Modifiable Areal Unit Problem (MAUP) Effects on Assessment of Accessibility via Public Transit

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Min Wan

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By: Min Wan

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Signed by the final Examining Committee:

______________________________ Chair
Dr. Alan Nash

______________________________ Examiner
Dr. Liou Xie

______________________________ Examiner
Dr. Sébastien Caquard

______________________________ Supervisor
Dr. Craig Townsend

Approved by ______________________________
Chair of Department or Graduate Program Director

____
Dean of Faculty

Date ______________________________

ABSTRACT

Modifiable Area Unit Problem (MAUP) Effects on Assessment of Accessibility by Public Transit

Min Wan

Integrating accessibility by public transit with land use planning is a crucial precondition for sustainable urban development. Accessibility by public transit has been widely assessed in a GIS environment using aggregated zonal data, such as traffic analysis zones, census tracts, dissemination areas, dissemination blocks, 200 * 200 m grids and 50 * 50 m grids. Nevertheless, it has been proved that the scale and zoning scheme of zones may alter analysis results, which is known as the Modifiable Areal Unit Problem (MAUP). Therefore, it is essential to know how the MAUP affects assessment of accessibility. This research addressed the MAUP effects, when evaluating accessibility based on cumulative opportunity measures. This research applied a cumulative accessibility measure, which calculated accessibility in terms of the number of urban nodes that could be reached within a given travel time or distance. The City of Windsor, Canada, was used as the study area. The MAUP effects were examined based on 6 types of zones (e.g. census tracts, dissemination areas, dissemination blocks, 0.6 km, 0.3 km and 0.15 km grids) at comparable scales or zoning schemes. It was found that the MAUP may significantly alter assessment results of accessibility and should be paid highly attention to. The two outcomes of the MAUP effects on accessibility measurements are: changes of accessibility score and alterations of policy implications that are based on accessibility measurements. Three ways were discussed to deal with the MAUP impacts on accessibility measurements: using disaggregate data if possible, using low aggregated data and selecting zones according to research purposes.

Key words: Accessibility; Cumulative Opportunity Measures; Public Transit; MAUP

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1. Introduction

Accessibility is a crucial concept in transportation planning and transportation modeling (Lei & Church, 2010; Liu & Zhu, 2004; Yigitcanlar et al., 2007). Accessibility via transit has been generally defined as the ease of reaching activity sites or urban opportunities from a given location (Chen et al., 2011). Defined in this way, accessibility is intimately related to the performance of transportation systems, land use characteristics, urban structure, distribution of activities, as well as responses of transit users (Liu & Zhu, 2004; Scheurer & Curtis, 2007; Yigitcanlar et al., 2007). Generally, increasing accessibility is one of the principal objectives of transportation and land use planning (Liu & Zhu, 2004; Yigitcanlar et al., 2007).

Accessibility plays an essential role in making decisions of land use and transportation planning (Bertolini et al., 2005; Yigitcanlar et al., 2007). Specifically, accessibility can be used to assess existing situations of accessibility levels, land use patterns, transportation service quality and travel demands in different areas, so transportation investments can be reasonably allocated according to the evaluation results. For instance, Yigitcanlar et al. (2007) used accessibility to measure future urban growth in Gold Coast City, and to make future master planning developments in Gold Coast local government area, Australia. Bertolini et al. (2005) used accessibility to evaluate current accessibility levels and test locations proposed for new residential areas in Delta Metropolis, Netherlands.

Additionally, improving accessibility by transit is important to promote sustainable development and decrease environment impacts (Mavoa et al., 2012; Yigitcanlar et al., 2007). Improvement of accessibility by transit may attract more people to shift travel mode from car to public transit. With decrease of car usage, there would be less traffic congestion and greenhouse gas emissions. Furthermore, accessibility by transit is related to social equity issues (Mavoa et al., 2012). Particularly, public transit provides mobility (and accessibility) to people who do not have access to cars. However, accessibility by transit is not available equally for all people, such as children, the elderly and people with disabilities.

There are considerable ways to measure accessibility from one place to another by transit. Many researchers summarized different approaches to measuring accessibility (e.g. Alam et al., 2010; El-Geneidy & Levinson, 2006; Lei & Church, 2010; Scheurer & Curtis, 2007). Some commonly used approaches to calculate accessibility by transit include: accessibility to transit system, travel impediment measures, cumulative opportunity measures, gravity-based measures, utility-based measures and space-time measures (Handy & Clifton, 2001; Scheurer & Curtis, 2007). Different measurement approaches are independent from each other, because the weighting parameters of various approaches are different. Analysis results based on different measurement approaches may be significantly different or incomparable (e.g. LaMondia et al., 2011).

Accessibility has been assessed based on diverse types of zones. Specifically, zones that have been used in accessibility studies include: traffic analysis zone (TAZ) (Alam et al., 2010; Zhu & Liu, 2004; Xin et al., 2005), census tract (CT) (Horner & Murray, 2004; Huang & Wei, 2002; Mamun & Lownes, 2011; Murray, 2001), dissemination area (DA) (Horner & Murray, 2004), census block groups (LaMondia et al., 2011), dissemination block (DB) (Horner & Murray, 2004), neighborhood (Bertolini et al., 2005), land parcel (Mavoa et al., 2012; Yigitcanlar et al., 2007), 200 * 200 m grid (Li et al., 2011) and 50* 50 m grid (Yigitcanlar et al., 2007). Generally, zones that were frequently used to calculate accessibility were in two zoning schemes: census geographic zoning scheme and grid zoning scheme. Compared to grids, census geographic zones were more commonly used because of data availability and quality. It is interesting to explore if assessment of accessibility would be affected by the use of different types of zones in analysis, given a variety types of zones have been used. Also, it is important to know how using a coarse resolution (e.g. CT) would influence the measurement of accessibility, if high resolution data (e.g. DB) are not available.

A well-known problem in geography and spatial analysis is that the scale (or size) and zoning scheme (or unit configuration) of zones may alter analysis results, which was the Modifiable Areal Unit Problem (MAUP) (Fotheringham & Wong, 1991; Horner & Murray, 2004; Wong, 2004). The MAUP has been studied for its influence on analysis results in numerous studies. The MAUP performed variously in different studies. In some studies (e.g. Kwan and Weber, 2008) changes to spatial units did not have an influence on analysis results. In some studies (e.g. Mitra & Buliung, 2012) analysis results altered randomly with the change of spatial units used in calculations. In some other studies the researchers (e.g. Horner and Murray, 2004) found that the MAUP effects were predictable, meaning that the accessibility measures changed systematically with the change of zone's scale or zoning scheme.

Researchers have addressed the MAUP impacts on assessment of accessibility. Kwan & Weber (2008) explored the MAUP effects on accessibility, when using a distinct measuring approach - space-time measures. Kwan & Weber (2008) calculated accessibility in terms of individuals' space-time travel paths within designated time constrains based on data at neighborhood and metropolitan scale. They found that space-time measures of accessibility were not affected by the change of scale from neighborhood level to metropolitan level. . Given the consideration that different accessibility measures are independent, Kwan & Weber (2008)'s findings of the MAUP effects are only logical for space-time measures of accessibility. Therefore, there are great potentials for studying the MAUP effects on accessibility when other approaches (other than space-time measures) are used, such as calculating accessibility based on travel impediment, people's preference of activities or cumulative number of opportunities.

Horner & Murray (2004) addressed the scale effects on accessibility to bus system in terms of differences in change of area and amount of population that were accessible to bus when different zones (CTs, census block groups and census blocks) were used in analysis. Horner & Murray (2004) found that with the decrease of zone's size, analysis results were less sensitive to scale effects, and the analysis results became better with the decrease of zone's size. Access to transit system is the precondition for travelers to use transit. It was proved by Horner & Murray (2004) that accessibility to bus varied with the change of zones' scale, and it is hypothesized it will eventually influence travelers' accessibility from origin to destination via transit. Given this consideration, it is essential to examine how the MAUP affects accessibility when doing analysis based on places (or zones).

Diverse types of zones have been utilized to calculate accessibility in the literature, while quite few have considered the MAUP effects. Accessibility is a key issue in decision makings on trade-offs and interdependencies between transportation service provision and land-use development (Bertolini et al., 2005). Differences in accessibility measurements resulted from the MAUP (change of zones) may lead to different or even the opposite policy implications on urban transportation and land use planning. Thus, it is essential to get deep insights into the MAUP effects on assessment of accessibility and explore ways to minimize the MAUP or ideally avoid the MAUP.

This research has three objectives: First, to fill the needs of the MAUP effects on assessment of accessibility. In terms of commonly used approaches to calculate accessibility by public transit and the MAUP effects, Kwan & Weber (2008) have explored the MAUP effects on accessibility when using space-time measures, and Horner & Murray (2004) have addressed the MAUP effects on accessibility to transit system. This research addresses the MAUP effects on accessibility when using cumulative opportunity measures. The MAUP effects on accessibility using gravity-based measures, utility-based measures and travel impediment measures are remaining topics for future research. Second, define the patterns of the MAUP effects on accessibility measurement and explore if the patterns of the MAUP effects can be used to minimize it. Third, evaluate the consequences of the MAUP effects on accessibility measurement and explore how to avoid or at least minimize the MAUP.

This research used a distinct type of accessibility measures, cumulative opportunity measures, to calculate accessibility by public transit. Accessibility will be calculated using zones at different scales or zoning schemes. The MAUP effects on accessibility measurement will be examined using the City of Windsor, Canada as a study location. Patterns of the MAUP effects, consequences of the MAUP and ways to deal with the MAUP on accessibility measurement will be discussed.

In summary, this thesis specifically addressed these research questions:

1. What is accessibility to job centers by public transit in the City of Windsor?
2. How does assessment of accessibility vary with the change of zone's scale or zoning scheme? How using a coarse resolution (e.g. CT or DA) could alter the assessment of accessibility compared to assessment of accessibility based on DBs?
3. What are consequences of the MAUP effects on assessment of accessibility?
4. How to deal with the MAUP effects on assessment of accessibility when using cumulative opportunity measures?

Chapter 2 provides an overview of the concepts and categories of existing accessibility studies, methods of calculating travel time and amount of population, scales and zoning schemes of zones that have been used in accessibility studies, and the MAUP effects in geography and special analysis. Subsequently, Chapter 3 discusses the data sources, design scale and zoning schemes, calculating population of different zones, creating a walking-bus network, evaluating accessibility in City of Windsor, and analyzing the MAUP effects on assessment results of accessibility. Chapter 4 presents the evaluation results of accessibility in City of Windsor, the MAUP effects on assessment of accessibility, consequences of the MAUP and ways to deal with it. Chapter 5 discusses policy implications, limitations of this study, potentials for future research and conclusions of this research.

2. Literature Review

This chapter begins by reviewing the definitions and measuring approaches of accessibility, followed by reviewing the development of calculating travel time from trip origin to destination and methods of calculating amount of population. This chapter also provides an overview of zones at different scales and zoning schemes that have been used in accessibility studies as well as researches on MAUP in geography and accessibility studies.

2.1. Definitions and Categories of Accessibility

The first section of the literature provides a review of definitions of accessibility and approaches to measure accessibility. A general definition of accessibility is the ease of reaching activity opportunities (or activity sites) from a given place by transportation (Chen et al., 2011). In essence, accessibility captures the performance of transportation system (e.g. headway and operation hours), distribution of activities, attractiveness of destinations as well as travel time or distance (or impedance) to reach the destination (Chen et al., 2011; Scheurer & Curtis (2007).

Given the various accessibility indicators, accessibility can be measured in many ways. More specifically, accessibility has been evaluated based on one specific indicator or lots of indicators, such as transportation attributes (e.g. travel speed), land use attributes (e.g. land use densities), economic objectives (e.g. access to suppliers and customers) and social goals (e.g. access to jobs and social services) (Bertolini et al., 2005).

Furthermore, accessibility has been defined according to the focus of people (or individuals) or places (or zones) (Huang & Wei, 2002). Most studies evaluate accessibility using zones (areas or places) as basic units rather than individuals. This is because zones may attach social-demographic, economic and land use data. Specifically, accessibility of zones (areas or places) is defined as how easily certain zones could be reached (Alam et al., 2010). Accessibility of zones assumes that all individuals in each zone have equal access to transit which neglects an individual's actual location (Alam et al., 2010). By contrast, individual accessibility is defined as the ease that a person or a group of people can reach certain places (Alam et al., 2010). Usually the ease to get to certain places is evaluated according to individuals' personal characteristics, such as age and gender (LaMondia et al., 2011). Additionally, assessment of personal accessibility is frequently based on individual trips (Alam et al., 2010).

In addition, accessibility has been defined according to the land use types of trip origins (or destinations). In particular, origin-based accessibility focuses on accessibility of households (where they live) to activity locations (Yigitcanlar et al., 2007). Destination based- accessibility focuses on accessibility of services, such as shops, workplaces or schools, to households (Yigitcanlar et al., 2007, p32).

Types of accessibility measures were categorized and summarized in numerous articles, and five overviews of types of accessibility measures are provided in Table 2.1. Scheurer & Curtis (2007) provided a comprehensive overview, which included the categories of most of the existing accessibility studies. Lei & Church (2010) also provided an extensive categorization of accessibility measures, but their categorization was less comprehensive than Scheurer & Curtis (2007). In addition, Alam et al. (2010), LaMondia et al. (2011) and Handy & Clifton (2001) provided an explanation of commonly used accessibility measures.

Table 2.1 Categories of Accessibility and Corresponding Researchers

Researchers	Accessibility Measures
Scheurer & Curtis (2007)	1) spatial separation measures (or travel impediment measures) 2) contour measures (or cumulative opportunity measures) 3) gravity measures 4) competition measures 5) space-time measures 6) utility measures 7) network measures
Lei & Church (2010)	1) system accessibility 2) system facilitated accessibility 3) integral accessibility (or cumulative opportunity measures) 4) space-time accessibility 5) utility-based accessibility 6) relative accessibility
Alam et al. (2010)	1) distance-based measure of accessibility (transit system accessibility or travel impediment measures) 2) cumulative opportunity measures 3) utility-based measure of accessibility 4) gravity-based measure of accessibility
LaMondia et al. (2011); Handy & Clifton (2001)	1) cumulative opportunity measures 2) gravity-based measures 3) random-utility based measures

In summary, current approaches of calculating accessibility via transit can be classified into five categories based on the weighting parameters (e.g. travel time or number of opportunities) used to calculate accessibility score and the focus of individual's accessibility or location-based accessibility. The commonly used categories of accessibility measures are: travel impediment measures, cumulative opportunity measures, gravity-based measures, utility-based measures and space-time measures. Table 2.2 presents the definitions, strengths, weaknesses and examples of present studies of the five types of accessibility measures.

Utility-based measures and space-time measures usually examine accessibility in terms of individual's accessibility. These two types of measures are not widely used because of the data requirement at a very detailed level - personal trips (Huang & Wei, 2002). Travel impediment measures, cumulative opportunity measures and gravity-based measures are commonly used to examine accessibility of places or locations. These three types of measures largely evaluate accessibility with zone-based data, such as census tracts, traffic analysis zones and city blocks. These geography units are frequently used because of stable and convenient data availability and quality from census and statistical bureaus (Huang & Wei, 2002). A zone is usually represented by its geometric centroid as the proxy when doing calculations in GIS based software. For instance, Murray (2001) used CT's centroid to represent it, when calculating the amount of population that had accessibility to the bus system in Brisbane, Australia. Horner & Murray (2004) used spatial unit's (CT, census block group and census block) centroid to represent it, when examining accessibility to bus system in Upper Arlington, USA. Bertolini et al. (2005) used neighborhood's centroid to represent it when calculating accessibility to major urban nodes by bus in the Delta Metropolis, Netherlands. El-Geneidy & Levinson (2006) used TAZ's centroid to represent it, when evaluating accessibility to opportunities (or potential jobs) by transit in the Twin Cities Region, USA. Li et al. (2011) used 200 * 200 m grid's centroid to represent it, when calculating accessibility to urban activities by car in Wuhan, China.

Table 2.2 Summary of 5 Commonly used Categories of Accessibility Measures

	Definition and Applications	Strengths & Weaknesses	Researchers
Travel impediment measures	Measures accessibility based on travel impediment or resistance between origin and destination (Scheurer & Curtis, 2007). The assessment of accessibility based on travel impediment measures provides information of the ease of access to destinations. Travel impediment could be described as: -Travel distance (Euclidean distance versus network distance) or (travel mode) -Travel time (road network status, e.g. congestion versus free flow) or (travel mode) -Travel cost (individual cost and social cost) -Transit service quality (e.g. transit frequency)	The impediment of a trip can be measured based on a variety of factors and provide information of travel distance, travel time, travel cost and transit service quality. This approach could be flexibly used according to the availability of different types of data, such as demographic data at contract level or city level. This approach can be developed by cooperating accessibility and land use patterns. -------------------------------------- This approach does not consider the distribution of opportunities.	Lei & Church (2010); Mavoa et al. (2012); Yigitcanlar et al. (2007)
Cumulative opportunity measures	Measures accessibility based on the cumulative number of opportunities within a specific travel time contour around a node (Handy & Clifton, 2001; Scheurer & Curtis, 2007). The travel time contour (or threshold) can be calculated using a specific straight-line distance or distance (or travel time) along street network from a node. The assessment of accessibility based on cumulative opportunity measure provides information of the scale of available opportunities that people could reach within a given travel time budget (LaMondia et al., 2011). The opportunities could be: the number of jobs, employees, customers and visitors (LaMondia et al., 2011).	This approach requires relatively minimal data (LaMondia et al., 2011). It is easy to interpret the evaluation results. -------------------------------------- All activities within the same level of contour are assumed equally attractive to travelers, which do not consider individuals' preferences (LaMondia et al., 2011).	Bertolini et al. (2005); Cheng & Agrawal (2010); El-Geneidy & Levinson (2006); LaMondia et al. (2011); O'Sullivan et al. (2000)

Gravity based measures	Measures accessibility on a zonal basis, as a function of the attractiveness of opportunities and travel distance or time between origin and destination (Alam et al., 2010; LaMondia et al., 2011). The assessment of accessibility based on gravity based measures provides information of relative accessibility levels of different zones or regions. The attractiveness of opportunities of a zone could be described as: number of employees of one or more industry types, and number of facilities of one or more industry types (LaMondia et al., 2011). Travel distance or time is measured by a distance-decay parameter as proxy for the disuse of transit with the increase of travel time or distance (Scheurer & Curtis, 2007).	This approach is widely used to calculate zonal accessibility. This approach is based on widely available data (e.g. data from census surveys). It is easy to interpret the evaluation results. -------------------------------------- It is difficult to define the distance-decay parameter for different types of trips in different study areas (LaMondia et al., 2011). This approach does not consider individual traveler's behaviors and characteristics.	Alam et al. (2010); Huang & Wei (2002); LaMondia et al. (2011); Liu & Zhu (2004)
Utility based measures	Measures accessibility based on the level of utility or satisfaction according to traveler's preference of opportunities (Alam et al., 2010; LaMondia et al., 2011). The assessment of accessibility based on utility based measures provides information of individual's preferences of the opportunities or the same type (e.g. woman versus man, old people versus youth people) of people's preferences of the opportunities (LaMondia et al., 2011). The level of utility is calculated based on the factors related to utility to reach the opportunities by individual's choice of choosing the best alternative to maximize their utility (Alam et al., 2010). The utility factors could be described as: socioeconomic factors (e.g. income), transportation modes and traveler's characteristics and travel costs (Lei & Church, 2010).	This approach is unique, which evaluates accessibility based on individual's preferences rather than assuming that people choose the nearest opportunity (LaMondia et al., 2011). This approach could measure accessibility according to various factors related to utility. -------------------------------------- It is difficult to interpret the evaluation results. This approach requires extensive survey data which is difficult and expensive to collect (LaMondia et al., 2011). This approach can hardly be developed (LaMondia et al., 2011).	Bhat et al. (1998); LaMondia et al. (2011)

Space-time measures	Measures accessibility based on individual's space-time travel paths within designated time constrains (Kwan & Weber, 2008; Scheurer & Curtis, 2007).	This approach is unique, which evaluates individual accessibility based on 3 types of time constrains.	Dong et al. (2006); Kwan & Weber, (2008)
	The assessment of accessibility based on space-time measures provides information of individual's space-time patterns for people's daily schedule (Kwan & Weber, 2008).	This approach considers both the freedom of individual traveling and the operating times of activities or transit services.	
	Time constrains could be described as:	-------------------------------------	
	-capability constrains (limitations of the number of opportunities an individual can reach within a designated time limit)	It is difficult to interpret the evaluation results.	
	-coupling constrains (to reach various fixed activities at different places and times)	This approach requires extensive survey data which is difficult and expensive to collect.	
	-authority constrains (limitations of the operating times of activities or transit services)	This approach can hardly be developed.	

Few studies have compared the analysis results based on different measures of accessibility. LaMondia et al. (2011) made a comparison of three measures of accessibility, cumulative opportunity measures, gravity based measures and utility based measures, when calculating accessibility to healthcare providers by paratransit in Austin, Texas. They found that the findings based on the three types of accessibility measures were drastically different and incomparable with each other. El-Geneidy & Levinson (2006) made a comparison of cumulative opportunity measures and gravity based measures, based on accessibility to opportunities (or potential jobs) in the Twin Cities Region, USA. El-Geneidy & Levinson (2006) found that the analysis results using cumulative opportunity measures and gravity based measures were highly correlated if the travel time limit was 10, 15, 20 and 30 minutes, while this relation declined as travel time increased (e.g. 40, 45, 50 minutes and more).

2.2. Types of Zones have been Used in Existing Accessibility Studies

Census data are the most frequently used data in accessibility studies. The first reason could be the high quality of census geographic data, which is reliable to be applied in academic research. Another reason may be the census data include information on the demographic characteristics and locations of households, and this data can be used in accessibility studies. Several scales of census geographic zones have been used to assess accessibility. Table 2.3 summarized the types of zones that have been used in studies on accessibility measurements. TAZ and CT are the geographic zones that have been most frequently used in current accessibility studies (see Table 2.3).

Accessibility has also been calculated using grids. Specifically, Yigitcanlar et al. (2007) proposed an index model to calculate accessibility by walking and/or transit based on travel time between potential origins (represented by land parcels) and destinations (represented by opportunity locations). Accessibility score of land parcels were allocated to 50* 50 m grids. Based on population density of the 50* 50 m grids, a population weighted index was introduced to identify the imbalance of accessibility and population density. Li et al. (2011) proposed a dynamic technique to examine accessibility by car using a high-resolution uniform grid (200 * 200 m) in Wuhan, China. Accessibility score of each grid cell (represented by grid cell centroids) was calculated based on the number of urban activities that could be reached from this grid cell within a given travel time budget by car (Li et al., 2011).

