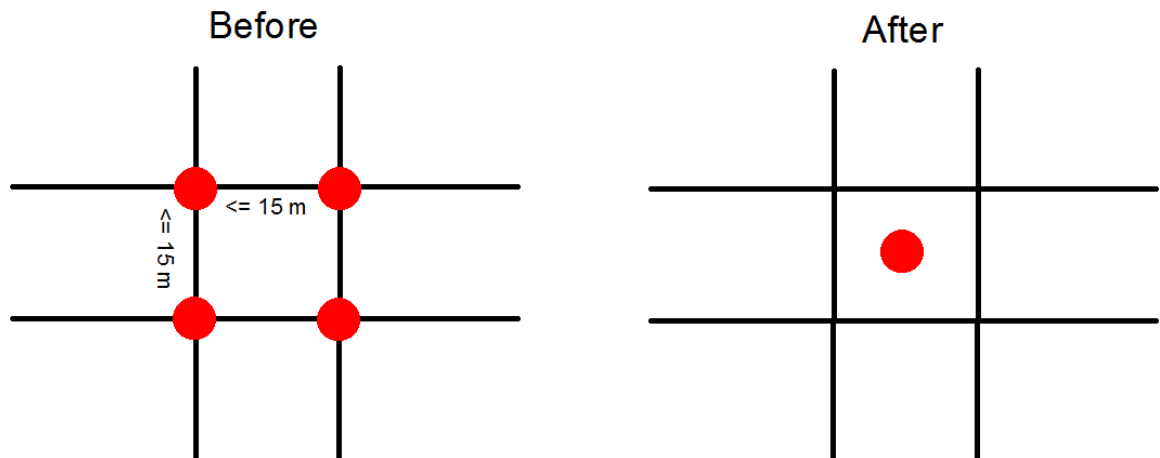


Figure 5: Example of intersection 'cleaning' at intersection of two divided roads

3.6 Results

After both sets of data were cleaned using the above method, the intersection density analysis was executed a second time. However, with respect to two-tailed t-tests, results continue to demonstrate that commercial road network data strongly differs from municipally-sourced data. 7 of the 12 comparisons returned $p < 0.1$, with 6 of those $p < 0.01$ focused on the Halifax, London, and Vancouver datasets (see Tables 2 & 3).

Cleaning the road network data did seem to benefit the accuracy of the Hamilton, Sarnia, and Regina road data. Accuracy was tested by comparing raw data against cleaned data with two-tailed t-tests. These results suggest that, in some but not all cases, will cleaning practices solve issues of this nature.

	Road Network	Land Use				
City	Intersection Density	Residential	Commercial	Institutional	Industrial	Park/Open Space
Halifax, NS	***	*	***		**	
Hamilton, ON		***	***	***		
London, ON	***	***	***			
Sarnia, ON		*	***			
Regina, SK	*		***			
Vancouver, BC	***	*	***			**

*p<0.1, **p<0.05, ***p<0.01

Table 2: DA level t-test results comparing commercial versus municipal data sources

This, however, only affords a small portion of the story. The post-intervention data returned a mean intersection density well below that of the unedited (pre-intervention) data, concluding that removing unwalkable roadways and correcting for the intersection overrepresentation issue must happen before performing any walkability analysis, as this alone will assist in improving results by a statistically significant margin.

LISA clustering analyses were applied to all 12 datasets to determine if the pattern of statistically significant instances of over or underrepresentation were consistent between both intersection density analyses. All 12 datasets were determined to exhibit statistically significant levels of clustering ($p < 0.05$). Sarnia, Hamilton (CT), Vancouver, Halifax, and London (CT) all returned results to suggest that commercially-sourced data over-represents in core areas and underrepresents in suburban and rural areas, with respect to municipal results. However, London's DA results are curious, in that they represent the opposite results to the CT data. London DA results suggest overrepresentation in the south areas containing high-order arterial intersections, and an underrepresentation in areas just to the east of the downtown core. Regina, although

significant as well, returned very few, small clusters in both areal units. Finally, Hamilton's DA results suggested no discernable pattern to the clustering, albeit significant in nature.

	Road Network	Land Use				
City	Intersection Density	Residential	Commercial	Institutional	Industrial	Park/Open Space
Halifax, NS	***		**		**	
Hamilton, ON			***	***		
London, ON	***	*	***			
Sarnia, ON			**	*		
Regina, SK			***			
Vancouver, BC	***	*	***			*

*p<0.1, **p<0.05, ***p<0.01

Table 3: CT level t-test results comparing commercial versus municipal data sources

Paired, two-tailed t-tests were applied to comparisons of disaggregated LUM and suggest a very similar result with respect to returned values for the six study cities. Of the 12 comparisons, all instances demonstrated results suggesting commercially-sourced data is statistically different from data sourced municipally.

The major reasons behind these results are the accuracy of the residential and commercial categories at the commercial level. Of the twelve analyses, commercial was statistically significant ($p < 0.05$) in all cases, and residential was statistically significant ($p < 0.1$) in 7 of the 12 cases. Institutional (Hamilton CT $p < 0.01$; Hamilton DA, $p < 0.01$; Sarnia CT $p < 0.1$), Industrial (Halifax CT & DA $p < 0.05$), and Park/Open Space (Vancouver CT $p < 0.1$; Vancouver DA $p < 0.05$) had only sporadic instances of significant difference.

LISA clustering analyses were performed on residential land uses. 10 of the 12 residential land use cases demonstrate statistically-significant clustering of difference values ($p < 0.1$); only Regina at both areal units did not.

It was decided that LISA clustering analyses would not be performed on commercial land uses because the underrepresentation was deemed to be too drastic. Given that 52 percent of DAs and 74 percent of CTs had their commercial land use provision underrepresented by the commercial dataset by 50% or greater, clustering analysis would have proved fruitless as these underrepresented departures would have been deemed normal, rather than a substantial anomaly.

This demonstrates that the commercial land use data is flawed. Municipal land use data acquired for this analysis is parcel-level or zoning-level data, which means that, in both cases, data was created from or is directly from municipal zoning information. Examples of this phenomenon are illustrated for London (see Figure 6), Sarnia (see Figure 7), and Regina (see Figure 8).

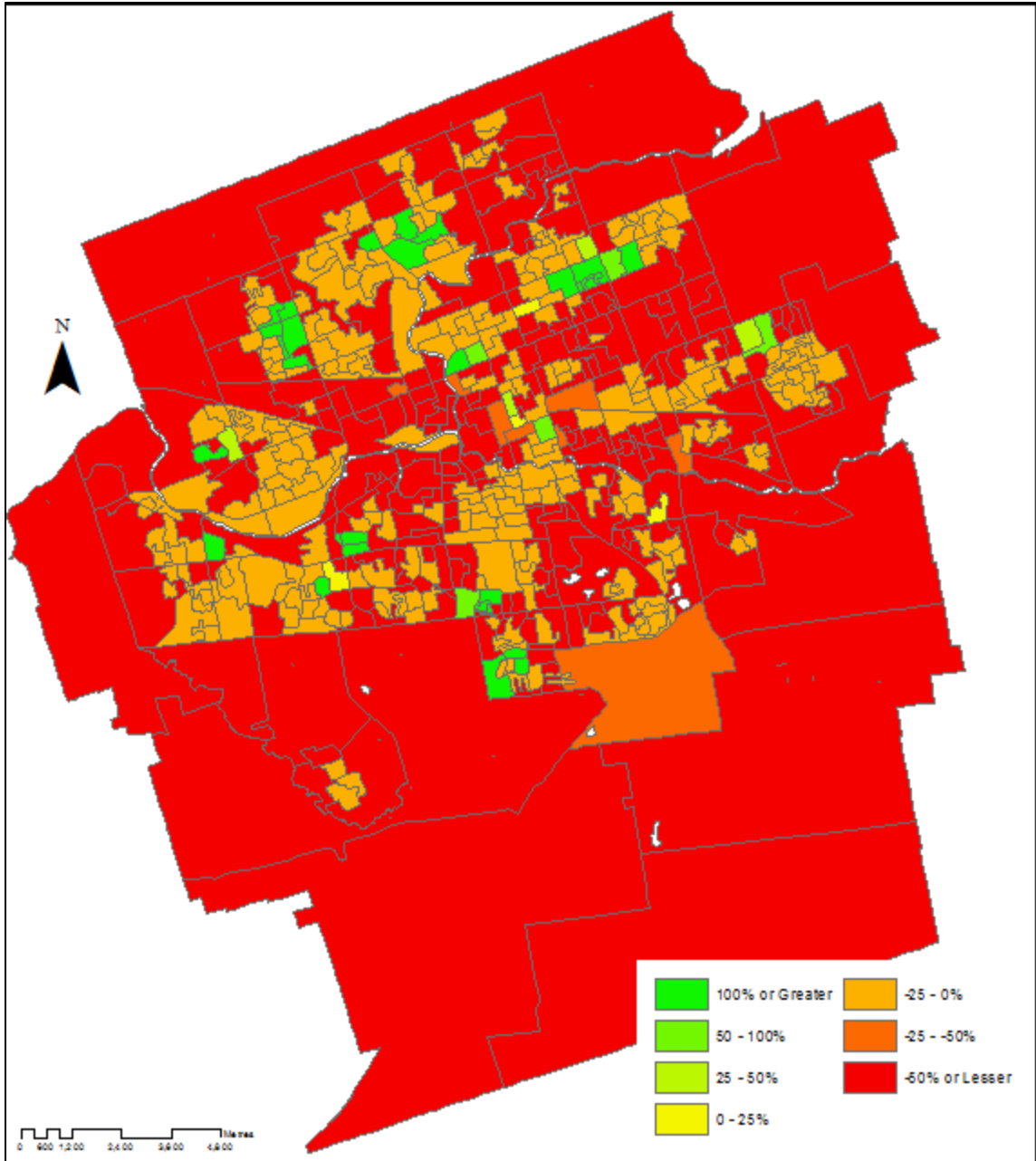


Figure 6: London commercial land discrepancy, relative to municipal data, at the DA level

Commercially-sourced data fails to identify a substantial portion of London's commercial land, whether the downtown core, automobile corridors, or shopping districts, a large portion of London's commercial land is represented incorrectly as residential or government/institutional, as noted by the green areas in London's north

end.

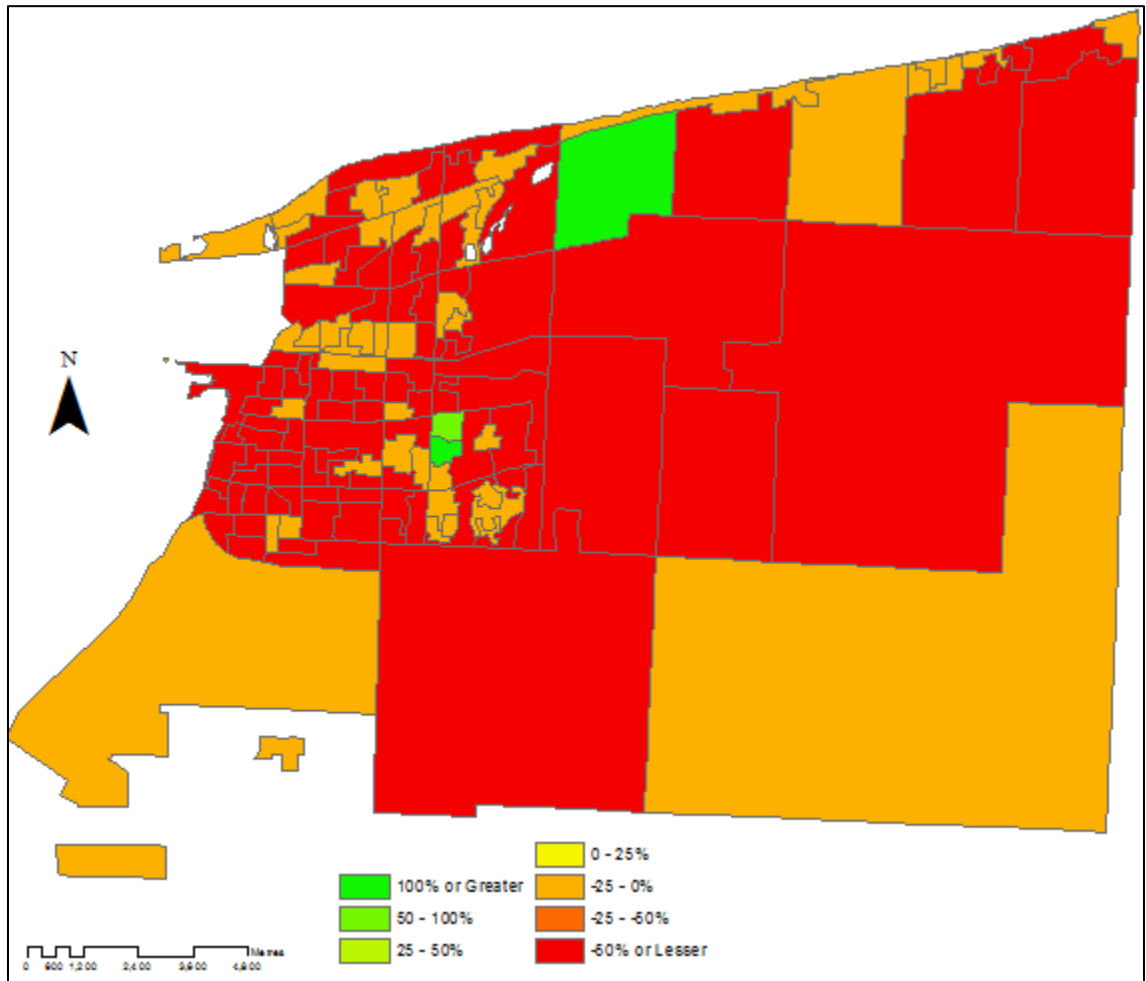


Figure 7: Sarnia commercial land discrepancy, relative to municipal data, at the DA level

The degree to which Sarnia's commercial lands are underrepresented by commercial data is striking. There are only 3 instances across the entire city where the commercial dataset managed to overstate the amount of commercial land and these areas are on the eastern and southeastern fringes of the core. The DAs that make up Sarnia's downtown contain understated commercial values ranging anywhere from 25% to 100% below municipal values.

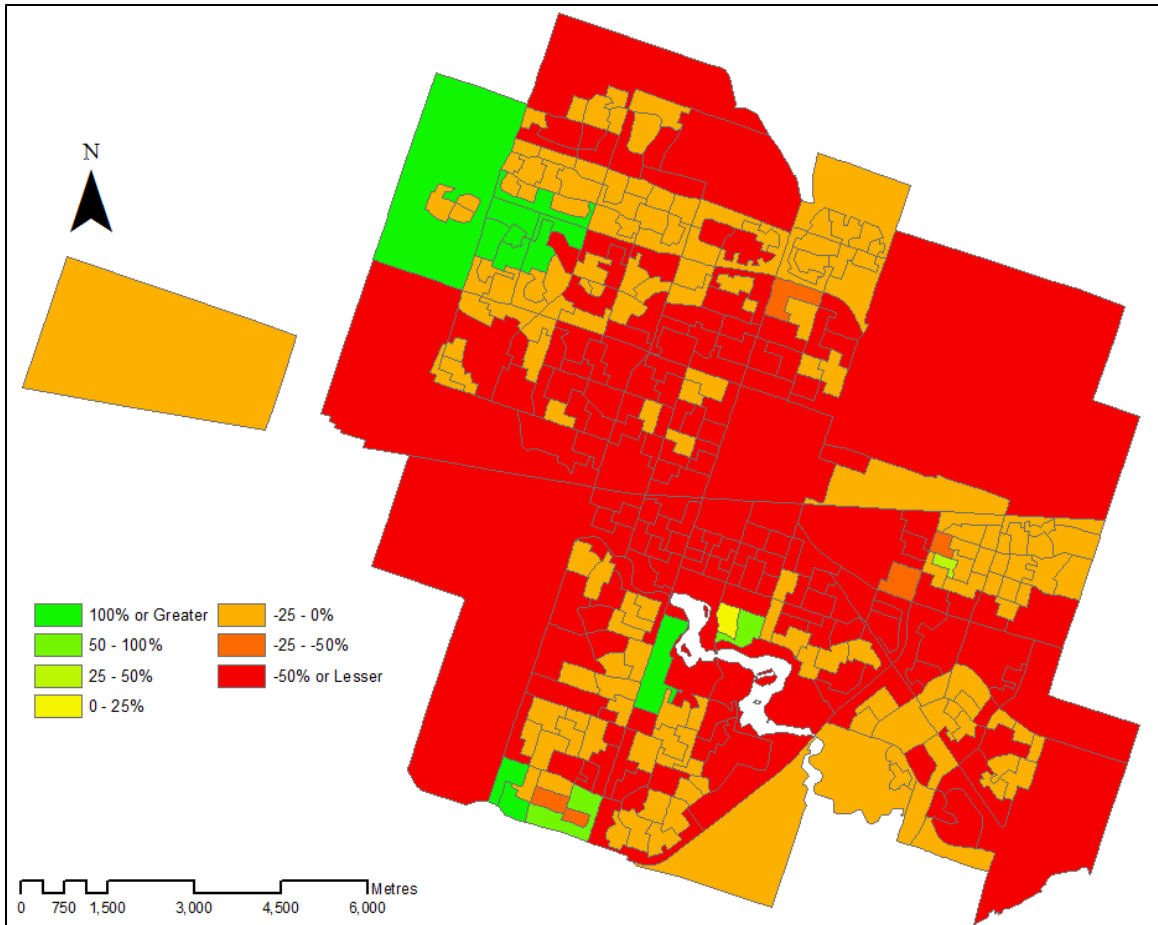


Figure 8: Regina commercial land discrepancy, relative to municipal data, at the DA level

As with London and Sarnia, the degree to which commercial data understates commercial lands is great. Only in a few instances in the northwest and south portions of the city are these lands overstated, and almost the entire core of the city is underrepresented by at least 50%, relative to municipal zoning data.

3.7 Discussion

The objectives of this paper were to quantify the built environment for six Canadian cities and determine whether statistically-significant differences existed between commercially-sourced and municipally-sourced datasets. Commercial and municipal road and land use data are not created equally. Since they are created by different organizations, potentially employing different methodologies, and the results

between the two, after correcting for issues of intersection overrepresentation, are so different one has to surmise that the datasets are intrinsically different.

3.7.1 Intersection Density

The municipal files that were obtained for this analysis contain municipal, or public, roads. Movement networks located on private lands (i.e. condominium complexes, unassumed public roads, adjacent to malls) are not included (see Figure 9.). This is evident in all study cities.



Figure 9: Private movement network (top left) not captured in municipal road data (bottom left), as illustrated by aerial imagery (source: Google Maps™)

A number of subdivisions in Vancouver have implemented rear lanes – a key element of New Urbanist planning (Duany, Speck, & Lydon, 2004). In the case of Vancouver, the municipal public roads file did not include these rear lanes (see Figure 10).