Table 2.3 Types of Zones that have been used in Assessments of Accessibility

Types of Zones	Researchers
Traffic Analysis Zone (TAZ)	Alam et al. (2010); Zhu & Liu (2004); El-Geneidy & Levinson (2006)
Census Tract (CT)	Horner & Murray (2004); Huang & Wei (2002); Mamun & Lownes (2011); Murray (2001)
Dissemination Area (DA)	Horner & Murray (2004)
Census block groups	LaMondia et al. (2011)
Dissemination Block (DB)	Horner & Murray (2004)
Neighborhood	Bertolini et al. (2005)
Land parcel	Mavoa et al. (2012); Yigitcanlar et al. (2007)
200 * 200 m grids	Li et al. (2011)
50* 50 m grids	Yigitcanlar et al. (2007)

Furthermore, scales and zoning schemes of zones may influence the analysis outcomes (the MAUP problem) (Fotheringham & Wong, 1991; Horner & Murray, 2004;

Kwan & Weber, 2008). Although diverse types of zones have been used to assess accessibility, little is known if the MAUP has effects on assessment of accessibility and if there are effects, how serious they are? Therefore, there are needs to identify the MAUP effects and provide interpretations of the nature of the MAUP effects on accessibility evaluations.

2.3. The Evolution of Calculating Travel Times More Accurately

There have been significant improvements to calculating travel times from trip origin to destination by public transit, when evaluating accessibility. Progress has been the result of advances in techniques and improvements to data availability and data quality (Lei & Church, 2010).

Factors that can affect travel times and components of a complete transit trip include: transit route patterns, transit operation hours, operation schedules (or frequency), time of day and locations of transit users (Lei & Church, 2010). Travel time of a complete transit trip comprises five components: walking time to transit facilities, waiting time at transit stop or station, in-vehicle travel time, transfer time and egress time (walking time from transit stop or station to destination).

The improvements of techniques to calculate travel time have been made by considering all components of a transit trip and using more detailed data. Travel times from origins to potential destinations were estimated by computing travel distance using the shortest distance algorithm provided by GIS applications. For instance, Liu & Zhu (2004) created a GIS application, a travel impedance measurement tool, to calculate accessibility by transit based on the shortest path between origins and destinations (represented by TAZ centroids). In Liu & Zhu (2004)'s study, travel distance contained 3 sections: walking distance from trip origin to the closest road network, travel distance along the road network, and walking distance from road network to a destination. Walking time and transit travel time were estimated using the travel distance and average speed of each mode. One shortcoming of Liu & Zhu (2004)'s approach was that they did not consider waiting time at transit stops or stations, and transfer time between transit routes.

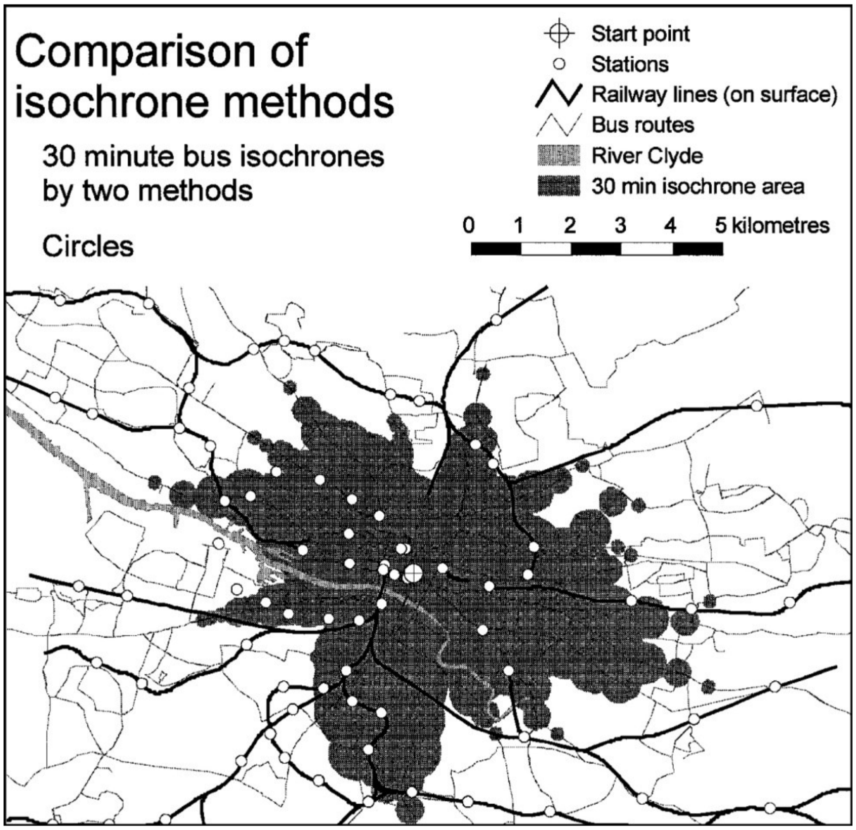


Figure 2.1 Isochrones of travel times from the city center in Glasgow, Scotland

Source: O'Sullivan et al., 2000

In an extension of Liu & Zhu (2004)'s approach, O'Sullivan et al. (2000) considered walking time to transit and transfer time between transit routes, when calculating travel time. They proposed a time-as-cost isochrone approach, which included 4 travel time components: estimated walking time to a transit stop or station, possible in-vehicle travel time, estimated transfer time, and estimated walking time to a destination. The time-as-cost isochrone approach was applied to calculate the shortest travel times to the city center in Glasgow, Scotland (see Figure 2.1). Although O'Sullivan et al. (2000) contributed to the theories of calculating travel time more accurately, their approach had severe shortcomings. Due to the lack of data of bus stops, walking time to a bus stop and transfer time between bus routes were simply estimated based on the location of bus routes. Particularly, the bus boarding points were represented by point on bus route that was closest to the traveler, and the transfer stops was represented by intersections of bus routes.

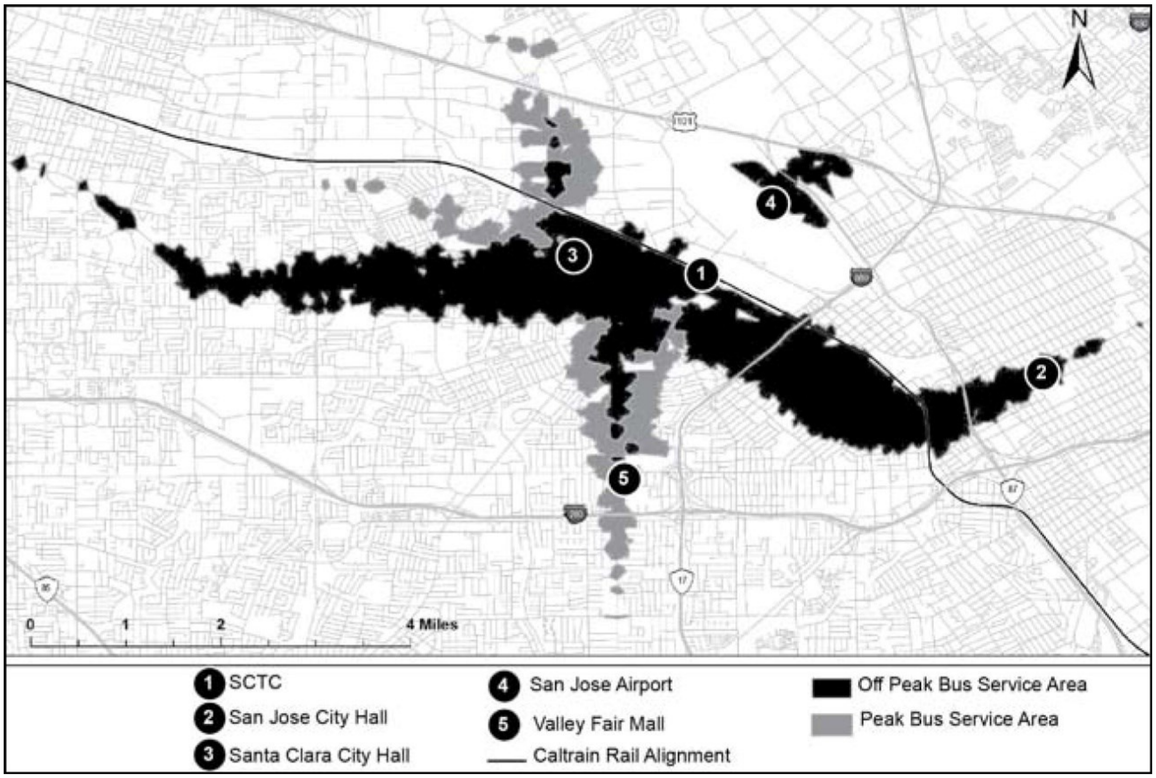


Figure 2.2 Isochrones of Travel Times from the Santa Clara Transit Center in San Jose, California

Source: Cheng & Agrawal, 2010

With the improvement of data quality, Cheng & Agrawal (2010) solved the defects of O'Sullivan et al. (2000)'s method. They proposed a Time-Based Transit Service Area Tool (TTSAT) for assessing accessibility by transit based on real travel time of door-to-door transit trips. The TTSAT approach integrated all the five components of a complete transit trip when calculating travel time by transit. The TTSAT approach was applied to assess the accessibility (by specified travel time constrains) via public transit of the Santa Clara Transit Center (SCTC) in San Jose, California (see Figure 2.2). Furthermore, Cheng & Agrawal (2010) studied the effects of changes of transit frequency on the outcomes of accessibility assessment. In summary, the TTSAT tool provides more flexibility in terms of its clear procedures and user-setting variables, such as maximum travel-time budget, speed of a travel mode and average waiting time at a transit stop (Cheng & Agrawal, 2010).

In an extension of the TTSAT method, Lei & Church (2010) proposed new refinements by considering the time-of-day factor, when calculating travel time. Lei & Church(2010)'s technique was used to calculate the areas that could be reached via public transit from the University of California, Santa Barbara campus within 8 travel time intervals, USA (see Figure 2.3). The technique proposed by Lei & Church (2010) is currently the most accurate technique to calculate travel time.

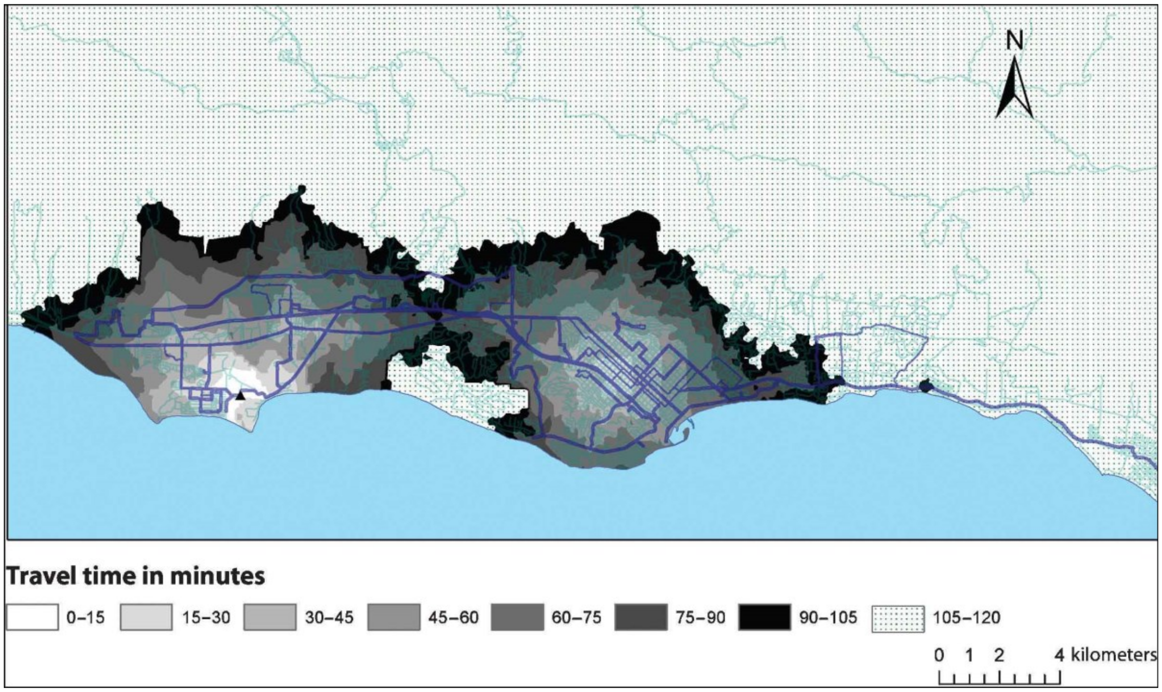


Figure 2.3 Isochrones of Travel Times from theUniversity of California, Santa Barbara campus, USA

Source: Lei & Church, 2010

2.4. Methods to Calculate the Amount of Population to be reached by Transit

There were four approaches to calculate the number of people that could be reached from a given place within a certain travel time limit. The four approaches were: centroid method, area-ratio method, network-ratio method and parcel-network method.

2.4.1. Centroid Method

The centroid method is straightforward to apply. If a zone's centroid could be reached within a certain travel time limit, the entire amount of population in the zone would be considered accessible. The centroid method has been applied in many accessibility studies. For instance, Murray (2001) used the centroid method to examine the amount of population that had accessibility to the bus system in Brisbane, Australia. Murray (2001) did analysis using census tracts. Specifically, if a CT's centroid fell within the 400 m straight-line distance buffer around a bus stop, population in this CT was taken as accessible to bus service (Murray, 2001). Horner & Murray (2004) applied Murray (2001)'s calculation to Upper Arlington, in the US. Horner & Murray (2004) did the analysis based on 3 scales of zones (CTs, census block groups and census blocks). The amount of population that had accessibility to bus services was calculated twice according to if a zone's centroid fell within the 400 m straight-line distance buffer around a bus stop or bus route. Bertolini et al. (2005) applied the centroid method to calculate the amount of population that could be reached within 30 minutes by car or by transit from each urban node in the Delta Metropolis, Netherlands.

The centroid method has been widely used to represent polygons when doing calculations in GIS. The strength of the centroid approach is that it is straightforward to apply. One shortcoming of this approach is that it is limited by the size of polygons. More specifically, the accuracy of representing a polygon using its centroid decreases when the size of the polygon is large.

2.4.2. Area-Ratio Method

The area-ratio method is used to calculate the amount of a zone's population that falls within an area (e.g. a contour or isochrone) by assuming that the zone's population is evenly distributed, and then taking the share of the zone's population that corresponds with the area's population. For example, if 50 % of a zone's area falls within a contour, then 50% of the population in this zone is considered as belonging to area within the contour. One shortcoming of the area-ratio method is that it assumes that population are homogeneously distributed in each zone, which is not always the fact in reality (Biba et al., 2010; Horner & Murray, 2004).

Horner & Murray (2004) applied the area-ratio method to calculate the amount of population that had accessibility to the bus system in Upper Arlington, USA. The calculation was made three times using CTs, census block groups and census blocks, respectively. The number of population was estimated according to the proportion of a zone that lies within the 400 m straight-line distance buffer around a bus stop or bus line.

2.4.3. Network-Ratio Method

The theory of the network-ratio method is similar to that of the area-ratio method. The difference is that the former calculates amount of population according to street network ratio while the latter according to area ratio. Specifically, the amount of population that could be reached is estimated according to the proportion of streets in a zone that falls within an area (e.g. a contour or isochrone). For instance, if 50 % of the streets in a zone lie within a contour, 50% of population in this zone is considered as belonging to the area within the contour.

One shortcoming of the network-ratio method is that it assumes that population are homogeneously distributed along each street segment in each zone, which is not the fact in reality (Biba et al., 2010). When applying the network-ratio method, the streets that are attached with population data should be pedestrian accessible streets. If the dataset does not contain data of pedestrian path, creating pedestrian network manually may need considerable work. Moreover, a serious problem of the network-ratio method is that it is unclear to define the belonging of boundaries, if zones share boundaries (Biba et al., 2010). See Figure 2.4, many census blocks share the boundaries. For the census blocks that share the boundaries and also are partially within the buffers, it is unclear which block owns the sharing boundaries. This problem is the main reason why the network-ratio method is not as widely used as the centroid method and the area-ratio method.

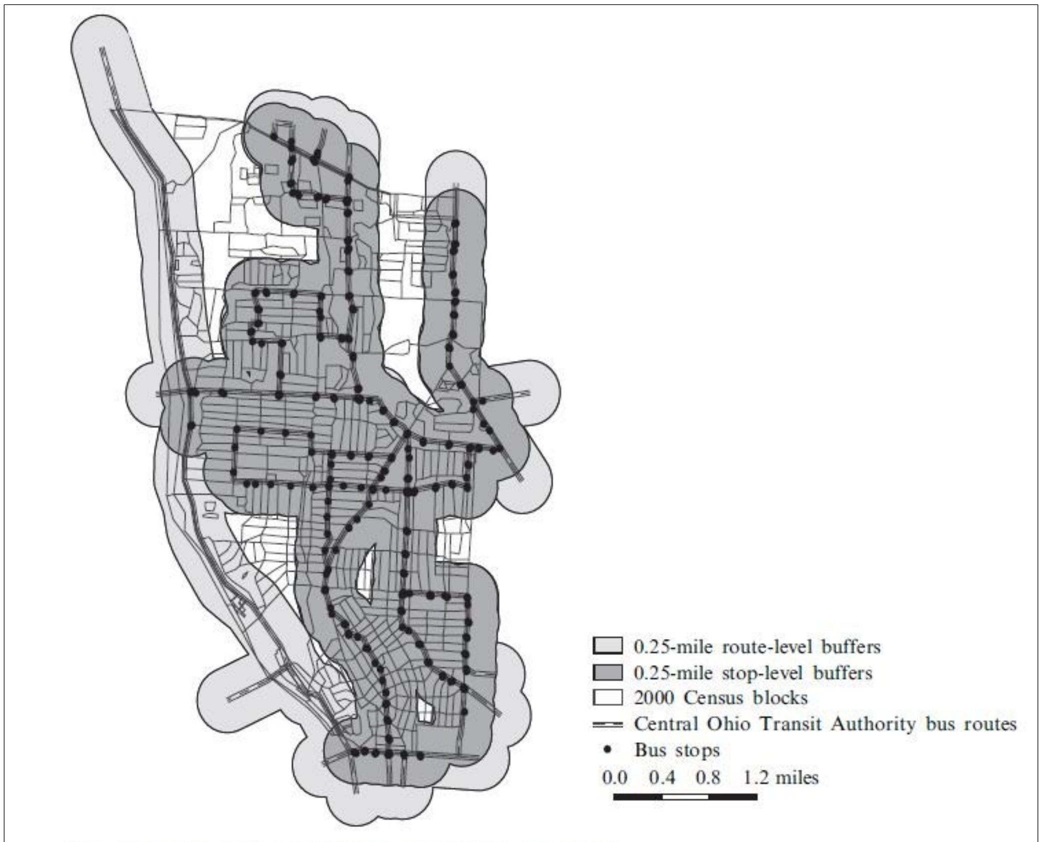


Figure 3. Stop and route coverage in Upper Arlington.

Figure 2.4 Census Blocks to be Reached by Transit

Source: Horner & Murray (2004)

2.4.4. Parcel-Network Method

Biba et al. (2010) proposed a parcel-network method to calculate the amount of population that has accessibility to transit service. The parcel-network method calculates amount of population based on a combination of land parcels' demographic characteristics and pedestrian network (Biba et al., 2010). The process of this method is described as below: firstly allocating population data from census blocks to land parcels; secondly creating a pedestrian network to connect the parcels and transit infrastructure; thirdly, finding the shortest path between land parcels and bus stops; lastly, identifying the parcels that are accessible to bus service (Biba et al., 2010). Figure 2.5 expresses an example of the results of parcel-network method, which presents the parcels to be reached within a given walking distance along street network.

The strength of the parcel-network method is that it is more accurate than other methods, as it calculates the amount of population using very small units. One shortcoming of the parcel-network method is that it requires the data at land parcel level (e.g. stores of buildings and residential types) when allocating population data from census blocks to land parcels. Another shortcoming is that doing calculations at land parcel level may need considerable computational work.

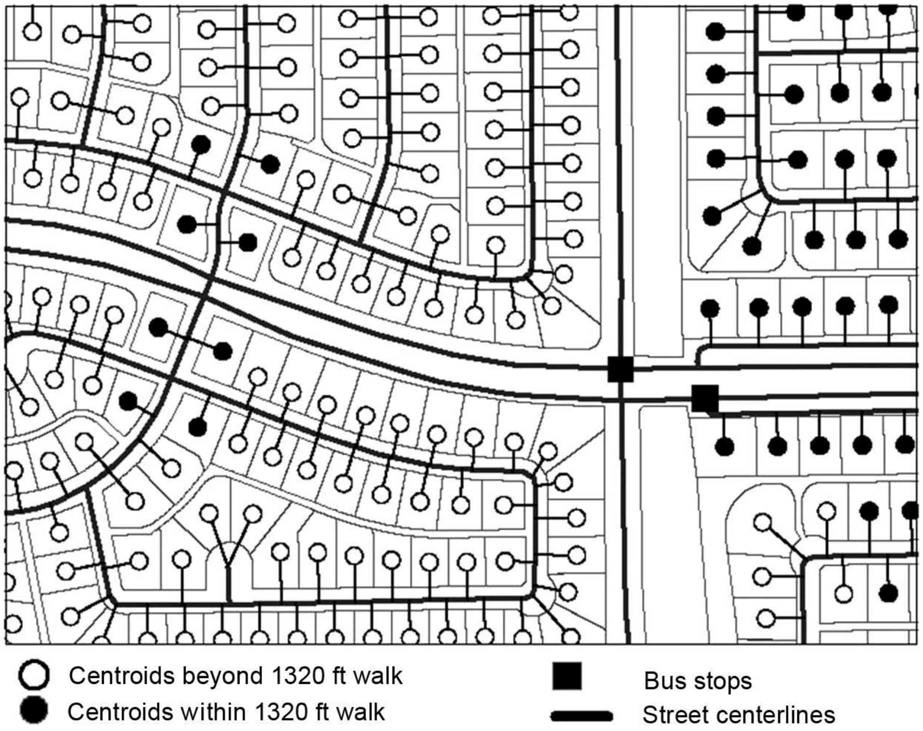


Figure 2.5 Parcel Centroids and Walking Network

Source: Biba et al., 2010

In summary, the centroid method and the area-ratio method are more frequently used than the other two approaches, because these two methods are easy to apply and understand. The network-ratio method is limited to use because of the difficulties to define the belonging of boundaries of zones. The parcel-network method is limited to use because of high requirement of data and extensive computational work.

Horner & Murray (2004) made a comparison of the estimation results of the centroid method and the area-ratio method, based on 3 types of zones, when calculating the amount of population that were within the bus catchment areas. The findings indicated that there were small differences in results using these two methods, when the zones were census blocks or census block groups. Given the centroid method is easier to apply, the centroid method is firstly recommended when doing analysis based on census blocks or census block groups.

2.5. Studies on the MAUP Effects in Geography and Spatial Analysis

The MAUP is a well-known concept in geography and spatial analysis. The problems regarding the use of areal data are known as the modifiable areal unit problem (MAUP): "the sensitivity of analytical results to the definition of units for which data is collected" (Fotheringham & Wong, 1991, p. 1025). The MAUP influences the outcomes of studies in two ways: scale effect (or level of aggregation) and zoning effect (unit configuration of zoning scheme) (Fotheringham & Wong, 1991; Horner & Murray, 2004, Kwan & Weber, 2008). Basically, the scale effect can be interpreted as the analysis results are affected by spatial resolutions of zones, and zoning effect refers to the analysis results are influenced by redefining zone boundaries at a given scale (Kwan & Weber, 2008; Wong, 2004).

Existing geography and spatial analysis have examined the MAUP effects on aspects, such as four-step traffic demand models (e.g. Chang et al., 2002), measurement of transit service coverage (e.g. Horner & Murray, 2004), landscape analysis (e.g. Jelinski & Wu, 1996), analytical modeling of urban form (e.g. Zhang & Kukadia, 2005), statistical analysis of the relationship between built environment and active travel to school (e.g. Mitra & Buliung, 2012) and accessibility by public transit with respect to space-time measures (e.g. Kwan & Weber, 2008).

Chang et al. (2002) only addressed the scale impacts on analysis outcomes. Particularly, Chang et al. (2002) proposed that scale of zones (e.g. TAZs) may strongly affect the results of traffic demand models, and analysis results altered systematically with the change of zone's scale. Furthermore, Chang et al. (2002)'s findings also proved the general observation in transportation planning that smaller TAZs produce better modeling results.

Jelinski & Wu (1996) analyzed the MAUP effects in the context of landscape ecology. Jelinski & Wu (1996) reported that both the scale and zoning scheme of zones have significant effects on results of landscape analysis. The scale effect was examined using N*N pixel grid (N=1, 3, 5, 7, 9 …300) to represent scale difference. The zoning effect was examined using 5 zoning alternatives at a small scale (16*16 matrix) and 9 zoning alternatives at a large scale (100*100 matrix), respectively.

Zhang & Kukadia (2005) addressed the MAUP effects on analytical modeling of urban form. Zhang & Kukadia (2005) involved two zoning schemes: census geographic zoning scheme and grid zoning scheme. The MAUP effects were evaluated based on three scales of census geographic zones (census block, block group and TAZ) and five scales of grid cells (1/16, 1/4, 1/2, 1, and 2 mile). Zhang & Kukadia (2005) selected the scales and zoning schemes according to their appearance in existing urban form studies. The scale effect was evaluated by comparing modeling results that used zones at different scales but in the same zoning scheme. The zoning effect was evaluated by comparing the modeling results that used zones in different zoning scheme but at the same scale, such as 2 mile grid cells versus TAZs, 1 mile grid cells versus block groups, and 1/4 mile grid cells versus census blocks. Zhang & Kukadia (2005) confirmed the presence of MAUP effects on analytical modeling of urban form. Furthermore, they proposed that the MAUP effects on analytical modeling of urban form were predictable. Specifically, analysis results vary systematically with the change of size of grids while randomly with the change of size of census geography zones.

Mitra & Buliung (2012) addressed the MAUP effects on statistical analysis of the association of built environment with active travel to school. Two zoning schemes associated with six scales of zones were used to measure the MAUP effects. Zones in the first zoning scheme were the radius buffers (250, 400, 800 or 1000 m) around a student's home and school, which represented the neighborhood built environment construct. Zones in the second zoning scheme were DAs and TAZs. The scale effect was examined by comparing the built environment coefficients of models that used zones at different scales. The zoning effect was examined by comparing the built environment coefficients of models that used zones in different zoning schemes such as 800 m buffers versus TAZs, and 250 m buffers versus DAs. Mitra & Buliung (2012) proved the presence of the MAUP impacts on statistical modeling of relationship between built environment and active travel to school. However, the modeling results altered randomly with the change of zonal scales, or in other words, the MAUP effects are not predictable.

2.6. MAUP Effects on Assessment of Accessibility by Public Transit

Horner & Murray (2004) addressed the scale impacts on analysis outcomes based on accessibility to the bus system in Upper Arlington, USA. Accessibility to the bus system was presented by the areas and amount of population that were accessible. Horner & Murray (2004) found that estimation results were sensitive to zones' scale, whether calculating transit service areas based on the straight-line distance buffer method or the street network buffer method, and whether based on transit routes or stops. Additionally, Horner & Murray (2004) proved that smaller zones produced better analysis results than that of bigger zones. In Horner & Murray (2004)'s study, census blocks produced the best analysis results, followed by census block groups and lastly CTs.

Kwan & Weber (2008) is a milestone in MAUP studies, which addressed the MAUP effects on assessment of accessibility by public transit based on space-time measures. Kwan & Weber (2008) calculated accessibility in terms of individuals' space-time travel paths within a designated time budget. Specifically, Kwan & Weber (2008)'s study was based on two highly aggregated scales of zones: at neighborhood scale and metropolitan scale. They proposed that space-time measures of accessibility were not affected by the change of scale from neighborhood level to metropolitan level. Furthermore, they concluded that zoning had no effects on space-time measures of accessibility, because individual's characteristics and activity behaviors in various neighborhoods had no differences (Kwan & Weber, 2008).

One weakness of Kwan & Weber (2008)'s research is that only two scales were utilized, and the scales of zones were high aggregated. Kwan & Weber (2008)'s research could be expanded by utilizing more scales of zones (rather than two types of highly aggregated zones) when examining the MAUP effects. Another weakness is that Kwan & Weber (2008) concluded that space-time measures of accessibility were zoning independent based on hypothesis rather than quantative analysis, which was arbitrary.

In summary, Kwan & Weber (2008)'s findings of the MAUP effects are applicable for space-time measures. More work is needed on evaluating the MAUP effects on other measures of accessibility, such as cumulative opportunity measures, travel impediment measures, gravity based measures and utility-based measures.

3. Methodology

The intent of this thesis research is to evaluate how accessible are the job centers in the City of Windsor by public transit, and how changing spatial units affects the calculation of accessibility using a cumulative opportunity measure, and whether the MAUP effects are predictable or not, and what are the consequences of the MAUP effects, as well as how to deal with the MAUP effects.

This research applied Bertolini et al. (2005)'s cumulative opportunity measure, which expressed accessibility in terms of the number of urban nodes (represented workplaces where employment is concentrated) to be reached within a given travel time or distance from a residential area. Bertolini et al. (2005)'s studied accessibility based on the cumulative number of 29 urban nodes that could be reached from residence to workplaces in the Delta Metropolis, Netherlands. A fine-grained spatial unit, neighborhood, which was attached with "readily available land use, socio-demographic and economic data", was adopted as the basic zone unit to calculate accessibility (Bertolini et al., 2005, p 210).

This study selected the City of Windsor as the study area because of two reasons. First, urban sprawl in the City of Windsor has been continuous in recent years and there has been increase of long commuting trips from suburbs to jobs in the city center (Maoh & Tang, 2012). Second, Windsor was an extremely auto-dependent city with just 3% of commuters relying on public transit travelling to work (Statistic Canada, 2015). Given these reasons, it is essential to study accessibility by public transit in the City of Windsor in order to have overall understanding of the service quality of public transit and finding ways to promote transit mode share. The City of Windsor had a population of 210,891 in 2011 (Statistics Canada, 2015). There were 12 normal bus routes (with 11,167 bus stops) in the City of Windsor in 2015. Fifteen major urban nodes in the City of Windsor were used to calculate accessibility from residential areas defined based on census geography.

This study calculated accessibility in the City of Windsor based on the number of major urban nodes that could be reached from a given residential area within 30 minutes by public transit including all components of a transit trip. The MAUP effects on accessibility were examined based on differences in analysis results when using zones at different scales or zoning schemes.

The methodology chapter contains 8 sections: designing an appropriate approach to assess accessibility in the City of Windsor, selection of major urban nodes in the City of Windsor, design scale and zoning schemes, calculating population of different zones, creating a walking-bus network, assessing accessibility in the City of Windsor, an experimental method of calculating accessibility using Google Maps, and analyzing the MAUP effects on accessibility measurement.

3.1. Designing an Appropriate Approach to Assess Accessibility in the City of Windsor

This study applied a cumulative opportunity approach to measure accessibility in the City of Windsor. Cumulative opportunity measures calculate accessibility in terms of the cumulative number of opportunities (or activity sites) within a specific travel time contour from a specified location (El-Geneidy & Levinson, 2006; Handy & Clifton, 2001; Scheurer & Curtis, 2007). The opportunities could be: activity centers, jobs, employees, customers and visitors (Handy & Clifton, 2001; LaMondia et al., 2011; Scheurer & Curtis, 2007).

There are three reasons of choosing cumulative opportunity measures. Firstly, cumulative opportunity measures of accessibility can provide essential information for dealing with trade-offs and interdependencies between transportation service provision and land-use development, which supports “sustainable accessibility” (Bertolini et al., 2005). More specifically, cumulative opportunity measures of accessibility can be used to finding areas that are lacking in transportation service and areas suitable for developing new residential areas. Secondly, cumulative opportunity measures are easy to interpret for urban planners and non-professionals (El-Geneidy & Levinson, 2006), compared to other types of approaches (e.g. utility-based measures and gravity based measures). This is essential when making joint designs of transportation and land use plans. Thirdly, cumulative opportunity measures can evaluate accessibility based on travels among spatial units (e.g. Benenson et al., 2016; El-Geneidy & Levinson, 2006; Ferguson et al., 2013; Kawabata & Shen,2005; Owen & Levinson, 2015 and Witten et al., 2003) or travels from spatial units (or zones) to opportunity locations (e.g. Bertolini et al., 2005; Li et al., 2011; O'Sullivan et al., 2000; Mavoa et al., 2012 and Yigitcanlar et al., 2007).

These two types of measures can be selected according to research purposes and data availability. The latter type of measures can provide better assessments than the former type, as actual opportunity locations better represent the distribution of urban activities than spatial units (activities are aggregated into zones). Also, the latter type of measures provides potentials to calculate accessibility in cities or regions where do not have reliable and adequate spatial data (e.g. census tracts or city blocks), because city area can be represented by grids and opportunities can be located using mapping websites (e.g. google maps). For instance, Li et al. (2011) used 200 * 200 m grid to represent Wuhan, China, and calculated accessibility based on the number of activities that can be reached from each grid within 10 minutes by car. This study calculated accessibility from small spatial units used in counting population for the census, to major "urban nodes" with concentration of employment in the City of Windsor. Accessibility was calculated in terms of the number of urban nodes (workplaces) that could be reached within a given travel time. The following section addresses the specification and calibration indices that are related to a cumulative opportunity measure of accessibility.

Specification indices include the degree of disaggregation of data, definition of origins and destinations and travel impedance (Bertolini et al., 2005). This study utilized 6 types of fine-grained zones which were attached population data. The spatial area units were used as origins, and buffers around urban nodes (created as points) were used as destinations. The number of opportunities (buffers around points representing urban nodes) to each residential unit were calculated using the maximum distance that could be reached using a specified travel time. Here travel time comprises 4 components of a complete bus trip: walking time from a residence to the nearest bus stop, initial waiting time at the bus stop, in-vehicle travel time and walking time to an urban node. This study adopted a 400 m (approximately 5 minutes by walk) as the limit walking distance from a zone to the nearest bus stop or from a bus stop to an urban node. The 400 m walking distance is widely accepted as people's preferred walking distance from/to a bus stop (Hsiao et al., 1997; Murray, 2001; O'Sullivan & Morrall, 1996; Ryus et al., 2000).

The calibration indices refer to the selection of the cut-off travel distance or time (or distance or travel time thresholds) when assessing accessibility using a cumulative opportunity measure (Bertolini et al., 2005). Previous studies chose a city's average commuting time as the cut-off travel time when assessing accessibility, such as Kawabata& Shen (2005) adopted 30 minutes for Boston and Los Angeles, USA and 45 minutes for Tokyo, Japan, as well as Bertolini et al. (2005) selected 30 minutes for the Delta Metropolis, Netherlands.

This study adopted a 30-minute travel time limit as the cut-off travel time based on the commuting patterns in the Windsor Metropolitan Area, which is formed by the City of Windsor and 4 towns. According to the 2011 National Household Survey in the Windsor Metropolitan Area, 34.3% of commuters frequently spent 0-14 minutes commuting to work, and 46.5% of commuters usually spent 15-29 minutes commuting to work (Statistics Canada, 2015). In summary, 80.8% of the commuters in the Windsor Metropolitan Area spent 30 minutes or less commuting to work.

3.2. Selection of Major Urban Nodes in the City of Windsor

Fifteen major urban nodes in the City of Windsor were identified using the City of Windsor Urban Structure Plan, version 2011, which formally identified nodes and corridors for the purpose of planning. “The purpose of the Urban Structure Plan is to formally illustrate the form of the city by identifying nodes and corridors and to provide the basis for the policy changes needed to implement the Urban Structure Plan” (City of Windsor-Urban Structure Plan, 2011, p iv). Urban nodes in the City of Windsor were defined as “existing or future locations of concentrated activity on the Urban Structure Plan that serve the societal, environmental and economic needs at a neighborhood and/or regional scale” (the City of Windsor Urban Structure Plan, 2011, p. 1). Urban nodes in the City of Windsor function as employment centers, where located large numbers of jobs (City of Windsor Official Plan, 2012). Specifically, regional commercial centers provide jobs in offices, retail, personal services and local institutions; and regional institutional centers provide jobs in healthcare, education, offices, research and development; and regional employment centers provides jobs in manufacturing and distribution of goods (City of Windsor Official Plan, 2012).

The City of Windsor Urban Structure Plan, version 2011, identified 17 current and 3 future urban nodes at the regional scale. Only the current urban nodes were used in this study and the future urban nodes were excluded because this study focused on evaluating the current accessibility levels in the City of Windsor. Furthermore, two of the 17 urban nodes were more than 400 m from a bus stop and as a result they were excluded from the urban node dataset.

In summary, 15 major urban nodes in the City of Windsor were used in this study, which were categorized into five types: Windsor City Hall, five regional commercial centers, five regional institutional centers and four regional employment centers. Figure 3.1 expresses the location of the major urban nodes and main streets in the City of Windsor. The major urban nodes in the City of Windsor were located close to highways and major streets (see Figure 3.1). Table 3.1 expresses the name, type and functions and intensification targets of the 15 major urban nodes in the City of Windsor.

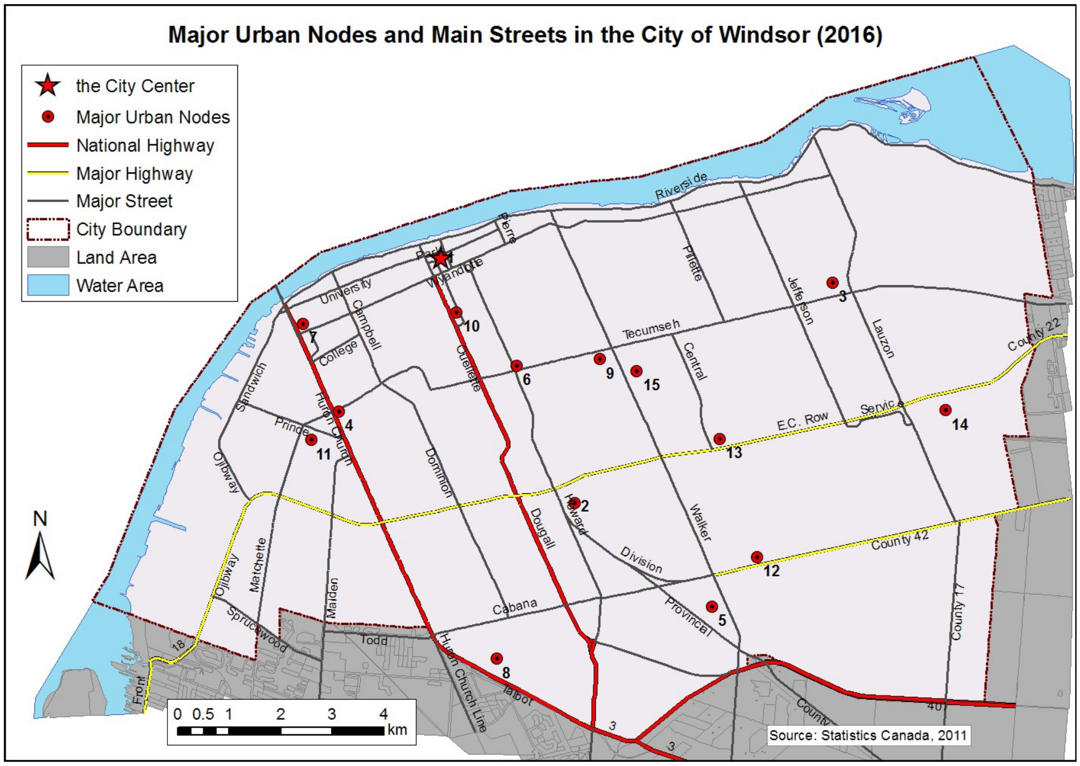
Table 3.1 Descriptions of the 15 Major Urban Nodes in the City of Windsor

Type	Number	Name	Descriptions
city center/ growth center	1	Windsor City Hall	• Gateway to the City of Windsor; • Located in the downtown core; • Focal areas for investment in public services, institutional, commercial, recreational, cultural and entertainment uses; • Accommodate and support major transit infrastructure; • High density major employment center.
regional commercial center	2	Devonshire Mall	• The largest shopping center in the City of Windsor; • Provides regional scale retail functions; • Located on the south side of the E.C. Row Expressway, east of Howard Avenue; • Offers various commercial activities such as financial institutions, department stores, pharmacies, restaurants, specialty retailers, personal services, professional studios and places of entertainment. • Connected to major roads and serves as a major transfer point of several public transit routes.
	3	Lauzon Parkway and Tecumseh Road East	• Sub-regional shopping center; • Located close to the intersection of Lauzon Parkway and Tecumseh Road; • Mainly provides grocery and retail commercial services; • Serves as a major transfer point of several public transit routes.

	4	Huron Church Road and Tecumseh Road West	• Regionally significant commercial center; • Situated approximately 1.6 km south of the University of Windsor • Serves local residents, the University of Windsor and tourists; • Provides basic commercial services, such as retail and commercial outlets.
	5	Walker Road South (and Provincial Highway 401)	• Provides regional and local services; • Located at northwest of the intersection of Walker Road and Provincial Highway 401; • Contains a series of big-box power center developments and retail commercial services; • Predominantly automobile oriented.
	6	Howard Avenue and Tecumseh Road East	• Located close to downtown Windsor, which is generally in the 400 m radius of the intersection of Howard Avenue and Tecumseh Road; • A Combination of commercial, industrial, institutional and residential uses; • Have high accessibility to road network and transit services.
regional institutional center	7	University of Windsor	• The biggest higher education institution in the City of Windsor and has a wide range of programs; • Located at the foot of the Ambassador Bridge and near the Detroit River waterfront; • Supports the commercial business along Wyandotte Street West and in Olde Sandwich Towne.
	8	St. Clair College	• Primarily provides programs in technological and skilled trades; • Located close to the intersection of Cabana Road West and Talbot Road West; • Have close relationship with the development in South Windsor.
	9	Windsor Regional Hospital-Metropolitan Campus	• Serves as a community hospital; • Located on Tecumseh Road, west of Walker Road; • Nearby uses include dentists, orthodontists, eye doctors, allergists and mobility doctors and physiotherapists; • Close to a transfer point between several public transit routes.
	10	Hotel-Dieu Grace Hospital	• The oldest hospital in the City of Windsor; • Serves as a regional and community hospital; • Premier tertiary acute care hospital;

		(Windsor Regional Hospital - Ouellette Campus)	• Located on the south of Windsor's City Center Planning District, fronting Ouellette Avenue and Goyeau Street; • Close to several public transit routes.
	11	Windsor Western Hospital Center (Windsor Regional Hospital-Western Campus)	• Community hospital; • A Center of Excellence for Rehabilitation, Complex Continuing Care, Specialized Mental Health, and Long Term Care; • Located close to the intersection of Prince Road and Tecumseh Road; • Have close relationship with the commercial development along Huron Church Road.
regional employment center	12	Windsor International Airport	• Employment contains advanced manufacturing facilities and an aircraft maintenance-repair-overhaul service provider; • Located in the southwest of Windsor; • High accessibility to major roads.
	13	Deziel/Rhodes Regional Employment Center (Transit Windsor Office)	• Has a wide variety of employment, including manufacturing, business park uses and municipal services; • Located surrounding the interchange of Central and E.C. Row Expressway; • Automobile oriented and have limited public transit services.
	14	Twin Oaks Industrial Park	• Covers a large area of land, bound by E.C. Row Expressway to the north, Little River to the west, the Canadian Pacific Railway tracks to the south and Banwell Road to the east; • Highly automobile oriented and have very limited public transit services.
	15	Chrysler Plant	• One of the single largest employment places in Windsor; • Located at the southwest of the intersection of Tecumseh Road East and Walker Road; • Close to several specialty retail, restaurants, banks and large numbers of specialty medical services; • Automobile oriented and have limited public transit services.

Note: The numbers were just made out for convenience of presentation and have no implications for the analysis.