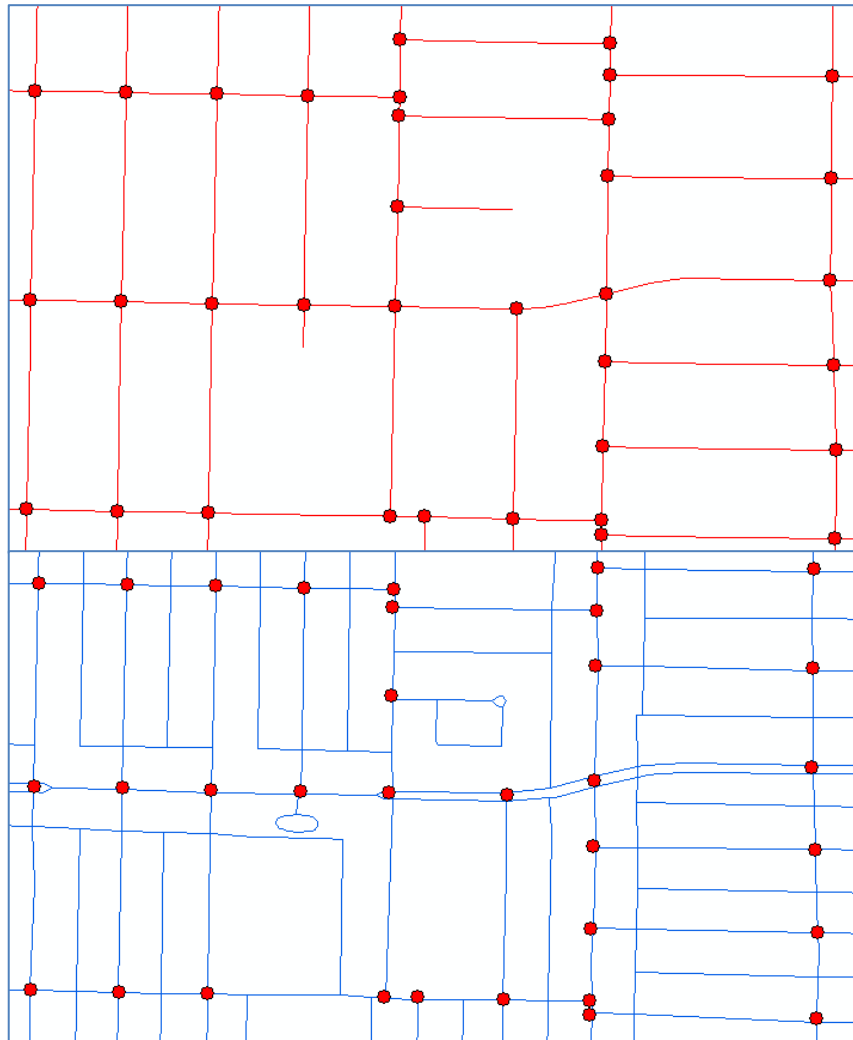


Figure 10: Vancouver municipal road network and intersection nodes (top) underrepresent circulation network due to lack of rear lanes. Commercial data utilizes rear lanes (bottom, with municipal intersection nodes to illustrate discrepancy)

This has major repercussions for the analysis of connectivity. Similar to road networks on private property, rear lanes are a viable part of a city's circulation system and should be included in the intersection density calculation. When these elements are not present, underrepresentation of an area's connectivity occurs. With respect to Greater

Vancouver, some neighbourhoods saw an intersection density 40 percent lower with municipal data than with DMTI, and this is the major culprit. While this might speak to a deficiency in public data, it also suggests that researchers should attempt to include these types of infrastructure when studying intersection density.

This explains why the LISA results for Vancouver, even post-intervention, are still representative of commercial overestimation. This is not an error in the dataset; rather, it represents an intrinsic difference between commercial and municipal data types.

In a number of instances, intersection density data was over-represented by commercial sources in the core regions, but under-represented in the suburban fringe. This appears to be linked to the nature of data versus the nature of development. Urban development is an ongoing process; it is dynamic and always evolving the urban fabric, while the data will only reflect one moment; it will not change and evolve over time automatically. Commercial data is updated and released annually, while municipal data is often updated and released on a more frequent basis (i.e. bi-annually or quarterly.) If a municipal dataset is more up-to-date than a commercial set, it will inherently have a better representation of the urban reality at that point in time. If a development had recently been erected and is captured by municipal data, but not commercial, the commercial set will under-represent that areal unit's connectivity. Over-representation, on the other hand, is a matter of methodology. In commercial data, divided roads or those with medians are often represented as two roads rather than one. This discrepancy is often present in more dense areas with larger intersections and where traffic is greater. Cleaning the data will assist in better representing intersections, but is far from perfect and this could account for the clustering in the core urban areas.

London results require some additional inference because of the curiosity of results. DAs and CTs were opposite in that DA data demonstrates overrepresentation in areas with higher-order arterial intersections while CT data notes underrepresentation. This could be two things: 1) data error; or, 2) scalar and zonal effect of MAUP. While DAs generally are not split by CT boundaries, CTs can contain up to 10 or more DAs within their scope. A CT representing a certain result might no longer do so once that

areal unit is divided up 10 or more times into DAs. Given the degree of ‘cleaning’ prior to re-analysis, it is not believed that the discrepancy, in this case, be attributed to data error. Rather, it is more likely the discrepancy is related to how the areal extent was divided (i.e. how the DA boundaries are delineated relative to CT boundaries).

The issues listed above, or combination thereof, could be reasons for why data cleaning did not rectify statistical differences in every study city. The absence of road network elements, rear lanes, and scalar and zonal effects of MAUP are evidence that not all data or analyses are perfect. In some cases, there are quantifiable results that demonstrate data cleaning creates significant change in the relationship between both forms of data while in others, the differences are not easily seen.

The above being noted, however, it is the municipal road data that requires less editing prior to analysis. Municipal roads with medians are represented as one entity and are less susceptible to overrepresentation. This phenomenon only appeared in commercial data. Within the realm of this study, after removing expressways and access ramps from the municipal data, the intersection correction procedure had little impact on the overall results. Municipal sources visualize their road networks in a cleaner, more accurate manner than commercial sources and require less editing before a meaningful analysis can commence. However, it could be argued that post-intervention, the commercial data is more robust and thus, more accurate for further use in walkability, built environment, or health studies.

3.7.2 Land Use

Regina was the only of the study cities to not exhibit statistically-significant clustering in the residential land use data. Reasons for why Regina differs from the other five cities are not readily present. One speculation is that the methodologies used to create Regina municipal and commercial data are similar, or commercial vendors are supplied some or all of the city’s land use data to use in a larger data set.

The complexity of zone codes could also have an effect on the accuracy of commercially-sourced land use data as it can be difficult to generalize zoning

information, especially in larger cities. Commercial land use data was categorized six ways and while smaller municipalities may have more simple zoning definitions, which could ease the conversion into these categories, larger cities tend to have far more complex zoning by-laws, which makes this more difficult. For instance, common zones such as Office Business Park, Office Residential, or Commercial Industrial illuminate this ambiguity. Two of the examples are hybrid Commercial and Industrial, while the other is Commercial and Residential. How these and other less obvious examples are generalized can potentially have a marked effect on land use mix calculations.

Overall, the seemingly apparent lack of land use accuracy harms researchers' abilities to accurately convey messages pertaining to the built environment's walkability and inherent association with dependent variables. Researchers should be cognizant of this glaring issue when reporting results and considering limitations of their studies.

3.8 Limitations

The MAUP always poses scalar and zonal limitations to geographic research. Results may vary based on the areal unit chosen for a specific analysis. It is feasible that results could be different at the postal code or dissemination block level; however, the DA and CT levels were used as neighbourhood proxies for this study because the literature suggests that they more accurately depict the neighbourhood in which one lives, works, and plays.

The nature of GIS data is one where a level of inaccuracy is always present. GIS data is technological representation of reality and the graphical digitization of road networks, land use boundaries, and areal unit boundaries leaves even the most accurate GIS open to scrutiny, thus, locational and attribute bias is a potential confounder for any GIS analysis.

Attribute bias was mitigated as much as possible through rigorous groundtruthing and analysis of land use data. Data from municipal land use sources were cross-referenced against municipal zone codes to categorize each attribute in a manner similar to that of the commercial land use data. Despite all bests effort, this could still potentially

pose a problem, especially if a specific zoning code was misinterpreted and, thus, categorized incorrectly. The potential for this error is magnified in larger municipalities, where multi- or mixed-use zones exist.

3.9 Conclusion and Implications

An unedited comparison of commercial and municipal data demonstrates some significant differences between the two types. After accounting for critical problems with respect to intersection density calculations, these differences still persist; differences that are inherent to the type of data being used. Commercial data includes private circulation networks, while most municipal data do not. On the other hand, municipal data is generally cleaner and requires less overall processing to make it usable for walkability analyses. This is also prevalent in the land use data. Data at the commercial level is inaccurate, with many errors, while municipal data is sourced at a parcel- or zoning-level and, after groundtruthing, is far more reliable. Researchers should take the relevant precautions prior to analyzing such data, including data cleaning and groundtruthing to confirm and rectify any possible discrepancies between the data and reality.

For intersection density calculations, the overrepresentation problem should be addressed, regardless of the dataset being employed. Expressways and access ramps should also be removed for any analysis employing a walkability index, as these particular entities are not walkable in nature. Researchers should also consider employing a dataset that includes private circulation systems, as these are viable parts of a greater, urban walkability network. Exclusion can unnecessarily skew walkability results and lead to inaccurate results.

LUM should be groundtruthed or cross-referenced with high-resolution orthophotography (as what is publicly accessible through Google Maps™ or Google StreetView™) to determine accuracy. If possible, acquire municipal land use data to employ the most accurate data possible for any LUM analysis as commercial data seem to drastically underestimate the amount of commercial lands at a municipal level.

Researchers should be cognizant of inherent limitations associated with the MAUP. Accuracy decreases when larger areal containers are employed (CT versus DA); however, sometimes it is unreasonable to use dissemination block or street segment level data, as they would be a poor overall estimator for the walkability or land use mix of a broader neighbourhood. CTs and DAs are generally used as proxies for neighbourhood area in geography and population studies (Healy & Gilliland, 2012).

This study suggests that commercially-sourced road network data is better than municipal, while the opposite is true for land use; municipal data is more accurate. Commercial road network data is superior due to its inclusion of private circulation networks and other network excluded from municipal data. Land use, however, is better at the municipal level. While issues might exist with respect to stewardship methods, in that different municipalities might have different standards for updating land use information, the data is of a finer resolution and is updated regularly (i.e. more frequently than on an annual basis, as with some commercially-sourced data). Researchers should note the type of data they choose for their particular study and state the requisite benefits and limitations for such data. Policymakers and industry practitioners should note that private circulation systems are important to the overall connectivity of a city. These tend to be excluded from municipal data, possibly because they have not been assumed by the municipality or are not yet public entities. Any analysis that takes connectivity into account should seek to include these circulation systems to increase study accuracy. Further, policies born out of similar analyses should explain the data's nature and rationale for usage so as to increase transparency with respect to the background analysis and methods.