Source: Statistics Canada, 2011

Figure 3.1 Major Urban Nodes and Main Streets in the City of Windsor

3.3. Design Scales and Zoning Schemes

There are diverse ways to aggregate dispersed locations or points representing things like residences or businesses into larger spatial areas or "zones". Commonly used zoning schemes are: census geographic zoning scheme, grid zoning scheme and postal zip code zoning scheme. Each zoning scheme has their strengths and shortcomings.

The census geographic zones are fine-grained spatial units which are attached with social-demographic and economic data for different years. A national census of population is carried out every 5 years by Statistics Canada. The boundaries of census geographic zones are relatively stable over time. Census geographic entities are coded to diverse geographic areas according to census geographic hierarchy. The three lowest hierarchies of zones have been frequently used in geography and spatial analysis. The three scales of zones are: census tract (CT), dissemination area (DA) and dissemination blocks (DB) (named by Statistics Canada). Furthermore, census data intentionally structures zone units according to the average amount of population in each zone (Moon & Farmer, 2001; Wu & Murray, 2005). As population density is usually high in city centers and low in suburbs, the size of census geographic zones becomes bigger as the distance from city centers to suburbs increases (Moon & Farmer, 2001). In some suburbs, where the population distribution is sparse, a DB may cover a large area of land (Moon & Farmer, 2001).

A census tract (CT) is defined as a small, relatively stable geographic area, which usually has 2,500 to 8,000 persons and its boundary follows permanent and simply recognizable physical features(e.g. roads, water feature, power transmission lines) (Statistics Canada, 2014). Dissemination area (DA) is lower in hierarchy than CT and a CT may contain one or more DAs. The boundaries of DA follow the boundaries of census subdivisions or census tracts and a DA usually contains 400 to 700 persons (approximately 250 households) (Statistics Canada, 2014). Dissemination blocks (DBs) are the smallest census geographic zones that have the data of population and dwelling counts (Statistics Canada, 2014). A DB is bounded on all sides by roads and/or borders of standard geographic areas (Statistics Canada, 2014).

Grids are consistent both in size and shape. Data of grids are attached with each grid cell. Compared with census geographic zones, resolution (or level of aggregation) of grids are more flexible and could be user-defined according to diverse research purposes. This advantage enables grids to be widely used in geography and spatial analysis. Moreover, grids provide more potential for studies in areas that do not have good quality census geographic data, especially developing world cities. For instance, Li et al. (2011) used grids to present the areas that could be reached within a given travel time, when evaluating accessibility in Wuhan, China.

This study used six different types of zones, which were defined in three scales and two zoning schemes. One zoning scheme followed the definition of census geographic boundary (i.e. CT, DA and DB). The other defined the zones using latitude-longitude quadrilateral grids at different cell sizes (i.e. 0.6 km, 0.3 km and 0.15 km grid).

The design and selection of scales and zoning schemes were according to two rules: firstly, the appearance of zones in existing accessibility studies (e.g. Huang & Wei, 2002; Horner & Murray, 2004; Li et al., 2011; Mamun & Lownes, 2011; Murray, 2001); secondly, zones are comparable in size or zoning scheme (i.e. 0.15 km grid is comparable in size to DB).

The census data were derived from Statistics Canada census profiles, version 2011. There were 53 CTs, 376 DAs and 2,314 DBs in the City of Windsor. A median was selected to represent the mid-point (or central tendency) of the size of CTs, DAs or DBs. A median was taken as a better measure than an average, because a few very high or low values in the dataset of size of CTs, DAs or DBs strongly affected the average values. The high standard deviations (SDs) of size of CTs (3.505), DAs (1.44) and DBs (0.207) indicated the high dispersion of data. In the City of Windsor, the median size of CTs, DAs and DBs was 1.994, 0.168 and 0.025 square kilometers (km2), respectively (see Table 3.2).0.6 km, 0.3 km and 0.15 km grids were selected as zones in grid zoning scheme at three scales.0.15 km grids(0.0225 km2) were selected as area units that are comparable in size to DB. The size of a 0.3 and 0.6 km grid is 0.09 and 0.36 km2, which is 4 times and 16 times of 0.15 km grid, respectively. The grids were created according to the boundaries of CTs, DAs and DBs, which tend to follow street patterns. The grids were set to cover all the area in the City of Windsor. Because of the irregular shape of the city, some grids exceeded the boundary of the city. The boundaries of census geographic zones followed the boundary of the City of Windsor.

Table 3.2 expresses the descriptive statistics of the six types of spatial units that were used in this study. The descriptive statistics include total units, the maximum size, the minimum size, median size and standard deviation (SD). The number of 0.15 km grid cells was more than DBs. This is because grids at the same scale are consistent in size while the size of census geographic zones rises with the increase of distance to city center.

Table 3.2 Descriptive Statistics of 6 Types of Zone Units

Descriptive Statistics	CT	DA	DB	0.6 km Grid	0.3 km Grid	0.15 km Grid
Total Units	53	376	2,314	469	1,751	6,712
Maximum Size (km^2)	25.245	25.244	3.483	0.36	0.09	0.0225
Minimum Size (km^2)	0.427	0.005	0.001	0.36	0.09	0.0225
Median Size (km^2)	1.994	0.168	0.025	0.36	0.09	0.0225
SD of Size	3.505	1.44	0.207	0	0	0

Note: SD, Standard Deviation; km^2, square kilometer

3.4. Calculating Population of Different Zones

The original population data were provided at DB level, which were derived from Statistics Canada census profiles, version 2011. Population at DA, CT, 0.6 km, 0.3 km and 0.15 km grids level were calculated in GIS using population at DB level.

Population of each DA and CT was summarized using population of DBs according to the DAUID (unique identifier of each DA) and CTUID (unique identifier of each CT), respectively. Population of 0.6 km, 0.3 km and 0.15 km grids was calculated by proportionally allocating the population counts from DBs to grids using an Area-Interpolation approach. The open areas, parks, water areas and recreational areas in each DB were excluded using the land-use data, which assumed that no people living in these areas and people living in residential, commercial and industrial areas. It was assumed that population was uniformly distributed in residential, commercial and industrial areas of each DB. The population of a grid cell was calculated based on the proportion of a DB's area that fell within the grid cell. For example, if 50% of a DB's area fell within a grid cell, then 50% of the DB's population was allocated into this grid. A grid cell's population equaled to the sum of population that was allocated from all overlapped DBs.

Table 3.3 expresses the descriptive statistics of population of 6 types of zones. The descriptive statistics include the highest, the lowest, mean and the SD of the number of population of a spatial unit. Two phenomena were interpreted. Firstly, the amount of population of a certain number of girds was 0 because they were partially within the boundary of City of Windsor. Secondly, the SDs of census geographic zones were high, which indicated a big difference in size of census geographic zones.

Table 3.3 Descriptive Statistics of Population of 6 Types of Zone Units

Population	CT	DA	DB	0.6 km Grid	0.3 km Grid	0.15 km Grid
Lowest	157	108	0	0	0	0
Highest	9,140	6,377	1,261	2,320	1,013	607
Mean	3,979	561	91	450	120	31
SD	1,856.26	413.45	111.87	471.3	138.2	38.62

Note: SD, Standard Deviation

3.5. Creating a Walking-Bus Network

A multi-mode network, combining walking and bus mode, is a basis to assess accessibility by both bus and walking mode in the City of Windsor using GIS. Arc GIS 10.2 was used to create a walking-bus network for the City of Windsor, which included the dataset of streets, bus routes, bus stops. Particularly, the walking-bus network contained 7 essential factors for calculating the distance that could be reached within 30 minutes of travel time: length and walking time of each street segment, average walking speed, length and travel time of each bus route segment, average bus operating speed and bus frequency (or headway). The following section provides interpretations on how the data of the 7 factors were collected and calculated.

The length of each street segment was calculated using the Calculate Geometry command in GIS. This study adopted an average walking speed of 80 m/min (approximately 5 km/h). This walking speed was used by El-Geneidy et al. (2011) and Yigitcanlar et al. (2007). The walking time of each street segment was estimated using the length of each street segment to divide the average walking speed. The street network data of the City of Windsor were derived from Statistics Canada census profiles, version 2011. The data were in GIS format, which contained the information of street name, street type, street rank code and street class code. As pedestrian paths were not included in the street network data, walk paths to bus stops were based on the physical street configurations.

Twelve normal bus routes (with1,167 bus stops) were in the City of Windsor in 2015. The city center had the best access to bus services, which had 10 bus lines passing through, while the southwest and southeast part of the City of Windsor were relatively lacking in bus services. The bus system data were derived from the Open Data Catalogue of the City of Windsor in 2015. The data of bus stops and bus routes were in GIS format, which contained the information of bus stop name, bus route name and operation direction. The published bus operation schedules were in PDF format, which provided information of bus operation periods and bus frequency.

The data of bus frequency and bus operation time were collected from published schedules for services operating during weekday morning peak periods (6:30 am to 9:30 am) in 2015. The length of each bus route segment was calculated using the Calculate

Geometry command in GIS. The average bus speed of each bus route was calculated using the total length of a bus route to divide the total operation time between two terminal bus stops. It was assumed that bus travels at an average speed along bus routes. The travel time of each bus route segmentwas calculated using the length of each bus route segment to divide the average bus speed of this bus line. Each bus stop was assigned a headway which represented the average interval time between two buses. An initial waiting time (or arrive to wait time) at a bus stop was estimated using one-half of the headway of this bus line. This estimation approach was developed by O'Sullivan et al. (2000), who assumed that people on average arrive at a bus stop in the middle of two bus arrivals. In other words, people wait one-half of the headway time at a boarding bus stop.

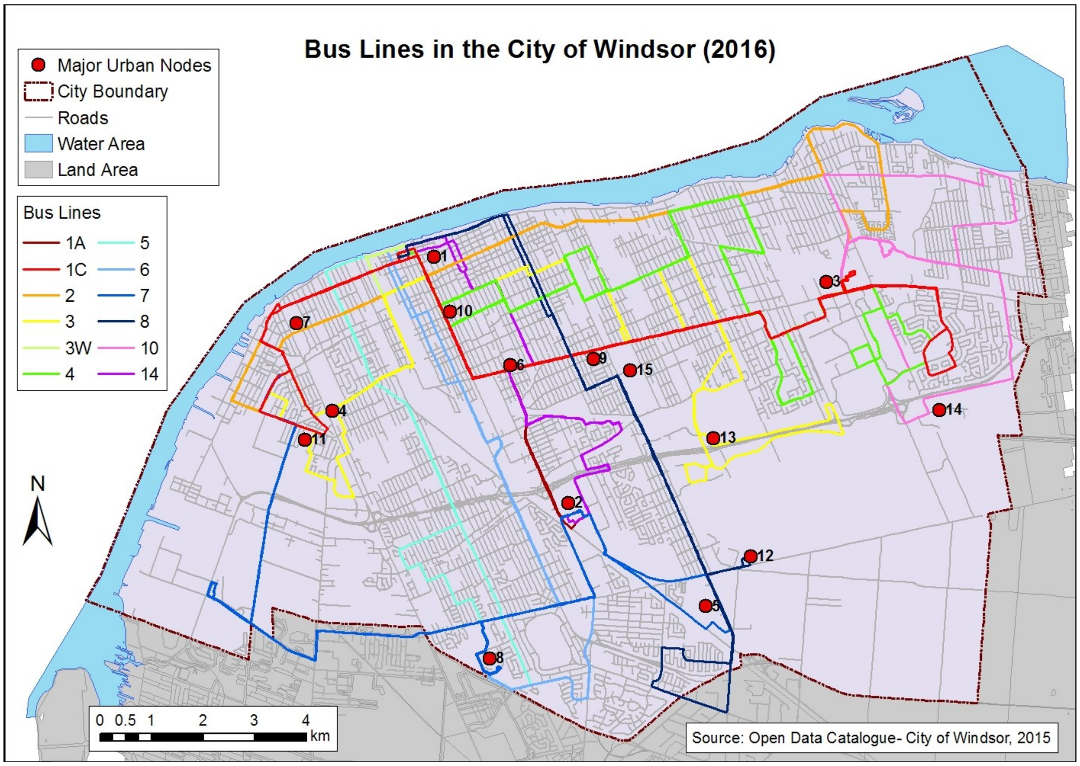


Figure 3.2 Bus Lines in the City of Windsor

3.6. Assessing Accessibility in the City of Windsor

Accessibility in the City of Windsor was assessed based on the number of major urban nodes that could be reached from a residence within 30 minutes by bus and walking. In general, the assessment of accessibility followed two steps: firstly, drawing lines connecting the points (or contours or isochrones) that could be reached within 30 minutes by bus and walking from each urban node; secondly, summarizing the results into a “reverse picture” and computing the number of urban nodes that could be reached from a residence within 30 minutes by bus and walking.

The isochrones of an urban node were computed using the “Service Area Analysis” function in GIS. The computation of isochrones of an urban node followed 5 steps:

1-Drawing lines and connect the points to be reached within 400 m straight-line distance from an urban node. The bus stops that were within 400 m buffers were considered as having access to an urban node (See Figure 3.3 - A). Figure 3.3 – A expresses an example of the bus stops that are within the 400 m straight-line distance from an urban node.

2- Within the 400 m buffers, selecting the bus stop on every bus route that was the nearest to an urban node (See Figure 3.3 - B), and then calculating the walking time (counted as T1) between boarding bus stop and the urban node (See Figure 3.3 - C). The waiting time at boarding bus stop before getting on board was counted as T2. Figure 3.3 – B expresses an example of bus stops that were nearest to an urban node and Figure 3.3 – C expresses an example of walking distance from an urban node to each boarding bus stop.

3- Computing the areas (Area 1) that could be reached within the remaining travel time T3 (equaled 30 minutes subtracting T1 and T2) (See Figure 3.3 - D). Figure 3.3 - D expresses an example of the areas that can be reached from an urban node within 30 minutes by bus and walking. T3 included in-bus travel time and walking time from an egress bus stop to potential origins. One problem was that Area1 may contain places that took over 5 minutes from an egress bus stop by walk, so the next step was to remove these places.

4-Drawing a 400 m street network buffer (Area 2) around each egress bus stop. Area 2 represented the areas that could be reached within 5 minutes by walk from each egress bus stop (See Figure 3.4 - E). Figure 3.4 - E expresses an example of 400 m street network buffers around potential egress bus stops.

5- Intersecting Area 1 with Area 2 and selecting the overlapped areas (Area 3) (See Figure 3.4 - F). Figure 3.4 - F expresses an example of how Area 1 and Area 2 were intersected and how the overlapped areas were removed. Area 3 represented the isochrones of an urban node, which were accessible with a total 30-minute travel time budget and 5-minute walking time limit (See Figure 3.4 - G). Figure 3.4 – G expresses an example of the final isochrones of an urban node. This process excludes trips that take more than 5 minutes by walk in assessment of accessibility.

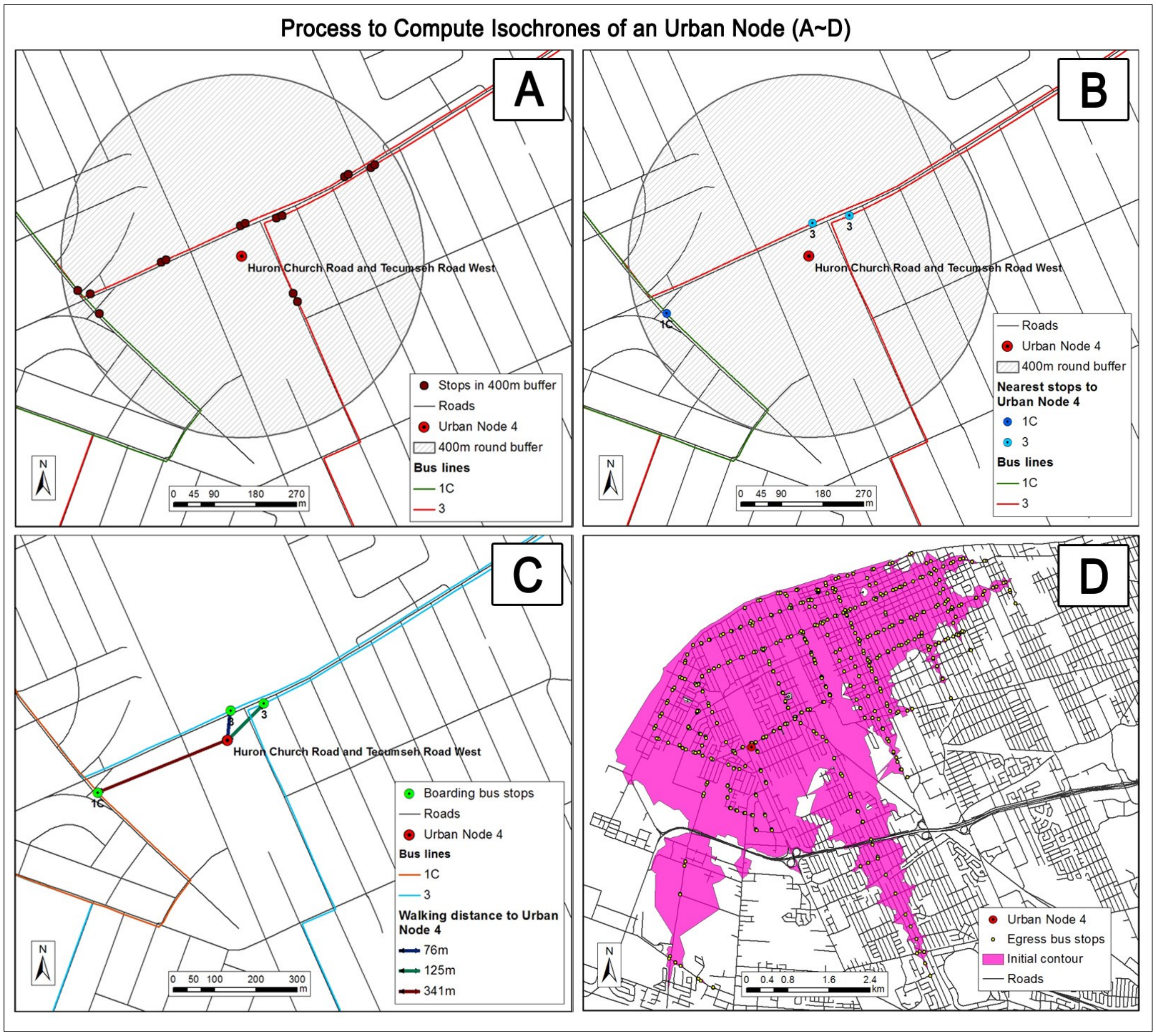


Figure 3.3 Process of Computing Contour of an Urban Node (A~D)

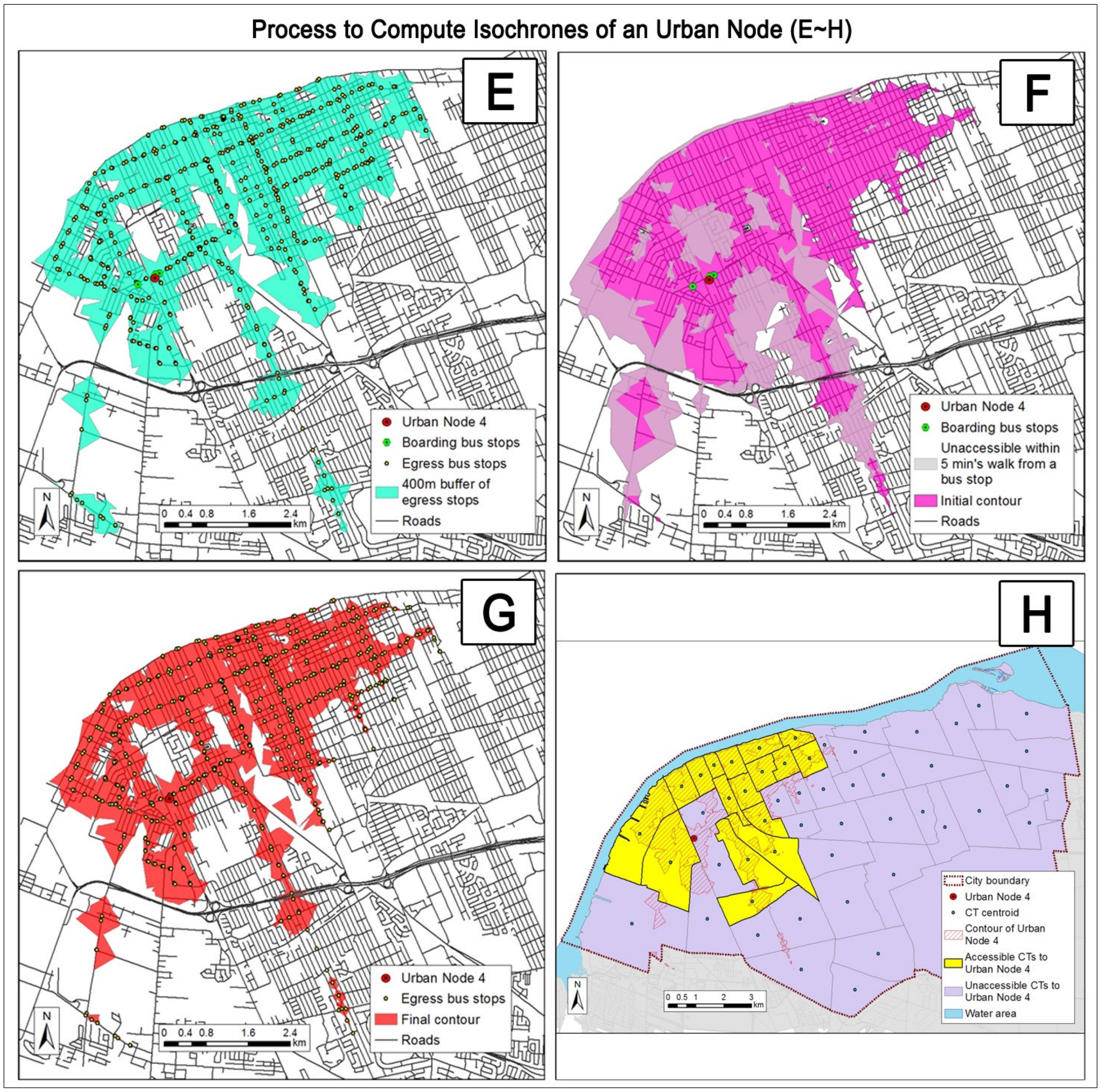


Figure 3.4 Process of Computing Contour of an Urban Node (E~H)

The number of inhabitants that fell within the isochrones of an urban node was calculated using a centroid method. The centroid method was simple to use. Each zone was represented by its geometric centroid in analysis. If a zone's centroid fell within the isochrones of an urban node, the entire inhabitants in this zone were considered as within the isochrones of an urban node or were accessible to the urban node. This computation was calculated using 6 types of zones (CTs, DAs, DBs, 1.5 km, 0.4 km or 0.15 km grids). Finally, a summary was made on the results that were calculated using 6 types of zones.