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4 Chapter 4 – Paper 2

GIS-Derived Built Environment Walkability and Associations with Journey-to-Work Travel Tendencies in Canadian CMAs for Three Census Years

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4.1 Abstract

In recent decades, the topic of built environment has attracted a lot of attention in urban and health studies. Much focus has been paid to the impacts of the quantified built environment on a variety of health-related outcomes, including body mass index (BMI), recreational activity levels, and utilization of healthy forms of transportation. As GIS data has become more easily accessible, GIS-derived walkability indices have been operationalized to quantify measures of the built environment and have afforded researchers the ability to draw associations with dependent variables. DMTI road and land use data and DA-level census data for 2001, 2006, and 2011 were sourced to analyze the Canada-wide association between neighbourhood-level walkability within Canadian CMAs and journey-to-work active and public transportation (AT/PT) tendencies. Prior to analysis, road network data was ‘cleaned’ to better represent walkable sections and intersections. A Spearman’s Rank correlation matrix analysis was used to study the association between neighbourhood level walkability index values and AT/PT usage. Correlations between walkability and AT, PT, and AT/PT values were positive and statistically significant ($r = 0.324 - 0.459$; $p < 0.01$) for all three census years. Walkability was also positively associated with older neighbourhoods ($r = 0.079 - 0.156$); $p < 0.01$). Contrarily, walkability was negatively associated with new neighbourhoods ($r = 0.043 - 0.221$) and median household income for all three census years ($r = 0.177 - 0.222$; $p < 0.01$). Neighbourhood walkability across Canada appears to be highly correlated with AT/PT usage. Although the study cannot prove causation, it does strongly suggest that denser urban forms, land use mixing, and multi-modal transportation options should be at the forefront of urban planning and transportation policies in Canadian CMAs.

Keywords: Urban, Walkability, GIS, data, areal unit, built environment, Spearman’s Rank, active transport, public transport

4.2 Introduction

In recent decades, the topic of built environment has attracted considerable attention in urban and health studies. Much focus has been paid to the impacts of the quantified built environment on a variety of health-related outcomes, including body mass index (BMI), recreational activity levels, and utilization of healthy forms of transportation. This growing body of literature has suggested that the built environment has a substantial impact on urbanites and their live/work habits, particularly pertaining to health. Studies looking to associate the built environment and active forms of transit tend to operationalize a walkability index to quantify the built environment. Commonly, walkability indices are aggregated into areal units for ease of computation. Metrics such as commercial floor area ratio (FAR), intersection density, land use mix (LUM), and population density can, then, be analyzed directly against aggregated transportation data using statistical methods.

In response, concerns around data aggregation and the employment of areal units have been noted, specifically, the Modifiable Areal Unit Problem (MAUP). The MAUP arises when areal units are used to represent aggregated data. Scalar and/or zonal biases in the size and juxtaposition of areal units can influence results and should be addressed.

Studies of the walkability of the built environment and health outcomes tend to be executed at an individual city level or across a greater metropolitan region (Glazier et al., 2008,2014; Jacques & El-Geneidy, 2014; Larsen, El-Geneidy, & Yasmin, 2010; Marshall, Brauer, & Frank, 2009). To the best of the author's knowledge there are no known studies that operationalize a walkability index to study health associations across an entire country. This is either due to data unavailability or data inconsistency, which would impede such a study.

The present study will address this gap in the literature by analyzing the relationship between the built environment and active and public transit (AT/PT) journey-to-work data for three census years (2001, 2006, and 2011) across all urban, Canadian Census Metropolitan Areas (CMAs). The paper utilizes three Canada-wide datasets, sourced from Desktop Mapping Technologies Incorporated (DMTI). These

datasets are deemed suitable for the analysis because of its areal coverage and consistent method of creation and stewardship. The dataset was used in a comparison between commercial and local data for six Canadian cities. Despite significant statistical differences between the two types of data, the commercial dataset was accepted as usable after unwalkable road segments were removed and the issue of over-representing intersections was addressed (Chapter 3). The primary objective of this paper is to determine if global associations of the built environment and AT/PT exist across Canadian CMAs. The study will quantify the built environment, at the Dissemination Area (DA) level, through a walkability index incorporating LUM, intersection density, and population density. Using a Spearman's Rank regression matrix analysis, this study aims to determine whether statistically-significant relationships exist when associating neighbourhood-proxy walkability scores with (AT) and (PT), age of development, and median household income data across Canada for three census years (2001, 2006, and 2011).

4.3 Background Literature Review

Since the early 1990s, studies of the built environment have grown to include many academic fields; one of the most prominent of which is that of travel behaviour (Handy, 1996a, 1996b). As a response to post-war, low-density urban form, policymakers, professionals, and scholars alike began to champion a remedy – Smart Growth. Smart Growth is a regionally-focused planning form that integrates local and regional growth management policies with increases in density, service and park provision, mixes of housing types and land uses, and connectivity between and within developments (Duany, Speck, & Lydon, 2004). It also promotes walkability, multi-modal transportation options, and brownfield redevelopment wherever possible. One of the major tenets of Smart Growth type urban form is that of multi-modal transportation opportunities. Combining studies of travel behaviour and the built environment allows policymakers and scholars to demonstrate how neighbourhood built environments of different sizes, in different locations, influence associated travel behaviour (Handy, 1996a).

The first incarnation of travel behaviour studies appeared in 1945. Liepmann, a German scientist, first used 1930s data from England on bike travel to study preferred

mode of transportation. Liepmann was the first to determine that time, cost, and purpose of travel affected mode choice (cited in Scuderi, 2005). Mitchell and Rapkin (1954) were the first American researchers to study the relationship between the built environment and travel behaviour. The authors were able to predict urban travel demand by studying it as a function of the spatial locations and distributions of urban employment (cited in Scuderi 2005). Fried et al. (1977) published a comprehensive doctrine on the theory of household-level travel behavior urban areas, which helped to frame the scope of the discipline and coalesced prevailing knowledge of the time. Fried et al. (1977) noted that households and individuals are influenced by the distribution and location of resources and amenities, respectively to their own location. These resources and amenities affect how people move, for work or leisure, around an urban area (cited in Scuderi, 2005). Fried et al. (1977) also found that the major determinants of activity and travel patterns were sociodemographic in nature, and included social class position, income, ethnicity, life cycle status, and residential location (Fried et al., 1977). Travel behaviour studies were bolstered further by computational contributions from Jones (1979), which is widely considered a watermark paper introducing a paradigm shift within travel behaviour studies (cited in Buliung, 2005). The activity paradigm, introduced by Jones (1979), shifts the focus on travel studies from discrete trip making to constrained patterns of trips, based on a household's relationship with its needs and surrounding destinations (cited in Buliung, 2005). Previous reviews of activity research have noted that a lack of appropriate data made modeling travel behaviour difficult in most contexts (Jones et al., 1990; Buliung, 2005).

The 1990s witnessed a massive increase in data collection and the arrival of travel diary and activity-based methods, which allowed for more rigorous research to be undertaken (Buliung, 2005.) Dissatisfaction with prevailing urban development policies (Stopher, 1993; Stopher et al., 1996; Pas, 1997), favourable public policy, and cutting-edge data storage and analysis techniques are suggested to have stimulated travel behaviour research since the start of this decade (Pas, 1997; Bhat & Koppelman, 1999; Buliung, 2005).

Further, in light of the desire to shift from post-war urban form to higher density, more environmentally-considerate development during the 1980s and 1990s, researchers began to shift their studies of travel behaviour towards its applicability to the urban planning landscape. Applying walkability, transportation, and recreation metrics as variables allowed researchers to correlate aspects of one's built environment to one's transportation tendencies (Dalton et al., 2011). The findings of these studies began to suggest what elements of a community encourage multi-modal transportation opportunities, and thus, which elements should be included as amenities within new developments.

Measures of BE have been leveraged to help quantify the nature of our urban forms in an attempt to study its morphology against a variety of outcome variables. Recently, common BE measures have been aggregated into walkability indices, which return values denoting the degree to which an area is walkable. The walkability index implemented by Frank et al. (2006) is most widely cited and integrated three or four measures, including LUM, intersection density, population density, and commercial FAR. Policymakers have cited issues with accurately interpreting which of the walkability measures is most positively associated with greater walkability, thus allowing for incorrect assumptions (Clark, Scott, Yiannakoulias, 2014). This has allowed for the proliferation of numerous other measures of the built environment, as noted below.

Although intersection density is the most often used metric to quantify road networks – operationalized as the count of 3+ leg intersection per unit area (see Figure 11)., there are many other measures. Alpha and gamma indices are expressed as connectivity factors taking into account the raw count of street segments and nodes, which represent 3+-leg intersections (Berrigan, Pickle & Dill, 2010; Leal et al., 2012; Scott, Dubowitz & Cohen, 2009). Street density is the number of individual street segments within a study area displayed as a density value (e.g. km²) (Cervero et al., 2009; McDonald et al., 2012; Michael et al., 2013; Rodriguez et al., 2012; Sarmiento et al., 2010; Titze et al., 2010). The connected node ratio is another common measure computed as the ratio between street segments and the number of 3+-leg intersections, expressed as a connectivity factor (Laxer & Janssen; 2013; Mecredy, Pickett & Janssen, 2011). The link/node ratio is

essentially the same as the connected node, but includes all nodes (e.g. cul-de-sacs and dead-end streets) (Boone-Heinonen et al., 2010; Gomez et al., 2010; Hou et al., 2010).