The computation of the number of urban nodes that could be reached from a residence (represented by CT, DA, DB, 1.5 km, 0.4 km or 0.15 km grid) with a 30-minute travel time budget by bus and walking followed 2 steps:

1- Assigning an accessibility score of 1 to the zone units, whose centroids were within the contours of an urban node; and then assigning an accessibility score of 0 to the rest spatial units. Figure 3.4 – H expresses an example of calculating accessible census tracts to an urban node.

2- Summing the accessibility score of each zone unit.

Accessibility score of a zone should be between 0 and 15, as there were total 15 urban nodes in the City of Windsor. In the end, a summary was made on the measurement of accessibility in the City of Windsor based on 6 types of zones. Figure 3.5 expresses the accessibility to urban nodes by bus in the City of Windsor based census tracts.

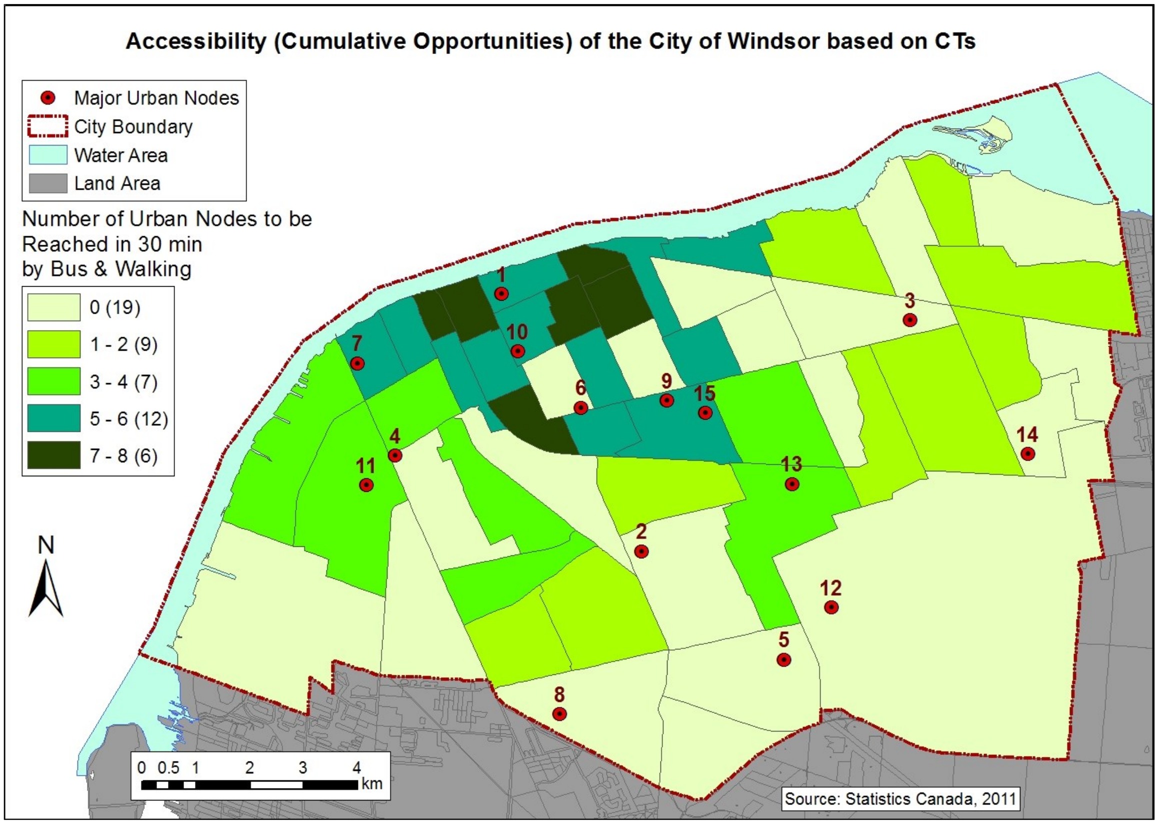


Figure 3.5 Accessibility in the City of Windsor based on CTs

3.7. An Experimental Method of Calculating Accessibility Using Google Maps

This research also tested a method of calculating accessibility in the City of Windsor using Google Maps, in addition to the foregoing approach using GIS. The experimental method was applied using CTs and major urban nodes in the City of Windsor. Accessibility was calculated based on the number of urban nodes that can be reached from each CT (represented by its geometric centroid) within 30 minutes by bus and walking. The depart time was set at 7:30 am on Monday.

The computation of accessibility in the City of Windsor followed 3 steps:

1- Typing in the location of a CT centroid (represented by X, Y Coordinates) as the trip origin and typing the location of an urban node as trip destination.

2- Selecting the route that takes the least travel time by transit and then record the walking distance from the CT centroid to boarding bus stop, walking distance from egress bus stop and total travel time into three tables.

3- Summarizing the number of urban nodes that can be reached within 30 minutes by bus and walking, and then mapping the assessment results.

Figure 3.6 expresses the assessment of accessibility in the City of Windsor using Google Maps. Figure 3.7 expresses the difference of accessibility score that calculated using the foregoing approach (based on GIS) and this approach. For the 53 CTs in the City of Windsor, 17 retained the accessibility score, and accessibility score of 33 CTs is increased when calculating using the second approach compared to the first approach. This is because the second approach of using Google Map does not limit the walking distance from trip origin to a boarding bus stop or from an egress bus stop to trip destination, and therefore, more urban nodes could be reached within 30 minutes by bus and walking. However, not limiting the walking distance may overestimate the assessment of accessibility, as it is unlikely that people would walk a long distance (e.g. 1 or 2 km) to catch a bus to work.

The strength of this approach is that it calculates accessibility from each CT to each urban node, which is straightforward. However, this approach has a number of weaknesses. First, this approach does not consider the waiting time at a boarding bus stop, which decreases the accuracy of the calculation of total travel time from origin to destination. Second, this approach does not limit the walking time (or distance) from trip origin to a boarding bus stop and from an egress to trip destination, which may involve long walking distance to or from a bus stop that people would rarely take in a weekday commuting trip. Walking distance from trip origin to a boarding bus stop ranges from 28 m to 2,700 m and walking distance from an egress to trip destination ranges from 82 m to 3,200 m. The average walking distance from trip origin to a boarding bus stop is 712 m (approximate 8.5 min) and the average walking distance from an egress to trip destination is 443 m (approximate 5.3 min). These walking distances are much larger than 400 m, which is a commonly used number as people's preferred walking distance from/to a bus stop (Hsiao et al., 1997; Murray, 2001; O'Sullivan & Morrall, 1996; Ryus et al., 2000).

In summary, this approach of calculating accessibility using Google Maps was not applied in this research because of the weaknesses.

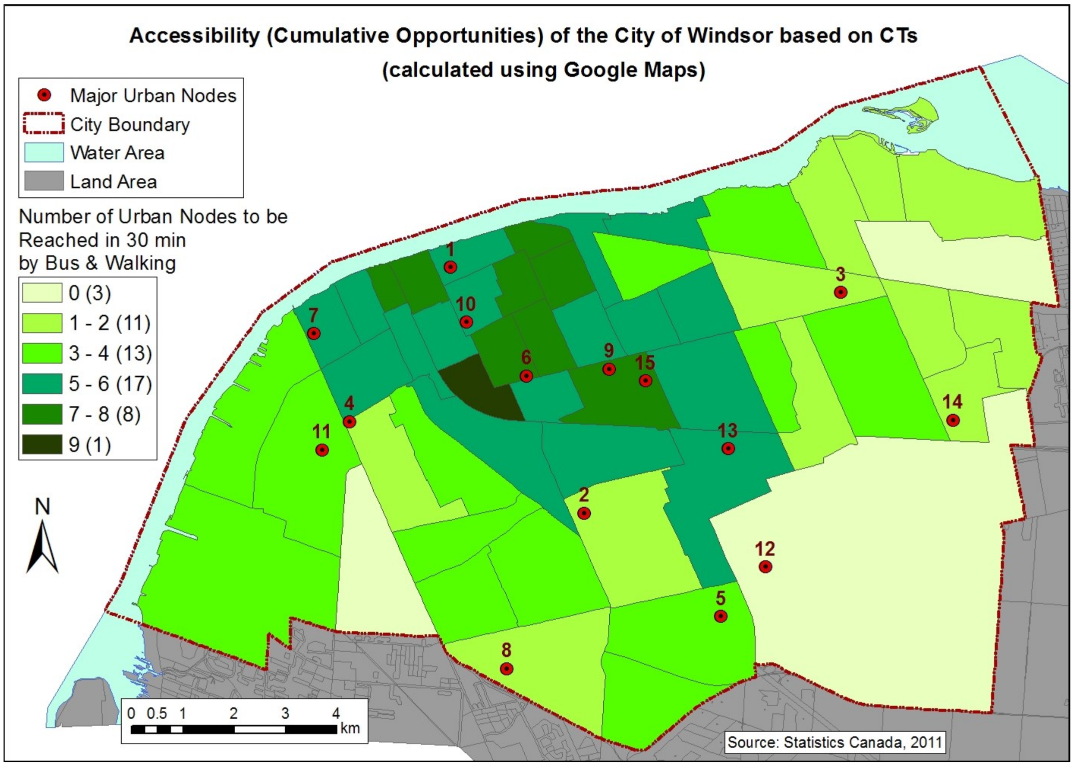


Figure 3.6 Accessibility in the City of Windsor Using the Google Maps Approach

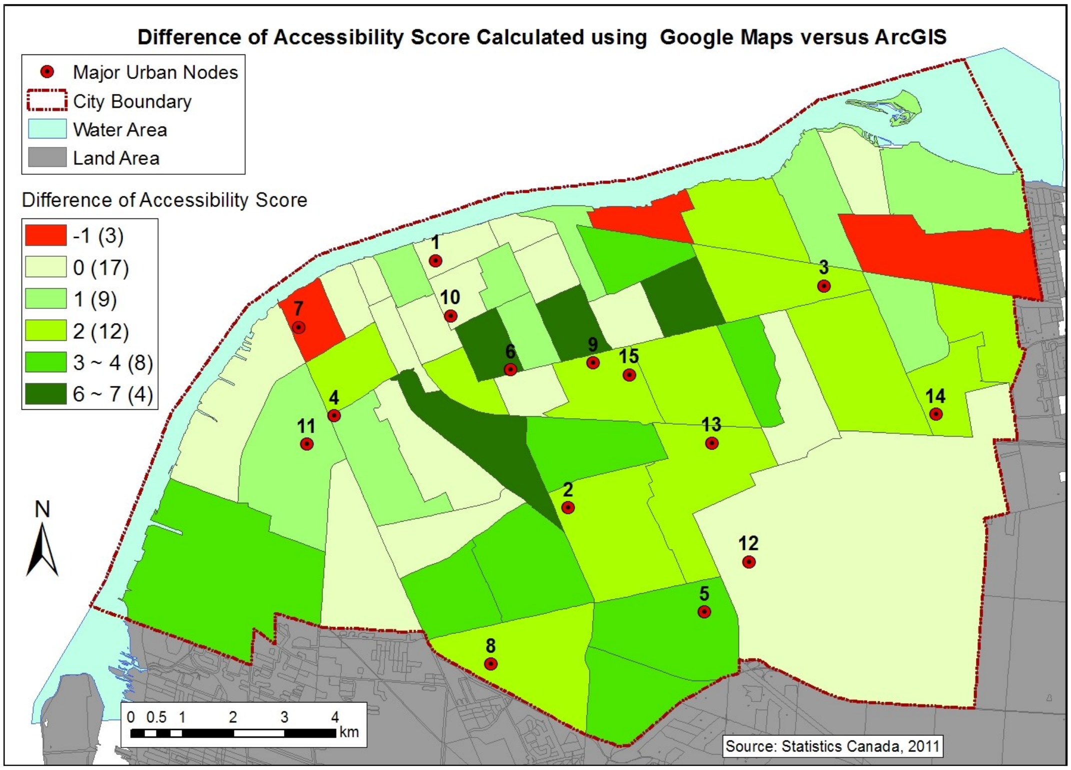


Figure 3.7 Difference of Accessibility Score Using Google Maps Approach versus GIS

3.8. Analyzing the MAUP Effects on Accessibility Measurement

The MAUP effects on assessment of accessibility were examined based on two aspects: scale effect and zoning effect. Basically, the idea was to calculate if changing zones' scale or zoning scheme may alter the measurement of cumulative accessibility, and how the assessment results vary with the change of zone's scale and zoning scheme?

This study applied a controlling variable method to evaluate the MAUP effects on assessment of accessibility. The controlling variable method has been commonly used in the MAUP studies, such as Zhang & Kukadia (2005) and Mitra & Buliung (2012). The nature of the controlling variable method is to keep all other variables constant or controlled when manipulating one variable. For instance, control zones' zoning scheme, when examining the scale effect on assessment of accessibility. Similarly, control zones' scale, when examining the zoning effect on assessment of accessibility.

The examination of the MAUP effects (scale and zoning) on assessment of accessibility was based on the changes of accessibility score of a zone when altering zones' scale or zoning scheme. Specifically, changes of accessibility score were presented by the extent of change as well as by the size of areas (e.g. 50% of the areas in the City of Windsor) that had alterations of accessibility score. Assessment of accessibility based on DBs was considered to be the most accurate (compared to the other 5 types of zones) and was used as referential numbers to examine the under or over-estimate rate based on other 5 types of zones.

The scale effect on assessment of accessibility was examined by comparing the differences of accessibility score based on 2 pairs of zones and a group of zones, which were at different scales but in the same zoning scheme. The 2 pairs of zones were: CT versus DB, DA versus DB. The group of zones was: 0.15 km grid versus 0.3 km grid and versus 0.6 km grid. More specifically, differences of accessibility scores calculated based on 0.15 km, 0.3 km and 0.6 km grids was evaluated according to the under or over-estimate rate compared to accessibility based on DBs.

The zoning effect on assessment of accessibility was evaluated by comparing the differences of accessibility score based on 3 pairs of zones: 0.15 km grid versus DB, 0.3 km grid versus DB and 0.6 km grid versus DB. 0.15 km grid and the average size of DB are the same in scale. 0.3 km grid is 4 times in size to 0.15 km grid, and 0.6 km grid is 16 times in size to 0.15 km grid. The size of the three scales of grids was considered when evaluating how assessment of accessibility varies with the change of zones' zoning scheme.

Finally, the patterns of changes of accessibility score were summarized. Features of the scale effects and zoning effects were summarized in order to provide information for ways to deal with the MAUP.

4. Results and Findings

The Results and Findings Chapter contains four sections, which address the research questions posed at the beginning of this research. This chapter firstly examines accessibility levels in the City of Windsor and summarizes the situation of public transportation provision and land-use development, which answers the first research question. Secondly, this chapter examines the MAUP effects based on 2 aspects: scale effect and zoning effect. This answers the second research question: how does assessment of accessibility alter with the change of zone's scale or zoning scheme? Thirdly, this chapter explores the consequences of changing the size and shape of area units on measures of cumulative accessibility, which is the third research question. Finally, the last research question, how to deal with the MAUP effects, is answered.

4.1. Accessibility in the City of Windsor

This section analyzes the general accessibility level in the City of Windsor based on the accessibility scores calculated using DB. Figure 4.1 expresses the assessment of accessibility in the City of Windsor based on DBs. Table 4.1 expresses the summary of accessibility in the City of Windsor. This section reveals the situation of public transportation provision in the City of Windsor, based on the comparison of accessibility scores with population distribution, land-use and location of bus stops and bus lines.

The maximum number of urban nodes that was accessible within 30 minutes by bus and walking was only 8 out of 15 in the City of Windsor. According to the analysis results based on DBs, 89,574 persons (approximately 42.5% of all population) and 98 km^2 (about 66.9% of all areas) were not accessible to any major urban node, and 60,431 persons (approximately 28.7 % of all population) could reach 1 to 4 urban nodes, and 60,886 persons (approximately 28.9% of all population) could reach more than 5 urban nodes within 30 minutes by bus and walking in the City of Windsor. This suggested that major urban nodes in the City of Windsor were poorly served by public transit.

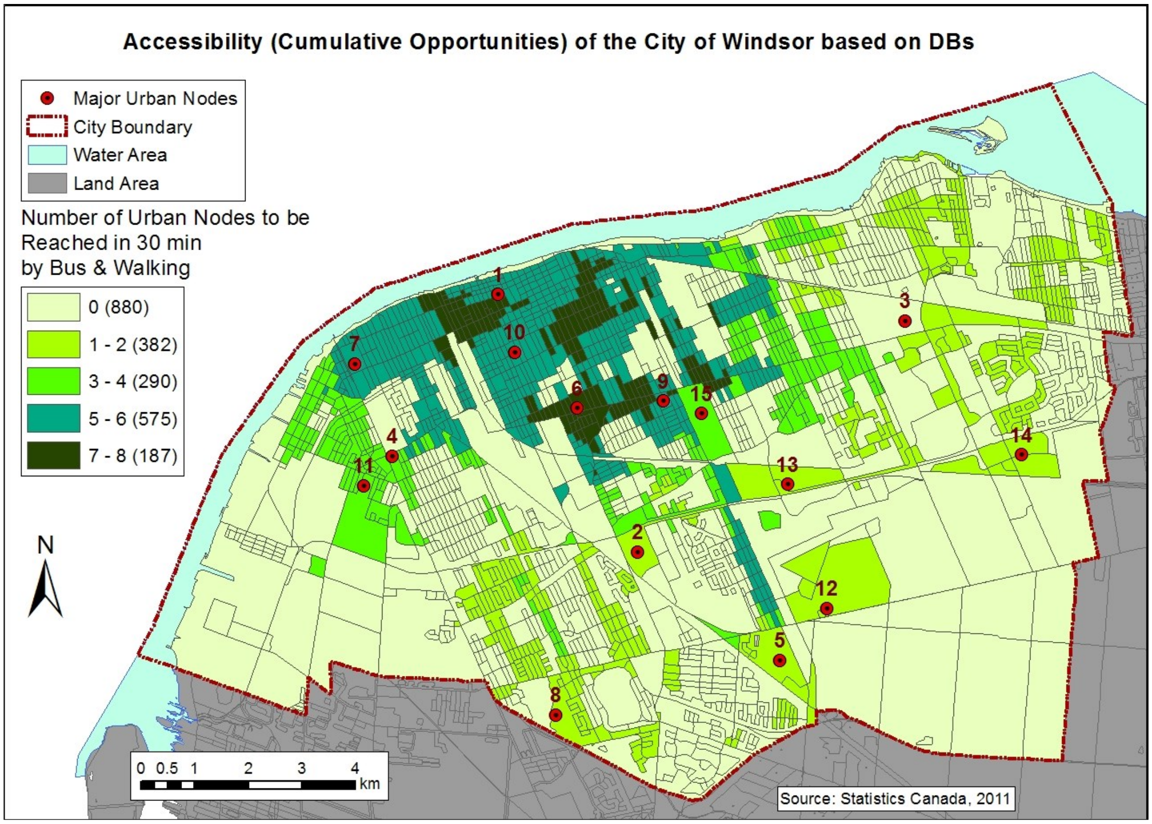
In general, accessibility scores decreased with the increase of distance to the city center in the City of Windsor. Areas directly adjoining the downtown core scored the highest, which could reach 7 to 8 urban nodes within 30 minutes by bus and walking. Areas adjoining the Urban Node 6 and 9 also had the highest accessibility score. Areas located in the southwest and southeast of the City of Windsor scored the worst, because of the lack of bus service these areas. This would not decrease the overall accessibility level in the City of Windsor, as areas in the southeast and southwest are mostly open areas or industrial areas and have very low population density. Areas had no accessibility to any urban node in 30 minutes scattered across the City of Windsor, and some are located in the central area in the city. This phenomenon can be interpreted using Figure 4.2, which expresses the location of bus lines and stops and accessibility score. Specifically, DBs directly surrounding the bus lines had higher accessibility score than DBs that were far away from the bus lines. When given a 30-minute total travel time and 5-minute walk time limit, large amount of areas could not reach any urban node because these areas do not have proximity to bus system.

As this research applied an approach that limited 400 m (approximate 5 minutes by walk) as the maximum walking distance from trip origin to boarding bus stop and from egress stop, trips that take more than 5 minutes by walk were excluded in assessment of accessibility. As a result, only the DBs that were within 400 m's distance to a bus stop were accessible to bus service (see Figure 4.1 and 4.2). This leads to some particular patterns of distribution of accessibility scores in the City of Windsor. It can be seen from Figure 4.2 that the accessibility score decreased with the increase of distance to bus lines. Areas adjoining the downtown core had a lower accessibility score than areas surrounding Urban Node 6 (see Figure 4.1 and 4.2).

Table 4.1 Summary of Accessibility in the City of Windsor

Number of urban nodes that are accessible within 30 minutes	Number of people	Percentage of people	Amount of area (km^2)	Percentage of area
0	89,574	42.5%	98	66.9%
1~2	35,967	17.1%	19.2	13.1%
3~4	24,464	11.6%	10.9	7.4%
5~6	44,206	21%	14	9.6%
7~8	16,680	7.9%	4.4	3%

Note: The total area of the City of Windsor was 146.384 km^2 in 2011 (Statistic Canada, 2015).



Source: Statistics Canada, 2011

Figure 4.1 Accessibility in the City of Windsor based on DBs

The comparison of population distribution, land-use with accessibility scores implies the situation of consistency of land-use development with public transportation provision in the City of Windsor. In general, the development of the downtown core was consistent with public transportation provision. Specifically, the downtown core had the densest population concentration and the highest accessibility score. Large residential areas in the south and northeast in the City of Windsor had high population density but had an accessibility score of 0 (See Figure 4.3 and 4.4). The south and northeast in the City of Windsor had a severe lack of bus service that many areas are not covered by bus service. Urban planners and decision-makers should pay highly attention to increasing accessibility by transit in suburbs of Windsor, given the continuous urban sprawl and long commuting trips from in the City of Windsor (Maoh & Tang, 2012). It would be a big challenge to increase accessibility via transit in the south and northeast suburbs of Windsor. This research provides some suggestions in the Discussion and Conclusion Chapter.

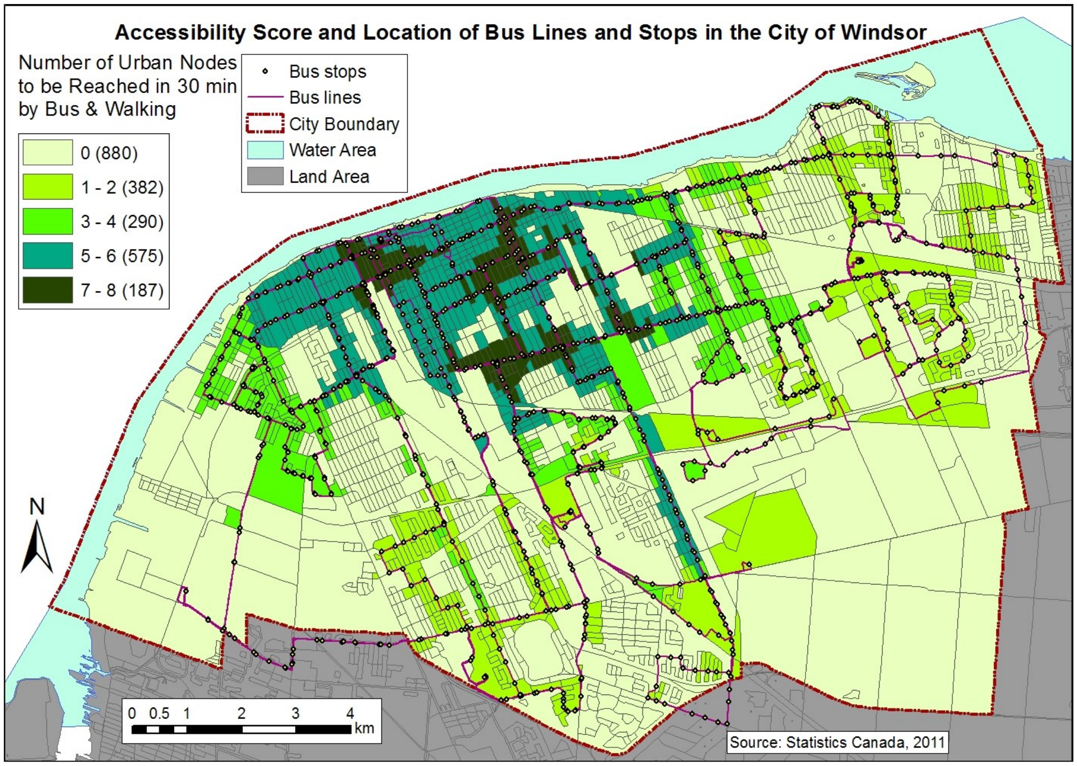


Figure 4.2 Accessibility Score and Location of Bus System in the City of Windsor

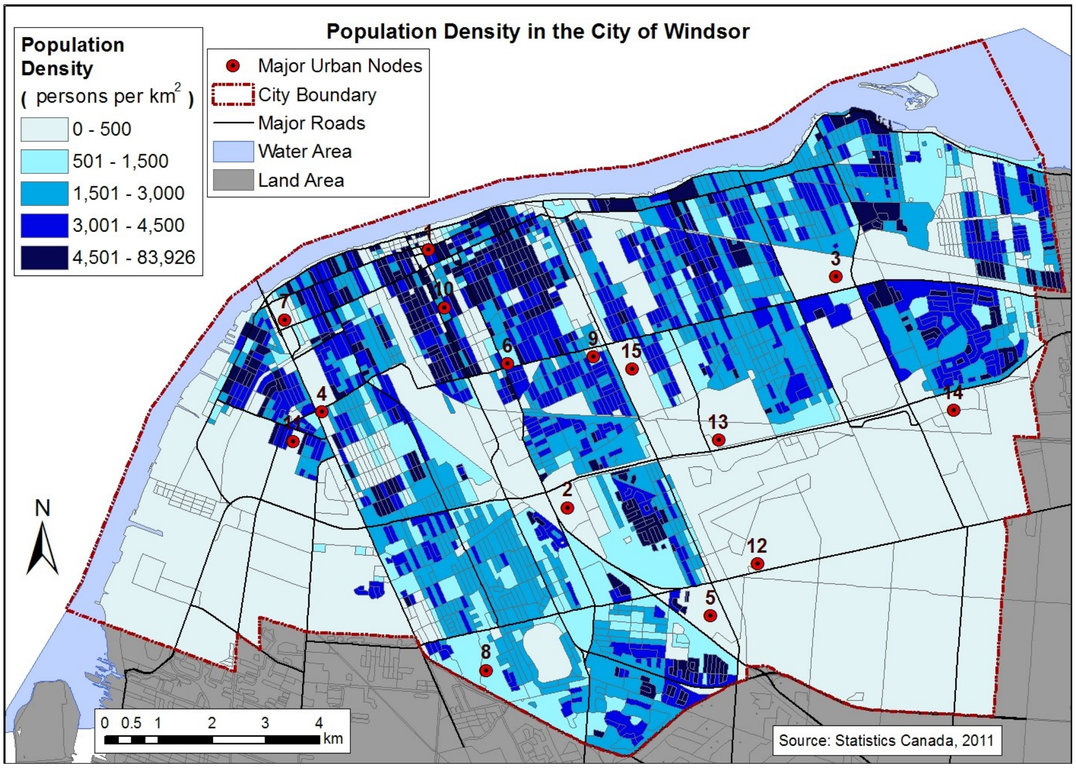


Figure 4.3 Population Density in the City of Windsor

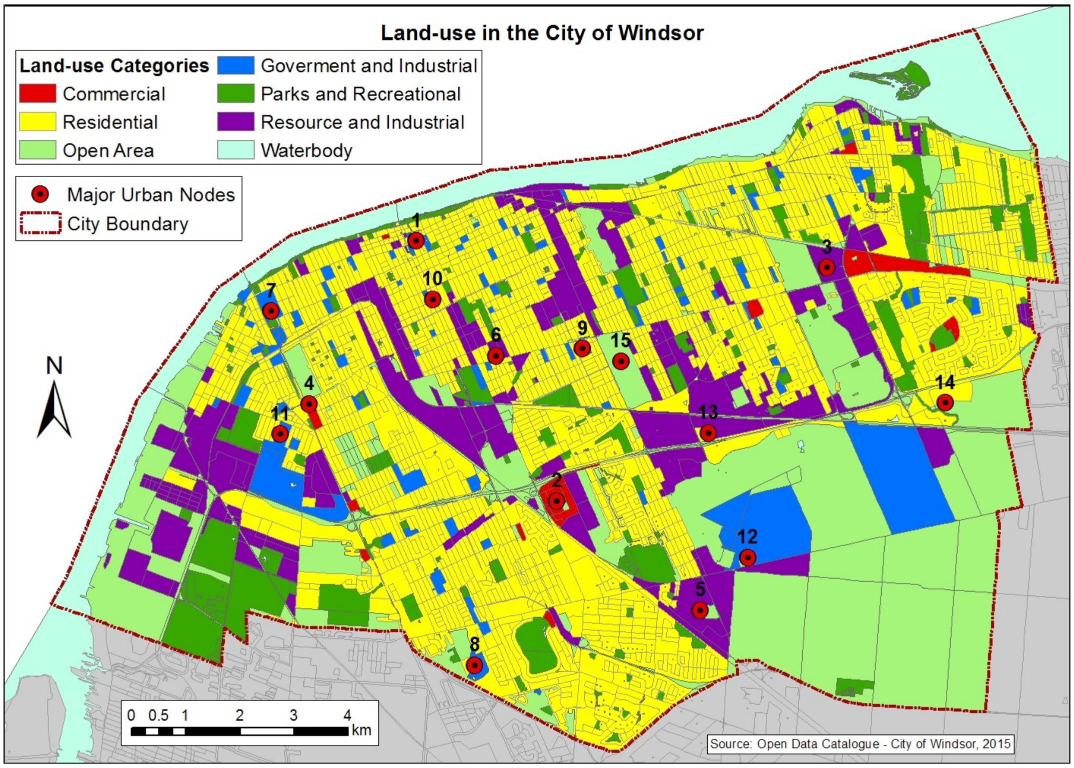


Figure 4.4 Land-use in the City of Windsor

4.2. The MAUP Effects on Assessment of Accessibility

This section analyzes the MAUP effects on accessibility when using cumulative opportunity measures. The MAUP effects were identified by comparing the differences of the accessibility scores (or cumulative opportunities) based on zones at different scales or zoning schemes. Assessment of accessibility based on DBs was considered to be the most accurate compared to calculations based on other zones (e.g. CT, DA, 0.15, 0.3 and 0.6 km grid). Therefore, assessment of accessibility based on DBs was used as reference numbers of estimate the over or under estimate rate when using other types of zones.

The MAUP effect was firstly examined by the change of overall assessment of accessibility when varying zone's scale or zoning scheme. The overall assessment of accessibility was represented by how many people have very low accessibility score, medium accessibility score and high accessibility score. Specifically, 89,574 people had an accessibility score of 0, 35,967 people had an accessibility score of 1~2 and 16,680 people had an accessibility score of 7~8, when calculating accessibility based on DBs. When varying zone's scale or zoning scheme, there was 8.9% to 18% (or 7,972 to 16,121 persons) of under-estimate of the number of people having an accessibility score of 0, and there was 7.8% to 24.4% (or 2,818 to 12,361 persons) of over-estimate of the number of people having an accessibility score of 1~2, and there was 9.1% to 44.7% (or 1,519 to 7,459 persons) of over-estimate of the number of people having an accessibility score of 7~8 (See Table 4.2 and 4.3). The change of zone's scale of zoning scheme may greatly alter the assessment of accessibility in terms of under or over-estimate from one thousand to 15 thousand of people that having a certain level of accessibility. Figure 4.5 expresses the difference of number of people that were accessible to a certain number of urban nodes when altering zone`s scale or zoning scheme.

In order to get deep insight into how does accessibility score of every residential area alter when varying zone's scale or zoning scheme, 5 maps were created to compare the difference of assessment of accessibility based on DA versus DB, CT versus DB, 0.15 km grid versus DB, 0.3 km grid versus DB and 0.6 km grid versus DB.

Table 4.2 Number of People that were Accessible to a Certain Quantity of Urban Nodes

Number of urban nodes that were accessible within 30 minutes	Number of people (calculated using six types of zones)					
	DB	DA	CT	0.15 km Grid	0.3 km Grid	0.6 km Grid
0	89,574	74,091	79,086	73,809	73,453	81,602
1~2	35,967	48,328	43,227	45,321	45,215	38,785
3~4	24,464	25,858	29,025	28,994	29,486	25,748
5~6	44,206	42,747	41,354	39,943	39,996	40,604
7~8	16,680	19,867	18,199	22,575	22,711	24,139

Note: The total population in the City of Windsor was 210,891 in 2011 (Statistic Canada, 2015).

Table 4.3 Difference of the Number of People Compared to DBs

Number of urban nodes that are accessible within 30 minutes	Difference of the number of people (number)				
	DA versus DB	CT versus DB	0.15 km Grid versus DB	0.3 km Grid versus DB	0.6 km Grid versus DB
0	-15,483	-10,488	-15,765	-16,121	-7,972
1~2	12,361	7,260	9,354	9,248	2,818
3~4	1,394	4,561	4,530	5,022	1,284
5~6	-1,459	-2,852	-4,263	-4,210	-3,602
7~8	3,187	1,519	5,895	6,031	7,459

Number of urban nodes that are accessible within 30 minutes	Difference of the number of people (percentage)				
	DA versus DB	CT versus DB	0.15 km Grid versus DB	0.3 km Grid versus DB	0.6 km Grid versus DB
0	-17.3%	-11.7%	-17.6%	-18.0%	-8.9%
1~2	34.4%	20.2%	26.0%	25.7%	7.8%
3~4	5.7%	18.6%	18.5%	20.5%	5.2%
5~6	-3.3%	-6.5%	-9.6%	-9.5%	-8.1%
7~8	19.1%	9.1%	35.3%	36.2%	44.7%

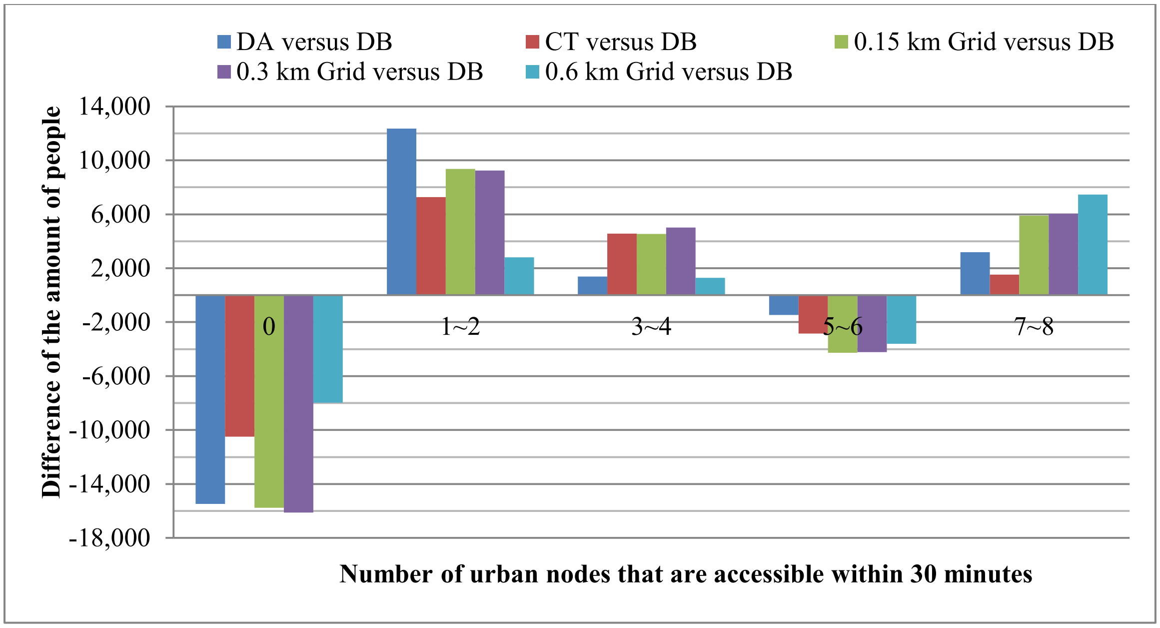


Figure 4.5 Difference of the Number of People Compared to DBs

Table 4.4 expresses the change of accessibility score in number and percentage when altering zone's scale or zoning scheme. Differences of accessibility score ranged from 1 to 8 or from -8 to -1 (or 14.3% ~75%, over 100%, -80% ~ -12.5% and below -100%). Differences in percentage were considered to be better expressing the differences of accessibility scores rather than differences in quantity. This is because accessibility of an area was represented by the relative accessibility level compared to other areas rather than the physical number.

Differences of accessibility score were empirically classified into 7 categories based on the extent of differences (see Table 4.4) and overestimate and underestimate rate. 0 represented no difference of accessibility score; "14.3% ~ 25%" represented slight over-estimate and an average change of accessibility score of 1; "33.3% ~ 75%" represented medium over-estimate and an average change of accessibility score of 1.5; ">=100%" represented great over-estimate and an average change of accessibility score of 2.6; "-28.6% ~ -12.5%" represented slight under-estimate and an average change of accessibility score of -1.1; "-80% ~ -33.3%" represented medium under-estimate and an average change of accessibility score of -1.6; "<= -100%" represented great under-estimate and an average change of accessibility score of -2.6. The average change of accessibility score in Table 4.4 referred to weighted average, which was calculated based on the differences of accessibility score (in quantity) and the size of areas that had changes of accessibility score (the size of areas was used as weight). The evaluation of differences of accessibility score only considered accessible areas by transit and inaccessible areas was excluded. Inaccessible areas refer to areas retained an accessibility score of 0 when varying one type of zone to another to calculate accessibility (e.g. from DB to CT).

Table 4.4 Differences of Accessibility Score and Descriptions

Difference (in percentage)	Difference (in quantity)	Average Change	Descriptions
<= -100%	-1 ~ -8	-2.6	great under-estimate
-80% ~ -33.3%	-1 ~ -5	-1.6	medium under-estimate
-28.6% ~ -12.5%	-1 ~ -2	-1.1	slight under-estimate
0	0	0	no difference
14.3% ~ 25%	1	1	slight over-estimate
33.3% ~ 75%	1 ~ 3	1.5	medium over-estimate
>=100%	1 ~ 8	2.6	great over-estimate

When calculating accessibility based on DBs and DAs, 56% of the areas in the City of Windsor had an accessibility score of 0 (or inaccessible to any urban node within 30 minutes by bus and walk), and these areas were excluded in the evaluation of differences of accessibility score. When changing zones from DBs to DAs, 18.3% of the areas in the City of Windsor retained the accessibility score, and 1.2% of areas had a medium under-estimate of accessibility score, and 1.6% of areas had a medium over-estimate of accessibility score, compared to 7.8% of areas had a great under-estimate of accessibility score and 12% of areas had an great over-estimate of accessibility score (see Figure 4.6 and 4.7, Table 4.5).

When calculating accessibility based on DBs and CTs, 44.3% of the areas in the City of Windsor had an accessibility score of 0 (or inaccessible to any urban node within 30 minutes by bus and walk), and these areas were excluded in the evaluation of differences of accessibility score. When changing zones from DBs to CTs, 11.5% of the areas in the City of Windsor retained the accessibility score, and 3.7% of areas had a medium under-estimate of accessibility score, and 1.3% of areas had a medium over-estimate of accessibility score, compared to 10.1% of areas had a great under-estimate of accessibility score and 24% of areas had a great over-estimate of accessibility score (see Figure 4.6 and 4.8, Table 4.5).

Table 4.5 Differences of Accessibility Score of DA, CT versus DB

Difference	DA versus DB		CT versus DB	
	Size of area (km^2)	Percentage of area	Size of area (km^2)	Percentage of area
<= -100%	11.5	7.8%	14.8	10.1%
-80% ~ -33.3%	1.7	1.2%	5.4	3.7%
-28.6% ~ -12.5%	1.7	1.1%	4	2.7%
0	26.8	18.3%	16.9	11.5%
14.3% ~ 25%	3	2%	3.4	2.3%
33.3% ~ 75%	2.4	1.6%	1.9	1.3%
>=100%	17.6	12%	35.2	24%

Note: The percentage of area was calculated using the area that had changes of accessibility score to divide the area of the City of Windsor.