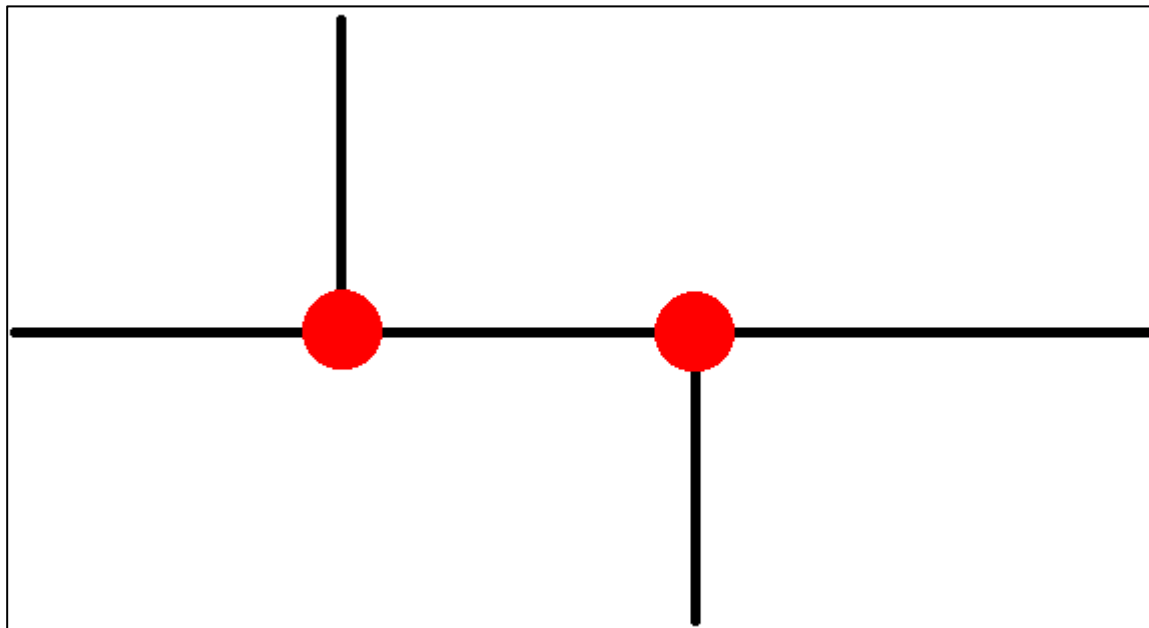


Figure 11: Graphic representation of 3-leg intersections (Not to Scale)

Although argued to be an objective measure, land use mix is subjective because the number of land use designations included in the LUM can vary. Commonly-employed indices include between five and seven land use designations. Chances for discontinuity of results arise because there is no specific guideline for the minimum number land use designations required for the LUM index to be deemed accurate.

Because of this, other measures seeking to quantify land use mixtures have permeated the literature. Areal unit retail counts demonstrate commercial land use concentrations (Eid et al., 2008). Per capita retail densities are a similar metric, but expressed as a density per unit of population (Yang et al., 2012). Percent of residential land use expresses each areal unit as a percentage based residential land use coverage (Lee & Moudon, 2008; Rutt & Coleman, 2005). LUM measures can also be subjective. NEWS and PEDS environmental audits train observers to quantify a study area's amenities based on specific criteria (Lee et al., 2012; Grow et al., 2008).

The MAUP is always a consideration when applying areal units in a study. Areal units can be census districts and can range in size from city blocks to electoral ridings, or larger. A number of studies also use buffers as areal units. Buffers can be calculated as straight-line distances or as transportation distances along movement networks and can range in size from 200 metres to as large as five kilometres. This poses a major problem for consistent built environment research. When summarizing the literature, Brownson et al (2009) discovered 18 different areal units employed within built environment research. Thus, it is worth suggesting that inconsistencies might exist within results derived at different scales. The MAUP can influence results based on two distinct effects – scalar and zonal. Scalar effects occur based on the level of spatial resolution [e.g. dissemination area (DA) vs. census tract (CT)]. In certain instances, a CT may contain upwards of ten DAs within its boundaries (see Figure 12). Zonal effects are dependent on the orientation of the areal units, where two different orientations of areal units could result in differing outcomes (Clark & Scott, 2014). There appears to be a general consensus in the literature that these effects can significantly influence results and researchers should be cognizant of their chosen geographical scales and possible problems associated with such effects.

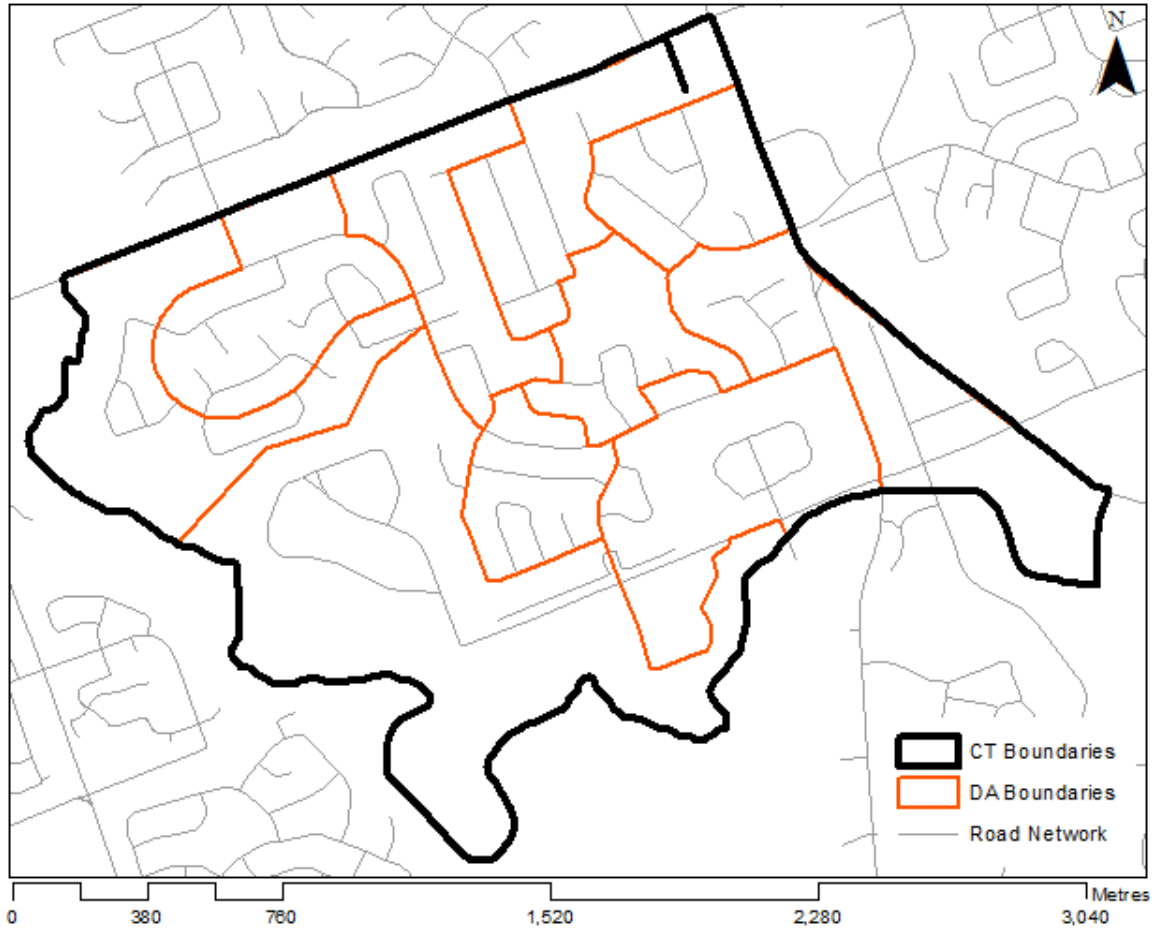


Figure 12: Spatial resolution of Census Tract boundaries versus Dissemination Area boundaries for London, Ontario

With respect to analysis techniques, numerous studies incorporate forms of regression as primary forms of data analysis (Glazier et al., 2014; Marshall, Brauer, & Frank, 2009). Regression matrices allow for large datasets to be analyzed with ease, especially when a dataset contains records or instances that are divided across a large geographical extent. The nature of the regression used depends on the nature of data and whether it violates requisite parametric tests and tests for normality. This is due to no spatial component being present to the analysis, which poses its own benefits and drawbacks. There are very few instances of spatial regression or spatial autocorrelation being used as analysis techniques. This could be due to the need for spatial proximity. While spatial regression and autocorrelative analyses would be worthy at a city-level, due to the inherent adjacency of areal units, a study at a state-, province-, or country-level

would prove difficult due to gaps in the spatiality of the respective urban fabric, which would exhibit undue influence on data visualization.

The research adds to the literature through a couple of key avenues. To our knowledge, previous studies have not compared walkability in numerous cities within Canada. . The study employs commercially-sourced datasets, which includes thirty-three Canadian CMAs, for the 2001, 2006, and 2011 census years and correlates them with AT/PT data from the Canadian census. This study not only analyzes the walkability of a breadth of urban CMAs, but does so against important transportation metrics. It also integrates a temporal dimension by studying three separate census years in an attempt to analyze any change over time, with respect to walkability and its effect on propensities to utilize AT/PT.

4.4 Methodology

The primary intent of the research is to study the effects of BE on AT/PT utilization in CMAs across Canada. To accomplish this objective, Canadian built environment data for the three subject years (2001, 2006, and 2011) was sourced from DMTI while associated census data was acquired from Statistics Canada. Data was accessed at the DA level and contained information on journey-to-work, age of development, and median household income.

Prior to analysis commencing, all road network files were cleaned to better represent global walkability. All access ramps and expressways were removed from the network and issues of intersection overrepresentation were corrected by utilizing GIS and 15-metre buffers around all intersection nodes (see Figure 13). Buffers that overlapped were processed to represent multi-point intersections as one entity (Chapter 3).

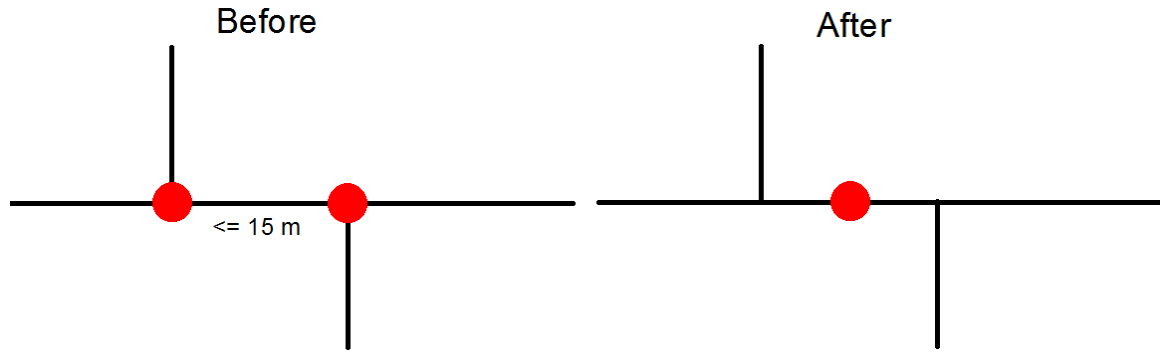


Figure 13: Example of intersection 'cleaning' along a standard municipal road

4.4.1 Intersection Density

Final intersection node files were created in ArcMap 10.2.2. DA boundaries were used as areal units for each of the three years and were intersected, respectively, with the node files. Intersection density values were calculated for each areal unit by dividing the intersection count by the area of each unit (km²).

4.4.2 Land Use Mix

LUM was calculated using the algorithm adopted by Frank, Andresen, & Schmid (2004). The land use dataset was intersected with the DA boundaries file. Area fields were added and calculated for each defined land use type (Residential, Commercial, Resource & Industrial, Government & Institutional, Park and Recreation, and Open Space) and then summarized within each, respective DA. The Waterbody land use was included within the Open Space land use type. This gives the areal extent for each land use category at the areal unit level.

4.4.3 Population Density

Population density was calculated for each census year by dividing the census population of each areal unit by the unit's area (km²).

4.4.4 Walkability Index

Using Frank, Andresen, & Schmid (2004)'s index, z-scores were calculated for each metric – intersection density, population density, and LUM – and aggregated to return a

walkability score for each areal unit. This is done to normalize the data for ease of analysis, as raw results can vary wildly between respective areal units or respective years. Further, Canadian data was aggregated into one dataset for 2001 (n=25,573), 2006 (n=34,500), and 2011 (n=37,728). This also acts to normalize the usage of z-scores. As z-scores are relative to the data from which they are derived, a z-score of -1 from study area A, for instance, might be more or less walkable than a -1 z-score from study area B if individual CMAs are analyzed discretely from one another. Aggregating the data mitigated the subjectivity and allows for a comprehensive view of walkability across the country.

4.4.5 Analysis

For this particular analysis, a Spearman's R correlation analysis was utilized. The Spearman's correlation coefficient, R, is a non-parametric statistic and can be used when data has failed specific parametric assumptions, such as normality of data; however, a Spearman's Rank can still be applied to parametric data. Spearman's test works by first ranking the data and then applying Pearson's equation (the standard parametric correlation test) to those ranks.

SPSS was used to calculate a Spearman's correlation matrix. Each variable was ranked and analyzed against all others, including itself, before being represented in the matrix output. The significance level for such a study is generally a 0.05 alpha, where a p-value < 0.05 (95%) suggests a statistically-significant relationship between any two associated variables. The relationship can be positive in nature, in that an increase in one variable will increase the second, or negative in nature, in that an increase in one variable will decrease the second.

Although direct conclusions about causality cannot be made, the correlation coefficient can be squared to produce the coefficient of determination, or R² value. The coefficient of determination is a measure of the amount of variability in one variable that is explained by the other.

4.5 Results

The Spearman's Rank analysis for all three census years returned statistically-significant results (see Tables 4, 5 & 6). At the DA level, walkability indices were significantly associated with all three transportation metrics and the three socioeconomic indicators at a $p < 0.01$ alpha level.

Spearman's rho		Walkability	Active Transport	Public Transport	Active & Public Transport	Age of Dev't - before 1960	Age of Dev't - after 1991	Median Household Income
Walkability	Coeff	1.000	.170**	.284**	.324**	.156**	-.124**	-.218**
	N		25573	25573	25573	25572	25572	25573
Active Transport	Coeff	.170**	1.000	.085**	.605**	.303**	-.063**	-.140**
	N	25573		25573	25573	25572	25572	25573
Public Transport	Coeff	.284**	.085**	1.000	.798**	.198**	-.153**	-.134**
	N	25573	25573		25573	25572	25572	25573
Active & Public Transport	Coeff	.324**	.605**	.798**	1.000	.345**	-.169**	-.204**
	N	25573	25573	25573		25572	25572	25573
Age of Dev't - before 1960	Coeff	.156**	.303**	.198**	.345**	1.000	-.228**	-.187**
	N	25572	25572	25572	25572		25572	25572
Age of Dev't - after 1991	Coeff	-.124**	-.063**	-.153**	-.169**	-.228**	1.000	.129**
	N	25572	25572	25572	25572	25572		25572
Median Household Income	Coeff	-.218**	-.140**	-.134**	-.204**	-.187**	.129**	1.000
	N	25573	25573	25573	25573	25572	25572	

** Correlation is significant at the 0.01 level (2-tailed)

Table 4: 2001 Spearman's Rank correlation matrix (n=25,573)

The walkability indices generated for Canadian CMA DAs were positively correlated with propensity to utilize active transportation (AT) ($r = 0.170 - 0.239$), public transportation (PT) ($r = 0.284 - 0.435$), and both modes combined (AT/PT) ($r = 0.324 - 0.459$; $p < 0.01$). PT appears to be the metric that contributes most substantially to the over correlation of AT/PT – a relationship that returns a moderate correlative association. The correlations between walkability and all three transportation metrics strengthened between 2001 and 2006; however, only AT strengthened between 2006 and 2011. The relationships with PT and AT/PT stayed approximately the same between the same time period (i.e. 2006 – 2011).

Spearman's rho		Walkability	Active Transport	Public Transport	Active & Public Transport	Age of Dev't - before 1960	Age of Dev't - after 1991	Median Household Income
Walkability	Coeff	1.000	.221**	.435**	.459**	.079**	-.221**	-.222**
	N		34495	34495	34495	34500	34500	34500
Active Transport	Coeff	.221**	1.000	.171**	.583**	.367**	-.188**	-.291**
	N	34495		34495	34495	34495	34495	34495
Public Transport	Coeff	.435**	.171**	1.000	.864**	.198**	-.237**	-.225**
	N	34495	34495		34495	34495	34495	34495
Active & Public Transport	Coeff	.459**	.583**	.864**	1.000	.348**	-.288**	-.338**
	N	34495	34495	34495		34495	34495	34495
Age of Dev't - before 1960	Coeff	.079**	.367**	.198**	.348**	1.000	-.364**	-.245**
	N	34500	34495	34495	34495		34500	34500
Age of Dev't - after 1991	Coeff	-.221**	-.188**	-.237**	-.288**	-.364**	1.000	.155**
	N	34500	34495	34495	34495	34500		34500
Median Household Income	Coeff	-.222**	-.291**	-.225**	-.338**	-.245**	.155**	1.000
	N	34500	34495	34495	34495	34500	34500	

** Correlation is significant at the 0.01 level (2-tailed)

Table 5: 2006 Spearman's Rank correlation matrix (n=34,500)

Walkability was also positively associated with DAs, where a greater proportion of dwellings were constructed prior to 1960 (p1960) ($r = 0.079 - 0.156$). This was the opposite for DAs, where a greater proportion of dwellings were erected after 1991 (a1991) ($r = 0.043 - 0.221$) – a negative correlation existed. Greater walkability of a DA was also associated with lower median household income ($r = 0.177 - 0.222$; $p < 0.01$).

Spearman's rho		Walkability	Active Transport	Public Transport	Active & Public Transport	Age of Dev't - before 1960	Age of Dev't - after 1991	Median Household Income
Walkability	Coeff	1.000	.239**	.417**	.402**	.122**	-.043**	-.177**
	N		37728	37728	37728	37728	37728	37728
Active Transport	Coeff	.239**	1.000	.129**	.741**	.249**	.013**	-.066**
	N	37728		37728	37728	37481	37481	37728
Public Transport	Coeff	.417**	.129**	1.000	.678**	.174**	-.090**	-.160**
	N	37728	37728		37728	37481	37481	37728
Active & Public Transport	Coeff	.402**	.741**	.678**	1.000	.287**	-.072**	-.166**
	N	37728	37728	37728		37481	37481	37728
Age of Dev't - before 1960	Coeff	.122**	.249**	.174**	.287**	1.000	-.265**	-.173**
	N	37728	37481	37481	37481		37481	37481
Age of Dev't - after 1991	Coeff	-.043**	.013**	-.090**	-.072**	-.265**	1.000	.193**
	N	37728	37481	37481	37481	37481		37481
Median Household Income	Coeff	-.177**	-.066**	-.160**	-.166**	-.173**	.193**	1.000
	N	37728	37728	37728	37728	37481	37481	

** Correlation is significant at the 0.01 level (2-tailed)

Table 6: 2011 Spearman's Rank correlation matrix (n=37,728)

However, relationships with age of development indicators (p1960 and a1991) did not become stronger over time. The strongest relationship between walkability and p1960 was in 2001, while the relationship between walkability and a1991 was 2006. The strongest relationship between walkability and median household income was in 2006 as well.

4.6 Discussion

The results are highly suggestive and appear to align with current trends in the existing scholarship. The general perception amongst academic and professional studies is that a neighbourhood that has increased walkability will avail its residents with more multimodal opportunities and thus, instances of greater use of alternative transport options, such as AT and PT, will exist (Frank et al., 2010).

It should be emphasized that, due to the nature of the analysis, this in no way determines a causal relationship. Rather, it suggests the possibility of its existence through an associative examination of the metrics. We still do not know whether a

neighbourhood, proxy, or areal unit, is more walkable because of the built environment itself or because the residents make it so.