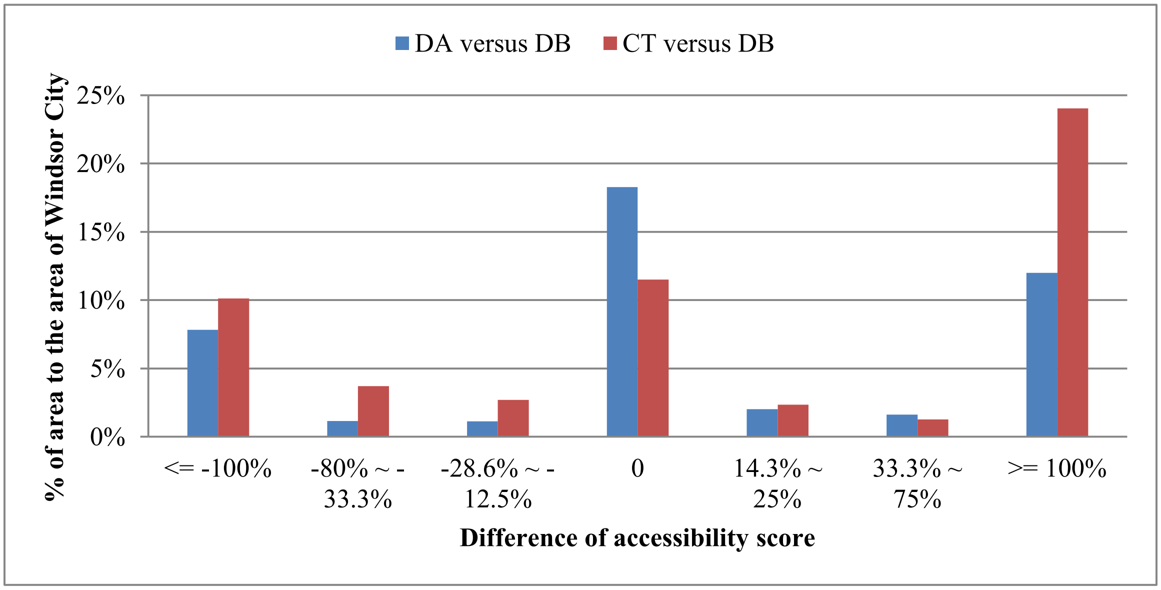


Figure 4.6 Differences of Accessibility Score of DA, CT versus DB

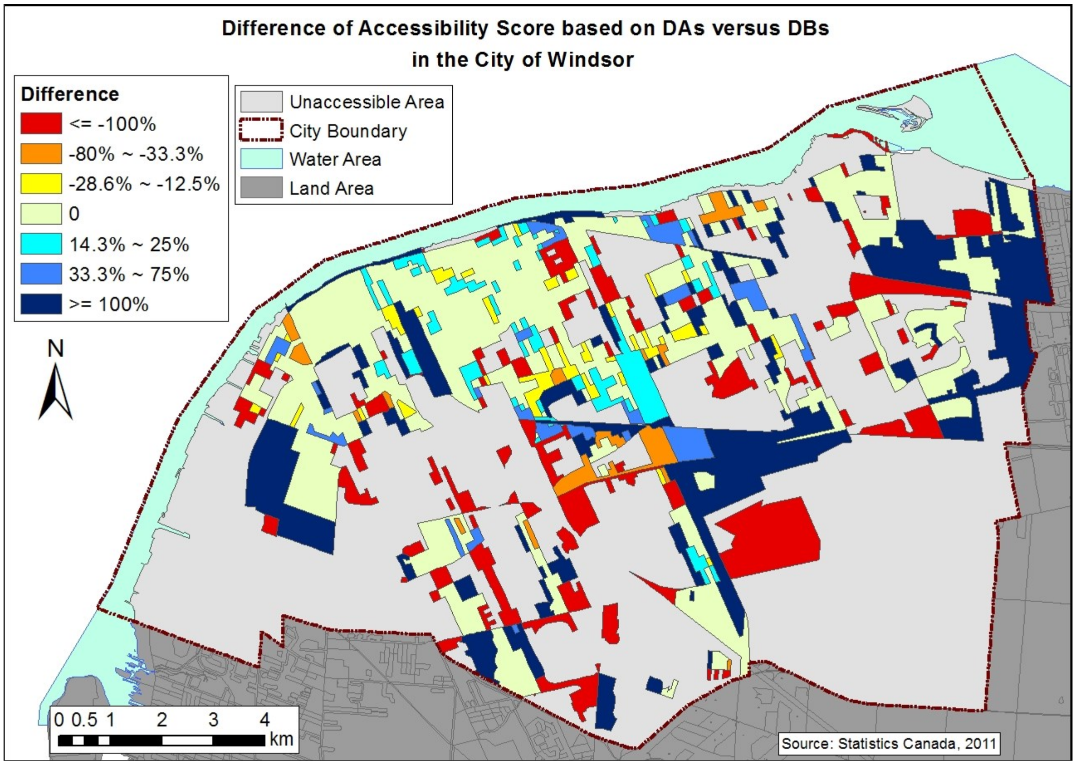


Figure 4.7 Differences of Accessibility Score of DA versus DB

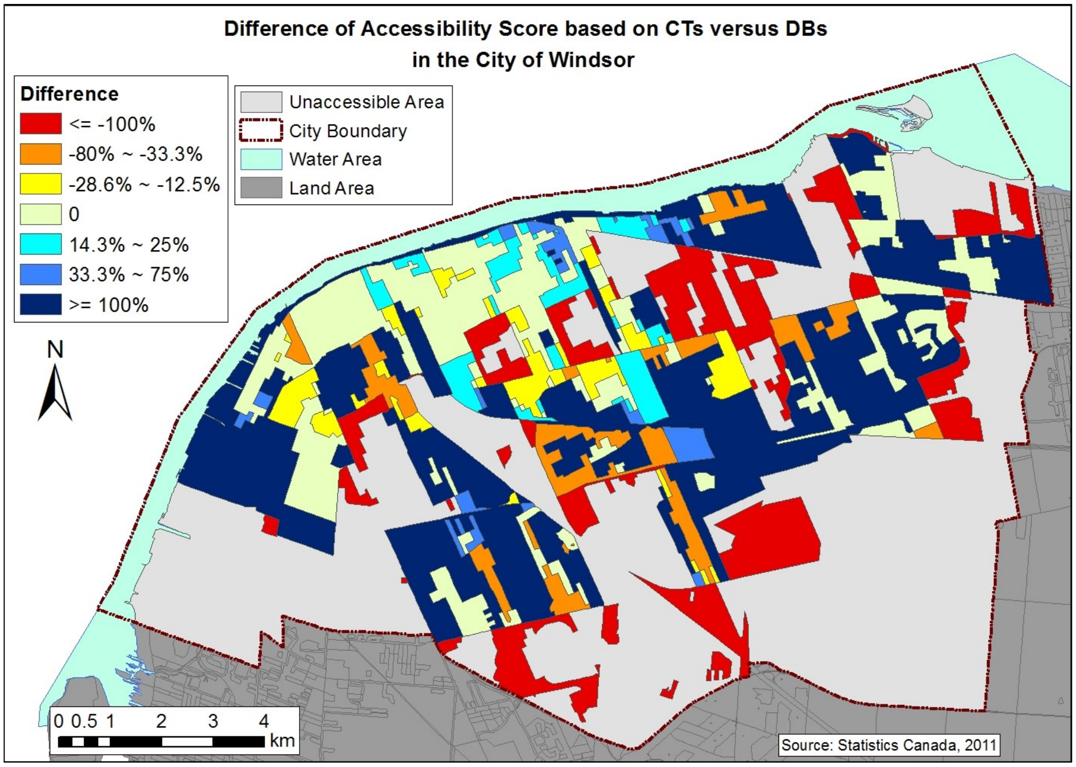


Figure 4.8 Differences of Accessibility Score of CT versus DB

When calculating accessibility based on DBs and 0.15 km grids, 54.6% of the areas in the City of Windsor had an accessibility score of 0 (or inaccessible to any urban node within 30 minutes by bus and walk), and these areas were excluded in the evaluation of differences of accessibility score. When changing zones from DBs to 0.15 km grids, 22.6% of the areas in the City of Windsor retained the accessibility score, and 0.7% of areas had a medium under-estimate of accessibility score, and 1.7% of areas had a medium over-estimate of accessibility score, compared to 3.1% of areas had a great under-estimate of accessibility score and 13.7% of areas had a great over-estimate of accessibility score (see Figure 4.9 and 4.10, Table 4.6).

When calculating accessibility based on DBs and 0.3 km grids, 52.7% of the areas in the City of Windsor had an accessibility score of 0 (or inaccessible to any urban node within 30 minutes by bus and walk), and these areas were excluded in the evaluation of differences of accessibility score. When changing zones from DBs to 0.3 km grids, 21% of the areas in the City of Windsor retained the accessibility score, and 0.9% of areas had a medium under-estimate of accessibility score, and 1.9% of areas had a medium over-estimate of accessibility score, compared to 3.9% of areas had a great under-estimate of accessibility score and 15.4% of areas had a great over-estimate of accessibility score (see Figure 4.9 and 4.11, Table 4.6).

When calculating accessibility based on DBs and 0.6 km grids, 50.6% of the areas in the City of Windsor had an accessibility score of 0 (or inaccessible to any urban node within 30 minutes by bus and walk), and these areas were excluded in the evaluation of differences of accessibility score. When changing zones from DBs to 0.6 km grids, 17.7% of the areas in the City of Windsor retained the accessibility score, and 1% of areas had a medium under-estimate of accessibility score, and 2.3% of areas had a medium over-estimate of accessibility score, compared to 7% of areas had a great under-estimate of accessibility score and 17.1% of areas had a great over-estimate of accessibility score (see Figure 4.9 and 4.12, Table 4.6).

Table 4.6 Differences of Accessibility Score of 0.15, 0.3 and 0.6 km Grid versus DB

Difference	0.15 km Grid versus DB		0.3 km Grid versus DB		0.6 km Grid versus DB	
	Size of area (km^2)	Percentage of area	Size of area (km^2)	Percentage of area	Size of area (km^2)	Percentage of area
<= -100%	4.6	3.1%	5.7	3.9%	10.3	7%
-80% ~ -33.3%	1	0.7%	1.3	0.9%	1.5	1%
-28.6% ~ -12.5%	1.9	1.3%	2.1	1.4%	2.6	1.8%
0	33.1	22.6%	30.8	21%	25.9	17.7%
14.3% ~ 25%	3.2	2.2%	3.7	2.5%	3.2	2.2%
33.3% ~ 75%	2.6	1.7%	2.8	1.9%	3.3	2.3%
>=100%	20	13.7%	22.5	15.4%	25	17.1%

Note: The percentage of area was calculated using the area that had changes of accessibility score to divide the area of the City of Windsor.

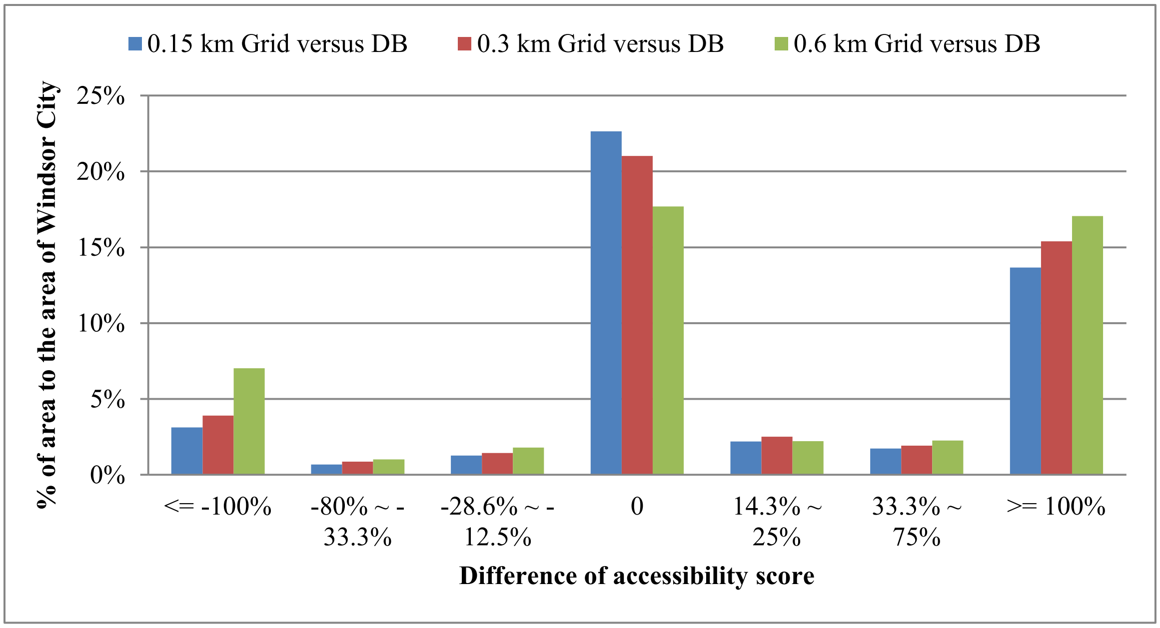


Figure 4.9 Differences of Accessibility Score of 0.15, 0.3 and 0.6 km Grid versus DB

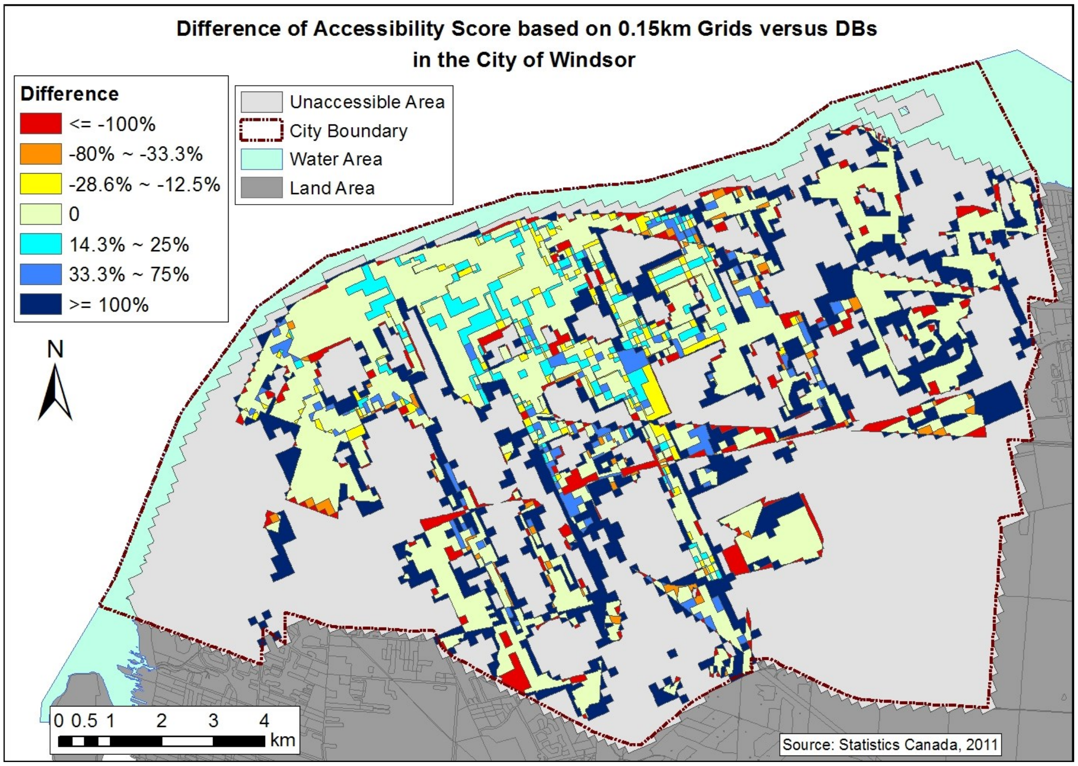


Figure 4.10 Differences of Accessibility Score of 0.15 km Grid versus DB

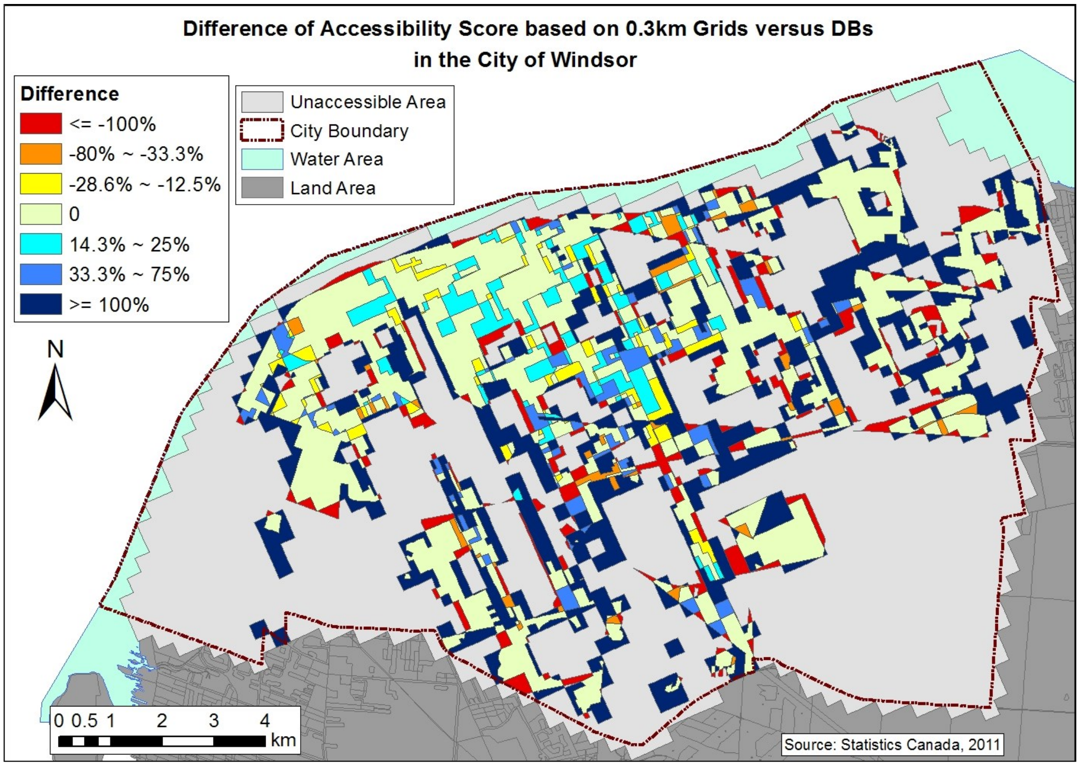


Figure 4.11 Differences of Accessibility Score of 0.3 km Grid versus DB

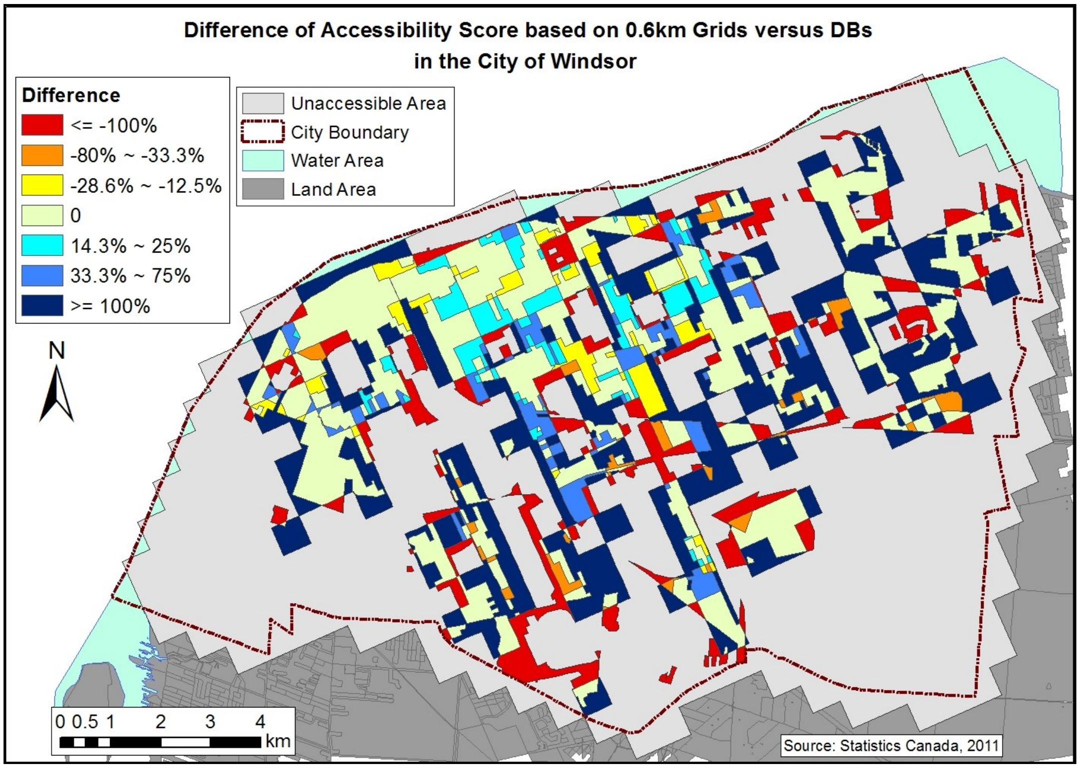


Figure 4.12 Differences of Accessibility Score of 0.6 km Grid versus DB

In summary, the findings of this section imply that the change of zone's scale or zoning scheme may significantly alter the assessment of accessibility, or in other words, the MAUP may have significant effect on assessment of accessibility when using cumulative opportunity measures.

Moreover, this research defined the potential under and over-estimate rate in accessibility measurements when only coarse data (e.g. CT and DA) are available compared to measurements based on DBs. This research addressed the scale and zoning effects based on a medium size Canadian city, the City of Windsor. The findings of this research can be used as referential information for many other cities which have similar geography and demographic characteristics as the City of Windsor. In this case (or in the City of Windsor), census geographic zones were not consistent in size: CT was on average 11.9 times of DA and DA was on average 6.7 times of DB. In terms of calculating accessibility using a cumulative opportunity measure, 7.8% of the areas in the city were greatly under-estimated and 12% of the areas were greatly over-estimated, if doing calculations based on DAs rather than DBs. Moreover, 10.1% of the areas in the

City of Windsor were greatly under-estimated and 24% of the areas were greatly over-estimated, if doing calculations based on CTs.

Grids were consistent in size: 0.6 km grid was 4 times of 0.3 km grid and 0.3 km grid was 4 times of 0.15 km grid. 0.15 km grid and the average size of DB are the same in scale. The difference of accessibility score based 0.15 km grid versus DBs was the smallest, compared to 0.3 km and 0.6 km grids. With the increase of zones from 0.15 km to 0.3 km and to 0.6 km, the difference of accessibility scores of grids compared to DBs increased continuously. This implies that the scale effect on assessment of accessibility increased continuously with the continuous increase of zone's size (e.g. 4 times each time) when zones are grids.

4.3. Consequences of the MAUP Effects on Accessibility Measurement

With the alteration of zone's scale or zoning scheme, assessment of accessibility may significantly alter when using cumulative opportunity measures. The variations of accessibility measurement can result in two severe consequences. The first consequence is the variation of accessibility score with the change of zone's scale or zoning scheme. The other consequence is the changes of policy implications that are based on accessibility measurements. The following section discusses the consequences of the MAUP effects on accessibility measurements in detail.

First of all, with the change of zone's scale or zoning scheme, there could be a great change of accessibility score of a zone. For instance, when changing zones from DBs to CTs, 10.1% of the areas in the City of Windsor had a great under-estimate of accessibility score and 24% of areas had a great over-estimate of accessibility score. Furthermore, the alterations of accessibility measurements may lead to different judgments on a city's overall accessibility level. 89,574 people had an accessibility score of 0, while 16,680 people had an accessibility score of 7~8, when calculating accessibility based on DBs. However, these numbers decreased to 74,091 and increased to 19,867, when calculating accessibility based on DAs.

As accessibility is a key factor in decision makings about land use development and transportation provision (Bertolini et al., 2005), variations on accessibility measurement can lead to different or even the opposite policy implications on residential development or transportation planning. The over or under-estimate of accessibility score of a region may provide wrong information about this region's actual accessibility level, and decision-makers may make wrong judgements on trade-off between transit service-provision and residential developments. Therefore, the use of different zones may result in total different decision makings, and the MAUP effects should be seriously considered when computing accessibility.

4.4. Approaches to Deal with the MAUP Effects on Accessibility Measurement

This section discusses three commonly used approaches for dealing with the MAUP on accessibility, with respect to cumulative opportunity measures. The first approach was designed to avoid the MAUP and the other two approaches aimed to minimize the MAUP if it cannot be avoided.

One way to avoid the MAUP is to do analysis based on disaggregate data (or original collected data), since the MAUP is caused by data aggregation (Zhang & Kukadia, 2005). In avoiding the MAUP effects on cumulative opportunity based measurement of accessibility, the data of individual's travels are recommended. More specifically, on the basis of individual's trips, accessibility is calculated in terms of the number of urban opportunities that an individual can reach within a given travel time limit. Obviously, this solution is not applicable when disaggregate data are not available. Moreover, assessing accessibility based on individual's travels requires extensive survey data which are difficult and expensive to collect. Also, doing analysis based on individual's trips may need considerable computational work, which is time consuming.

Another solution to the MAUP is to use low aggregated data (e.g. small zones like DBs or DAs) when disaggregate data are not available. This approach may minimize the MAUP effects but cannot avoid the MAUP. This approach was suggested according to previous finding that accessibility measurement was less sensitive to the variation of scale or zoning scheme when zones were small in size. Therefore, for the six types of zones that were used to calculate accessibility in the City of Windsor, DBs were firstly recommended, followed by DAs, while CTs were not recommended.

The third solution to the MAUP is to select zones according to research purposes. Following previous findings, small zones are recommended for accessibility measurements in order to minimize the MAUP effects. However, using small zones in calculations increases the amount of computational work. Therefore, it is essential to balance the tradeoff between using small zones and minimizing amount of computational work, when selecting zones to estimate accessibility. A good resolution is to select zones according to research purposes. For instance, if the research purpose is to identify new residential areas in a metropolitan region (e.g. Bertolini et al., 2005), it is not necessary to calculate accessibility based on small zones (e.g. DBs or DAs). Bertolini et al. (2005) made a proper selection that calculated accessibility based on neighborhoods in the Delta Metropolis, Netherlands. By contrast, if the purpose is to locate a new bus line in a local district (e.g. Yigitcanlar et al., 2007), small zones are recommended in accessibility measurements. Yigitcanlar et al. (2007) made a reasonable selection that calculated accessibility based on 50 m grids in the Gold Coast City Council local government area, Australia.