Additionally, the general walkability of a neighbourhood appears to decline as the overall age of development decreases; older communities are more walkable. Older neighbourhoods developed in a grid road network had more intersections, were more compact, and often included neighbourhood commercial uses such as small restaurants and convenience stores. Since population density and intersection density are two of the main quantifiers of the walkability index, it makes sense that a neighbourhood surveyed in this form will garner a higher walkability value. These neighbourhoods also tend to be located closer to the core of a CMA, which generally affords closer proximity to key transportation and utilitarian amenities. Older communities also have a lower median household income, which reinforces mid-late 20th century notions of suburban expansion perpetuating exoduses of urban cores across Canada. Wealthier residents moved further away from the downtown areas because they could afford it, which left behind those who could not necessarily relocate elsewhere. It is hard to say whether the growing relationship between walkability and the three transportation metrics (AT, PT, and AT/PT) are a trend or an anomaly. As noted, relationships with PT did not strengthen between 2006 and 2011, while relationship with AT did. This is likely so because of a combination of two reasons. First, added municipal infrastructure catering to multi-use pathway systems, sidewalks, bike paths and their increased range and connectivity can encourage greater AT. Second, the resurgence of many core neighbourhoods and the willingness to live near places of work can make it more viable to simply walk or bike to and from places of employment rather than rely on personal automobiles or PT. However, research into transportation, walkability, and the built environment would have to expand its focus and analyze previous census results (pre-2001) to construct a more robust understanding of broader trends. Additionally, this study does not analyze each walkability measure individually against transportation outcomes. While the walkability index itself might be highly-correlated with these variables, the study does not shed light on which measure, if any, is more greatly associated with greater utilization of AT/PT.

We understand that prevailing literature and historical documents explain how neighbourhoods that were born out of the early-20th century were built more dense and with a grid road network. High dwelling and population densities, coupled with high intersection density values by way of a grid network, have been linked strongly to higher walkability (Frank et al., 2006). Thus, it is of little surprise that older communities continue to be more walkable, in a global sense, than their newer counterparts.

This began to change rapidly in the 1940s with the establishment and growth of suburban built form and the cementing of the automobile as a primary transportation option. This lends credence to the notion that the opposing construct is also true, where newer communities, which are decidedly more dispersed, single-use, and automobile-dependent are far less walkable because they are not built for walking as a primary transport option.

Furthermore, the notion that older, more walkable communities contain a lower median income suggests that shadows of suburban expansion and economic trends of the mid-to-late 20th century are still affecting urban environments today. In a broad sense, those who are financially-able to escape the urban realm for the quieter marriage of urban-and-rural in the suburbs have continued to do so.

4.6.1 A Reversal of the Trend?

It is worth stating again that walkability's relationships with age of development (b1960 and a1991) and median household income are not deepening; while still highly significant, their coefficients suggest a slight pull-back.

Canadian municipalities have shifted towards more economical, environmentally-sound planning and development policies in recent decades (Grant, 2002). Municipalities, such as Toronto, are adopting forms of urban design and development, which are more consistent with early-20th century, pre-automobile urban styles (Bunce, 2004). Movements such as New Urbanism, Smart Growth, Transit-Oriented Design, Sustainable Development, and associated hybrid forms have come to the forefront of planning across Canada. This has most recently been exhibited by London, Ontario. London's new

Official Plan is a marked shift in the direction of walkability, urban design, and public transportation (City of London, 2015). Additionally, recent changes to the Planning Act – known as the Smart Growth for Our Communities Act, or Bill 73 – have helped reinforce sustainable, strategic planning in Ontario. Newer development is slowly becoming more walkable, which would divert such trends that have been established over the last 70 years.

It is necessary to address the MAUP with respect to the results herein. The chosen DA scale was deemed as the most viable proxy for neighbourhood size and was operationalized as such. Utilizing a smaller areal unit, such as the Dissemination Block (DB) would allow a finer overall resolution study-wide; however, what might be gained by higher resolution would be lost when quantifying metrics, LUM in particular. Using a smaller areal unit might distort the relevancy of LUM. The catchment area shrinks, thus narrowing the potential to include more land uses in the aggregation and return a more complete rendering of the overall land uses in an areal unit. Contrarily, applying a larger areal unit, such as the Census Tract (CT), would allow for a greater inclusion of land uses for the LUM metric, but would reduce the overall resolution. CTs might also be too large of an area for a neighbourhood proxy.

Zonal effects of the MAUP area also relevant, but cannot be addressed in the same manner as scalar effects. DA boundaries are delineated by an official census body, and while they can likely be reorganized over the extent of an urban area to garner a different overall orientation, they are based roughly on population density and might skew results.

4.7 Limitations

Walkability indices have been criticized heavily in the literature for their wide interpretation and general subjectivity regarding what can be included in their computation (Brown et al., 2009).

The nature of LUM, as a measure of neighbourhood walkability, brings with it a couple of rather large limitations that can decrease its utility to agents of change at the

local, state/provincial, or federal levels. First, when studying active transportation or journey-to-work, quantifying the land use mix of one's home neighbourhood only gives policymakers half the story. To completely model the objective walkability, analyzed against utilitarian, or active, transportation, both the home and work (or destination) environments must be modelled. Some studies have even applied buffers to travel corridors themselves to model the changing land use mixtures along the entirety of trips. Otherwise, only a portion of the story is being told through application of an entropy index.

Second, the entropy index, regardless of the number of land uses integrated into the model, may misrepresent the degree to which land uses are actually mixed in reality. Brown et al. (2009) demonstrate, through six different scenarios, that the six-variable entropy index most commonly employed within the literature (sometimes as a five- or seven-variable index) can substantially misrepresent the degree to which land uses are actually mixed on the ground (Brown et al, 2009). So much so that, for instance, a neighbourhood returning a high entropy value might actually have less walkable land uses than a similar neighbourhood with a far lower entropy value. One of the most telling scenarios demonstrates that Community A with $1/6$ multifamily + $1/6$ single family + $1/6$ office + $1/6$ retail + $1/6$ education + $1/6$ entertainment, and Community B with $1/2$ multifamily + $1/2$ single family, will both garner an entropy value of 1.0 – the highest possible value – however, Community B is, in actuality, 100 percent residential while Community A is not (Brown et al., 2009).

Additionally, DMTI data has an identified problem with land use accuracy, returning results that are significantly-different than that of municipally-sourced data as noted in Chapter 3. A study utilizing data from these individual municipalities could very well return different results.

The MAUP exists within the scope of this study. Using DAs rather than CTs alleviates some of the problem, with respect to areal accuracy; however, it is theoretically not as good as the Dissemination Block (DB) or a network buffer application. While

network buffers are likely the best overall option for a study of this nature, the general scope of the study precludes this.

4.8 Conclusion

Studies employing a walkability index have become popular within health and built environment studies. This aggregate study employed a commonly-used walkability index and applied it to DAs within urban CMAs across Canada to determine whether a global trend existed between walkability and tendencies for people to leverage AT and PT in the journey-to-work over three census years (2001, 2006, and 2011).

Using a Spearman's Rank correlation matrix analysis, the results determined that statistically-significant relationships existed between walkability and six dependent, transportation, built environment, and socioeconomic variables ($p < 0.01$). Walkability was positively associated with propensity to use AT, PT, and AT/PT in all three census years. The correlations were strongest between walkability and AT/PT, which appears to be driven by the correlation between walkability and PT. It was also positively-correlated with the proportion of a DA constructed before 1960 (b1960) and negatively-correlated with both the proportion of a DA constructed after 1991 (a1991) and with median household income. Despite the weak correlation, given the nature of the data, the relationship was still statistically-significant ($p < 0.01$).

Municipalities across Canada have begun to shift to more walkable, environmentally-sound urban forms over the past decade. Results suggest that the relationships between walkability and dependent variables have continued to be quite strong over the study's 10-year timeframe.

The implications from this are great. Planning and development professionals across Canada should continue to build upon the perpetuation of the associations between BE walkability and multi-modal transport options. Possibilities for strengthening multi-modal transportation options, including but not limited to multi-use pathways, trail systems, park- and greenbelt connections, and public transportation networks should be explored.

In larger municipalities, professionals should be looking to capitalize on shifts to more walkable, dense forms of (re)development by bolstering or advancing public transit by way of bus rapid transit (BRT) or light rail transit (LRT). In particular, studies across North America have shown that the establishment of LRT has capitalized into increased land values and denser urban forms, even prior to construction (Cervero & Duncan, 2002; Hess & Almeida, 2007; Knapp, Ding, & Hopkins, 2001). Reinforcing primary multi-modal people-moving infrastructure is paramount to continuing a paradigm shift that has been active since the late-20th century.

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5 Chapter 5 – Discussion, Implications, and Conclusions

5.1 Introduction

This chapter summarizes the main findings of this thesis, the methodological contributions with regards to BE studies of walkability, in particular, issues surrounding data employment and accuracy prior to analysis. It also provides a discussion of the potential policy implications surrounding urban walkability, journey-to-work travel, AT/PT utilization, and contributes to discourses around multimodal urban planning theories.

5.2 Revisiting Study Objectives

Using a walkability index to quantify the BE has become popularized in a variety of applicable disciplines over the last decade; this study aimed to calculate walkability values for DAs across Canadian CMAs for three census years (2001, 2006, and 2011) and to caution researchers and policymakers about potential pitfalls in analyzing raw data without careful scrutiny. Specifically, this thesis sought to determine if commercially-sourced data was more accurate than municipal data and whether associations existed between GIS-derived BE walkability measures and journey-to-work AT/PT. Population and journey-to-work census data for all three years was retrieved from Statistics Canada while ArcGIS was employed to aggregate and tabulate relevant intersection density and land use mix metrics to the specified areal unit boundaries.

Recall, the primary objectives of the research were as follows:

1. To examine the literature and establish a brief timeline for the progression of walkability and transportation geography.
2. To establish an understanding of best practices and study findings within areas of urban walkability and the built environment.
3. To determine the viability of large, commercial datasets and their overall benefits and limitations.

4. To suggest best practices for data cleaning and the mitigation of data inaccuracy prior to analysis
5. To determine if any associations exist between urban walkability and journey-to-work transport data across Canadian CMAs.
6. To establish policy implications for urban and transportation planning efforts in municipalities across Canada.

5.3 Summary of Findings

Given the suggestive results of the exploratory groundtruthing exercise on London, Ontario data, a formal examination of six Canadian cities was executed. Local and commercial road network and land use datasets for the Cities of London, Sarnia, Hamilton, Halifax, Regina, and Vancouver were analyzed at the 2011 census year at DA and CT levels. Paired two-tailed t-tests of means were used to compare results for each city, at both areal units, to determine if statistically-significant difference existed ($p < 0.05$). The results not only confirmed statistically-significant differences existed in the raw data, but also in the cleaned data. Differences between the two datasets were made evident because of their own unique benefits and limitations, which have to be considered in future research.

The land use data obtained from the commercial data source is clearly less reliable than municipal data. Overall, commercial lands are grossly underrepresented and issues with the accuracy of industrial, institutional, and park lands are also quite evident. It should be noted, though, that the road network data from commercial data providers is quite robust, especially after the data is cleaned. Road network data includes private road and circulation networks, including rear lanes, which is often left out of road networks in municipal datasets. Commercial data also has a greater spatial extent than individual municipalities and is likely created and stewarded in a consistent methodology, which cannot be confirmed for the municipal data sets. Thus, commercial data was deemed reasonable for further study.

DMTI RouteLogistics data was used as the baseline for continued analysis due to the spatial extent of the datasets and the results from the cautionary assessment. ArcGIS and three years of census data were also obtained for the particular analysis to compare

neighbourhood walkability and associated dependent variables, including journey-to-work AT/PT in Canadian CMAs. Analyses were performed at a DA level using a Spearman's Rank matrix for 2001, 2006, and 2011 transportation data, age of development, and median household income. Findings from the study corroborate many of the prevailing studies in the literature. For all three census years, neighbourhoods that are quantified with higher walkability values correlate significantly into greater utilization of journey-to-work AT/PT ($p < 0.01$). Additionally, for all three census years, higher walkability is significantly associated with older neighbourhoods (i.e. those constructed primarily before 1960) and lower median household income. Consequently, lower walkability is significantly correlated with newer communities (i.e. those primarily built after 1991) for all three years.

The overall results further establish that urban walkability appears to have a substantial positive association with propensity to use AT/PT modes of transportation and thus, a negative association with other modes, which are predominantly automobile-dependent.

5.4 Methodological Contributions

This study contributes to the literature on both data stewardship practices in walkability data analysis and AT/PT correlations with GIS-derived urban walkability. It offers an understanding on how to approach and properly scrutinize road and land use raw data prior to any rigorous computational methods and also how urbanites most often utilize their transportation options when travelling to their place of work. Although GIS approaches to BE walkability have become quite common in recent years, studies tend to focus their scope on singular urban areas, rather than adopting a comparative approach. This study aggregated all CMAs, at the DA level, into one dataset to more robustly consider urban walkability and any associations with AT/PT. This both establishes a dataset of great size and decreases the likelihood that any individual CMA could affect study results. It also seeks to establish global trends and removes the focus from individual CMAs, which might exhibit associations that are not congruent with overall trends.

The study establishes that, while commercially-sourced datasets are usable for large-scale BE analyses, local land use data sets might be more appropriate for land use mix analysis and should be considered when possible. Further, common road network concerns such as intersection overrepresentation and ‘unwalkable’ segments must be addressed. Data that is sloppily cleaned or groundtruthed may translate into inaccurate results that would not otherwise be known to external researchers and policymakers. Establishing a high standard for data stewardship and reiterating data set limitations builds a body of context that can be both referenced and furthered in future academic and policy research.

5.5 Policy Contributions

There are a number of planning and transportation policy recommendations that have emerged over the course of this study. The results suggest that the prevailing views around greater neighbourhood walkability translating into AT/PT utilization are correct. In particular, older neighbourhoods with greater population and intersection densities and greater mixes of land uses translate into higher propensity for using a form of AT/PT for utilitarian travel. Developing urban areas around these three principles establishes the seed of greater, future multimodal transit usage. Higher population densities inherently suggest small overall neighbourhoods, which shrink the degree to which a resident might travel out of necessity or leisure. With decreased distances, the likelihood of AT/PT increases. Higher intersection densities are a symptom of more dense road networks and thus, greater choice for residents. A person travelling to work has more options pertaining to choice of path, which can make usually mundane travel, such as journey-to-work, more interesting. Additionally, more roads could translate into more sidewalks and bike paths, meaning a greater ability to walk safely in one’s own neighbourhood. Lastly, greater land use mixing increases the number of utilitarian and recreational destinations within x units of distance. Many mid-to-late 20th century communities were developed in an environment of single-use or exclusionary zoning (Arbury, 2005; Newman, 1992). This form of policy separates large swathes of residential lands from commercial, park, and so forth. Separation not only increases distance between home and amenity, but entrenches a perception of automobile reliance (Burchell, 1997a; Burchell, 1997b;

Burchell & Mukherji, 2003; Burchell *et al.*, 1998a; Burchell *et al.*, 1998b; Burchell *et al.*, 2000). Mixing uses helps to dissuade residents from driving and seeks to reinvigorate the notion of active travel.

New Urbanism and Smart Growth have built themselves around these and other principles. Thus, in using these principles as a foundation to discourage automobile reliance, future planning and urban transportation policies in Canadian municipalities should seek to reflect the next recommendation this study volunteers: Supplying residents with more abundant, safe transportation options will positively affect the degree to which they utilize those options. These options range from safer sidewalks, bike paths, and multi-use paths up to efficient rapid transit systems. Applying a synoptic planning approach while utilizing the foundational policies of modern planning theories, such as Smart Growth and TOD, at micro- and macro-levels will assist in moving urban society away from expansive, costly, automobile-dependent urban forms toward denser development that fosters healthier living, healthier residents, lower costs of development, and more viable transportation options for residents. This research and current literature substantiate this assertion. Survey-based literature has shown that demand exists for these types of denser, pedestrian- and transit-centric urban forms (Belden Russonello, & Stewart, 2003; Belsen Russonello, & Stewart, 2004; Handy et al., 2008) and that demand for such forms are likely to increase (Myers & Gearin, 2002; Nelson, 2006). Thus, focusing on these types of urban development could have monumental effects on the viability of municipal governments and their associated assessments and property revenues (Bartholomew & Ewing, 2011). In fact, municipal governance is moving in that direction, not only in larger areas such as the Greater Vancouver Regional District and Toronto (Bunce, 2004), but in medium-sized cities all the way to rural counties and municipalities. For instance, London's new Official Plan is built around two spines of rapid transit (City of London, 2015) and even the County of Peterborough is working with its lower-tier municipalities and residents to establish an Active Transportation Plan (County of Peterborough, 2016).

It is imperative, however, that these networks reach even into the most suburban areas of our communities. As many of our urban residents still locate in the suburban

fringes of our neighbourhoods, an established, efficient multimodal network of transit options becomes moot if those residents cannot access an entry point. Not only should networks of bike and multi-use pathways seek to reach every corner of our urban areas, but our metropolitan public transportation systems should do the same. Policies which afford every resident a reasonable opportunity to decrease automobile dependence, even at a higher present investment cost, can translate into lower ongoing infrastructure, health care, and social costs in the near future.

Smart Growth and TOD principles can also be applied to large-scale transit solutions in larger municipalities. Many medium and large Canadian municipalities have established, or are in the process of developing rapid transit networks. Rapid transit, in particular LRT, has been shown to have a strong impact on surrounding commercial land values (Cervero & Duncan, 2002; Hess & Almeida, 2007; Knapp, Ding, & Hopkins, 2001). A municipality's ability to capitalize on the advantages of higher-order public transit may reap the benefits of higher land values and property tax income; greater land use density adjacent to affected corridors, which could translate into greater ridership; and, less strain on present and future municipal transportation infrastructure.

5.6 Limitations

Even though this thesis has made some important theoretical, methodological, and policy contributions, there are some limitations that must be addressed for the consideration of future research. First, despite the findings of the cautionary analysis, data is never perfect. The land use data that was used for the study in Chapter 4 contained some substantial issues that cannot adequately be rectified. Commercial lands were significantly underrepresented in each case study city examined in Chapter 3, while Industrial, Institutional, and Park lands were all significantly underrepresented in at least one instance. Given this, it is reasonable to assume that any land use index created from such data might be inaccurate and thus, could translate into issues with the overall walkability index itself.

Second, because of the nature of the study, the potential effects of the MAUP should be further mentioned. The MAUP affects any study that employs an areal unit as

the primary unit of analysis and is hard to completely avoid. In this case, the zonal effects are most prudent. Zonal effects refer to the arrangement of areal units over a study area. Reorienting the boundaries could be used for vetting the legitimacy of land use and intersection density metrics, but would not be beneficial for population density as this data is aggregated strictly to established DA boundaries. Scalar effects were mitigated to the best possible degree by employing the DA areal unit, which best represents the neighbourhood area. Lastly, the walkability index associated at statistically-significant levels with the AT/PT and other dependent indicators. However, it is not known which metric, or metrics, used within the walkability index associated to the same degree with the dependents.

5.7 Directions for Future Research

Future research that approaches notions of BE walkability and AT/PT should seek to establish stronger correlation or causation. The use of a walkability index does not allow a researcher or policymaker to determine which metric might be the most significantly associated with their desired outcome. Associating a walkability index and its individual metrics with a dependent variable would help build this particular section of the literature and could help inform policymakers, thus eliminating a consistent unknown in BE research (Clark, Scott, & Yiannakoulis, 2014).

Tangentially, much of the work that populates the literature focuses on associations and correlations tied to individual urban areas. To build upon these findings, choice and/or preference surveys could be employed to determine whether residents choose communities based on their perceived or actual walkability, or if it is the residents who influence the walkability of the communities they choose. Studies that move the field closer to causality will help create urban policies that are directly influenced by the behaviours of their own community residents.

Further GIS and statistical analysis could help researchers and policymakers delve deeper into potentially important differences between CMA groupings. Differences including population size, areal extent, urban typology, morphology, geographical

location, and climatological factors can help guide local policies and further establish potential trends for changes in urban walkability as urban areas evolve over time.

Lastly, microanalyses studying the effects of individual transportation projects could prove beneficial for the development of municipal transport and planning policies. Considering longitudinal studies of neighbourhoods affected by large-scale multi-use pathway, bike pathway, and/or rapid transit system development could study land use and density changes, AT/PT usage, commercial densities, land values, and other urban metrics over time. Understanding the direct cost/benefit of individual projects to the overall urban fabric of individual municipalities would not only inform future policy, but would add to BE research and transportation research more generally by establishing or bolstering a different angle of study.

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