In summary, solutions to the MAUP effects on accessibility measurements were proposed according to a comprehensive consideration of three aspects: data availability, reasonable computational work and purposes of research. A good recommendation to test new methods is to do pilot projects, as accessibility related studies are usually complicated and may take considerable amount of work. In fact, this approach has been widely used in present accessibility studies, such as Bertolini et al. (2005) and Yigitcanlar et al. (2007).

5. Discussion and Conclusion

This chapter begins by discussing the policy implications for the City of Windsor according to the findings of this research, and then summarizes several limitations of this research and meanwhile outlines some directions for future research to expand the findings of this research, and the last section is the conclusions of this research.

5.1. Policy Implications

Policy implications are mainly relevant to improving public transportation provision as well as accessibility from residences to urban opportunities by public transit in the City of Windsor.

Windsor was an extremely auto-dependent city with just 3% of all commuters relying on public transit to commute, which almost ranked the bottom among Canadian cities, as reported in the 2011 national household survey (Statistic Canada, 2015). What is worse, the trend of car mode share for commuting trips increased from 90.6% (83.1% drivers and 7.6% passengers) in 2006 to 91.3% (85.9% drivers and 5.5% passengers) in 2011 (Statistic Canada, 2015). Given these data, it is a serious challenge for policymakers if the government wants to encourage more people to shift travel mode from car to public transit in Windsor.

For the purpose of designing sustainable development in Windsor, reducing road congestion and decreasing greenhouse gas emission, it is necessary to encourage more people to commute to work by public transit. The key effort to achieve these goals is to improve the competitiveness of public transportation to cars. Two specific ways were discussed. The first effort is to improve the public transit service quality, which specifically contains five aspects: availability, comfort and convenience, travel time, travel cost, safety and security (Kittelson & Associates, 2003; Litman, 2011). The second approach is to improve the accessibility between residences and urban opportunities by public transit.

Three conditions should be considered when trying to promote the competitiveness of public transit. First, do the best effort to use existing public transportation infrastructure, if possible. Second, try if adjusting the location of existing bus lines or stops could solve problems before making plans on developing new bus lines or new stops. Third, pay attention to increasing accessibility between residences and regional employment centers by transit, because considerable commuting trips begin from or end with the industrial parks.

Before moving on to finding ways to improve accessibility by public transit in the City of Windsor, the starting point was to understand the present situation. As found in the Results and Findings chapter, the downtown core was served well by public transit which had the highest accessibility score. Areas away from the downtown core were not properly served by public transit and a certain size of suburban areas was not accessible to public transit services. This happened because of two reasons. Firstly, there was a lack of public transit services in some suburban areas, such as residential areas in the south and east of the City of Windsor. Secondly, bus lines and stops were improperly located and people cannot reach a bus stop within an acceptable walking distance, for instance, 400 m (Hsiao et al., 1997; Murray, 2001; O'Sullivan & Morrall, 1996; Ryus et al., 2000).

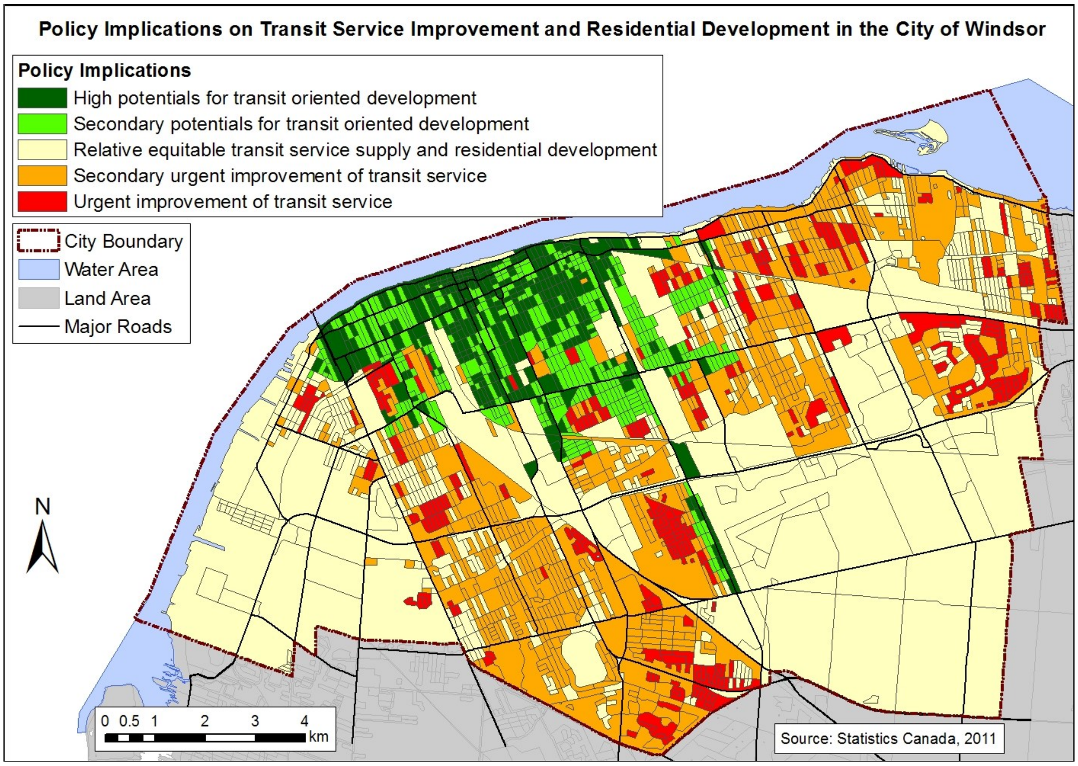
This study suggested two ways to enhance accessibility by public transit in the City of Windsor, based on accessibility scores of different zones and population distribution. The first way was to improve public transportation provision in the places where were lacking in public transit services. The second approach was to develop the residential areas which had high accessibility scores. Areas Accessibility score and population density of each DB was classified into 5 categories (see Table 5.1). The comparison of accessibility score and population density was made in a relative manner and not through comparing numbers directly. Accessibility score of 0 was taken as low accessibility score and accessibility score of 5 or more was taken as relatively high accessibility score. Population density of less than 500 persons/km^2 was taken as low population density, 500 to 3,000 persons/km^2 was taken as medium population density and 3,001 persons/km^2 or more was taken as high population density. Based on relative high or low accessibility score and population density, areas had potentials for transit oriented development and areas needed transit service improvement were maped.

The areas with high accessibility score but low population density were considered as having high potentials for transit oriented development. The areas with high accessibility score but medium population density were considered as having secondary high potentials for transit oriented development. The areas with low accessibility score but high population density were considered as needing urgent improvement of transit service. The areas with low accessibility score but medium population density were considered as needing secondary urgent improvement of transit service. The rest areas (with medium accessibility score and low to high population density, high accessibility score and population density, as well as low accessibility score and population density) were considered as having relative equitable transit service supply and residential development.

Table 5.1 Policy implications based on relative accessibility score and population density

Categories	Accessibility Score	Population Density (persons/km^2)	Policy implications
High accessibility score and low population density	5 to 8	Less than 500	High potentials for transit oriented development
High accessibility score and medium population density	5 to 8	500 to 3,000	Secondary high potentials for transit oriented development
High accessibility score and high population density	5 to 8	3,001 or more	Relative equitable transit service supply and residential development
Medium accessibility score and medium population density	1 to 4	Less than 500; 500 to 3,000; 3,001 or more	Relative equitable transit service supply and residential development
Low accessibility score and low population density	0	Less than 500	Relative equitable transit service supply and residential development
Low accessibility score and medium population density	0	500 to 3,000	Secondary urgent improvement of transit service
Low accessibility score and high population density	0	3,001 or more	Urgent improvement of transit service

According to the figure of Policy Implcations on Transit Service Improvement and Residentail Development, areas that had potentials for transit oriented developed were mostly located in the downtown core and adjoining the downtown core (see Figure 5.1). Areas that needed improvement of transit service were located scattered in the city (see Figure 5.1). Large areas in the south and northeast part in the City of Windsor were lack of transit service , which indicates bus service in these areas was behind the development and needed to be improved.



Source: Statistics Canada, 2011

Figure 5.1 Policy Implications on Transit Service Provision and Residential Development in the City of Windsor

As a city that has high auto manufacturing industry concentrations, Windsor has large areas of industrial land-uses, which are scattered in the city (Maoh & Tang 2012). The regional employment centers were highly automobile oriented, as reported in the City of Windsor Urban Structure Plan, 2011. This study found that the regional employment centers were poorly served by public transportation. Specifically, the Deziel/Rhodes Regional Employment Center was the only one that had bus lines running through and the other three regional employment centers only had bus lines running along the edges of industrial zones (see Figure 3.2). Under this circumstance, people had to walk a long distance (usually more than 400 m) to reach bus services from their workplace. This finding implied the reason why only 3% of all commuters in Windsor relying on public transit to commute.

This study suggested three ways to enhance accessibility by public transit to regional employment centers (industrial parks that have high concentrations of jobs) in the City of Windsor in terms of improving transit service quality (the first approach) and accessibility to transit services (the last two approaches). The first way is to increase bus frequency during the morning peak and afternoon peak hours. The second way is to adjust the current bus lines and stops according to the design of the industrial parks and ensure that people could reach a bus stop within an acceptable walking distance (e.g. 400 m). Third, transportation agency could cooperate with the industries and provide shuttle bus services in the industrial parks, which could carry people from their workplaces to the bus stops. In summary, the improvement of accessibility by public transit to regional employment centers was recommended due to five reasons: firstly, increasing the usage of public transit; secondly, decreasing road congestion; thirdly, decreasing greenhouse air emission; fourthly, saving the users' travel cost; and lastly, saving the management costs of the parking lots in the industrial parks.

5.2. Limitations

Limitations of this research are basically relevant to the methodological challenges when assessing accessibility or studying the MAUP effects. Two limitations are discussed.

One limitation concerns the travel time or distance limit when assessing accessibility based on cumulative opportunity measures. This research adopted 30 minutes as the travel time limit based on the national household survey data, 2011, which reported that 80% of commuters in the Windsor Metropolitan Area spent less than 30 minutes travel to work. The 30-minute was described as a usual commuting time, while in reality people's commuting time is affected by considerable issues, such as individual's features, attractiveness of urban opportunities and travel purposes. Therefore, a better travel time to assess accessibility in the City of Windsor could be based on the average travel time to a specific urban opportunity type. If possible, the travel time budget can be derived from individual's preferences.

Another limitation is that this research just considered trips by walking and bus mode and limited a 5-minute walking time from trip origin to boarding bus stop and from egress bus stop to trip destination. Although the 5-minute was selected based on proper reasons of people's preferred walking distance from/to a bus stop (Hsiao et al., 1997; Murray, 2001; O'Sullivan & Morrall, 1996; Ryus et al., 2000), it was found that this 5 minute walking time limited accessibility levels in some walkable areas, such as university campus and squares in downtown core. It can be seen from Figure 4.1 that some areas adjoining the Urban Node 10 (Hotel-Dieu Grace Hospital) did not have the highest accessibility score, although these areas were high accessibility with many bus lines running through. The third limitation is that the urban nodes may not represent the urban opportunities very properly, given the urban nodes are locations of concentrated activities (the City of Windsor Urban Structure Plan, 2011) but there are many activity sites scattered across the City of Windsor. Other possible solutions to represent urban opportunities could be business and industrial land parcels (Huang & Wei, 2002) and land use destinations (represented by points) (Yigitcanlar et al., 2007). However, when the land use destinations are in detail, some destination points may be very close to each other, and therefore, accessibility scores in some areas may be much higher than other areas because of proximity of land use destinations rather than the number. Thus, the selection of urban opportunities is essential for assessment of accessibility and should be carefully selected.

5.3. Future Research

This research studied the MAUP effects on assessment of accessibility with respect to cumulative opportunity measures based on a small city. Findings from this research can be expanded by additional research. This subsection suggests three possible directions for future research.

The first recommendation for future research is to use a big metropolitan area (e.g. the Montreal Metropolitan Area) as study area to explore the MAUP effects on accessibility with respect to cumulative opportunity measures. The purpose of this recommendation is to explore how the MAUP effects on accessibility measurement vary when different features of zones, multi-mode of public transportation and a large quantity of urban nodes are involved in analysis, since this study interpreted how the MAUP affected accessibility measurement in a small city where there was single type of public transportation, a few quantity of major urban nodes and three hierarchies of census geographic zones. It was hypothesized that the MAUP effects on accessibility measurement in a big metropolitan region might not follow the findings of this study.

This study assessed accessibility in terms of the number of urban nodes to be reached within a given travel time, which did not consider the type and attractiveness of urban nodes. It is wondering how the assessments of accessibility vary with the change of zone's scale or zoning scheme, if the type and attractiveness of urban nodes are considered.

The literature review summarized five types of commonly used accessibility measurements. As assessment of accessibility based on different approaches is incomparable, the examination of the MAUP effects on accessibility should be based on a specific assessing approach. Kwan & Weber (2008) have explored the MAUP effects on assessment of accessibility with respect to space-time measures. This research examined the MAUP effects on assessment of accessibility when using cumulative opportunity measures. Therefore, future research can focus on studying the MAUP effects on assessment of accessibility when using travel impediment measures, gravity-based measures or utility-based measures.

5.4. Conclusion

This thesis studies the MAUP effects on assessment of accessibility via public transit when using cumulative opportunity measures. Specifically, this research addresses four research questions: First, what is accessibility via public transit in the City of Windsor? Second, how does assessment of accessibility vary with the change of zone's scale or zoning scheme - and does assessment of accessibility change significantly or not, and does assessment of accessibility change systematically or randomly? Third, what are consequences of the MAUP effects on assessment of accessibility? And finally, how to deal with the MAUP effects on assessment of accessibility when using cumulative opportunity measures - and is it possible to avoid the MAUP - and if not, how to decrease it?

In response to the first research question, accessibility level is the City of Windsor is low that 42.5% of the entire population has no accessibility to any urban node within 30 minutes by bus and walking. Areas adjoining the downtown core had the highest accessibility level but the south and northeast part in the City of Windsor had the lowest accessibility level.

In response to the second research question, the MAUP was found to have significant effects on assessment of accessibility when using cumulative opportunity measures. Accessibility score of residences (represented by zones) may greatly alter with the change of zones' scale or zoning scheme.

In response to the third research question, the consequences of the MAUP effects on accessibility measurements were about the variation of accessibility scores and changes of policy implications that are based on accessibility measurements. When using zones at different scales or zoning schemes to calculate accessibility, accessibility score of residences may greatly change, which may lead to different or even the opposite decision makings on residential development or transportation service provision.

In response to the fourth research question, three ways were recommended to deal with the MAUP when assessing accessibility. The first way is to do analysis based on disaggregate data, or more specifically, calculating accessibility in terms of the number of urban opportunities that an individual can reach within a given travel time limit. This approach could avoid the MAUP but it is limited by the data availability of individual's trips. Another solution is to minimize the MAUP effects if it cannot be avoided, which is calculating accessibility using low aggregated data (e.g. small zones like DBs).The third solution is to select zones according to research purposes. For example, Bertolini et al. (2005) calculated accessibility based on neighborhoods in the Delta Metropolis, Netherlands, with a purpose of choosing new residential areas. Yigitcanlar et al. (2007) calculated accessibility based on 50 m grids in the Gold Coast City Council local government area, Australia, with a purpose of locate a new bus line in a local district.

Overall, this research contributes to the studies of the MAUP and accessibility via public transit. Methods and findings of this research can serve as important references for future research, as the MAUP effects on accessibility remains a topic to be continued.

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Appendix A

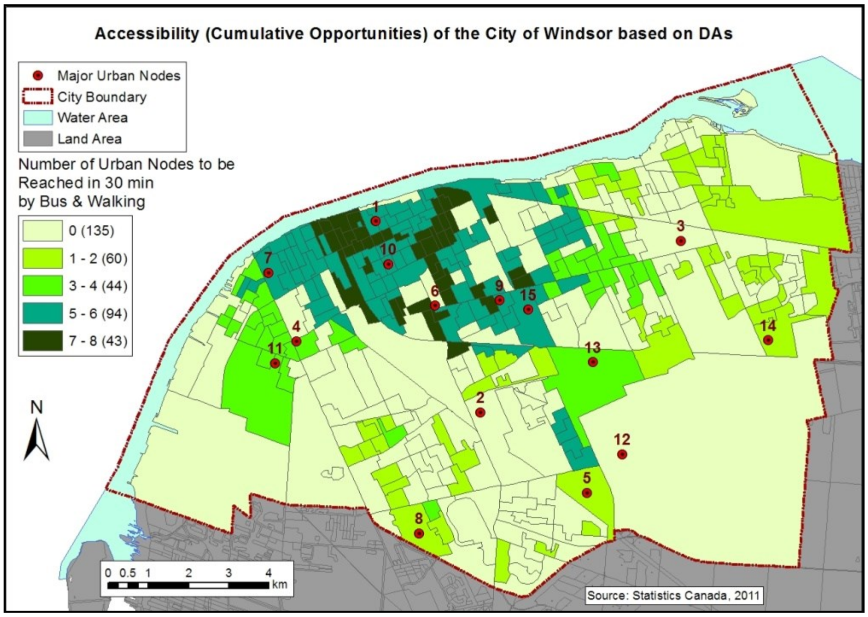
Table of bus summary

Route Name	Route Number	Average Frequency Northbound /West	Average Frequency Southbound /East	Number of Stops
Transway 1A	1A	23	23	52
Transway 1C	1C	13	13	154
Crosstown 2	2	13	13	171
Central 3	3	22	22	149
3 West	3W	60	60	56
Ottawa 4	4	19	19	132
Dominion 5	5	25	25	74
Dougall 6	6	40	40	82
South Windsor 7	7	50	50	74
Walkerville 8	8	32	32	108
Lauzon 10	10	35	35	53
Parent 14	14	38	38	62

Note: average frequency refers to bus frequency during the weekday morning peak periods: 6:30 am to 9:30 am.

Appendix B

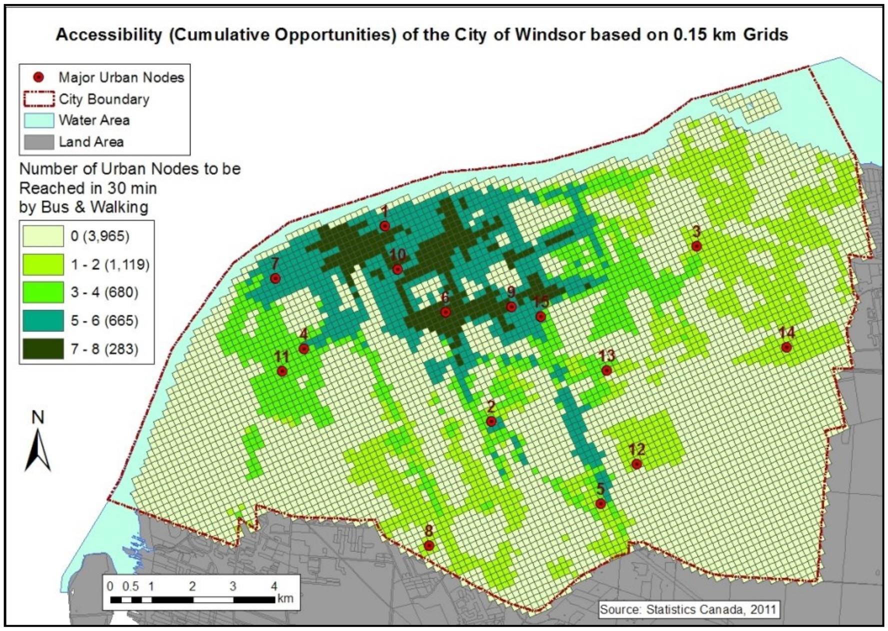
Accessibility in the City of Windsor based on DAs, 0.15 km, 0.3km and 0.6km Grids



Accessibility (Cumulative Opportunities) of the City of Windsor based on DAs

Source: Statistics Canada, 2011

Figure 1. Accessibility in the City of Windsor based on DAs



Accessibility (Cumulative Opportunities) of the City of Windsor based on 0.15 km Grids

Source: Statistics Canada, 2011

Figure 2. Accessibility in the City of Windsor based on 0.15 km Grids

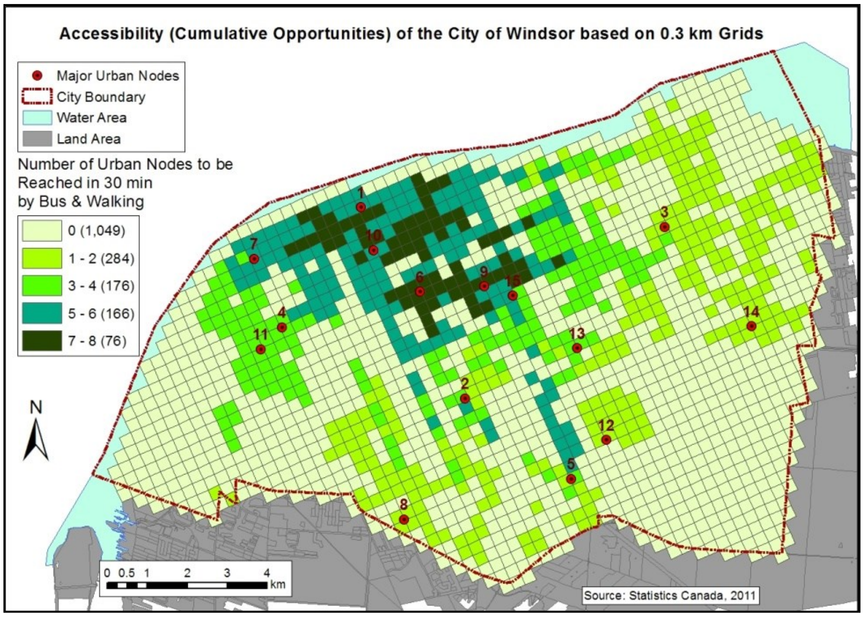


Figure 3. Accessibility in the City of Windsor based on 0.3 km Grids

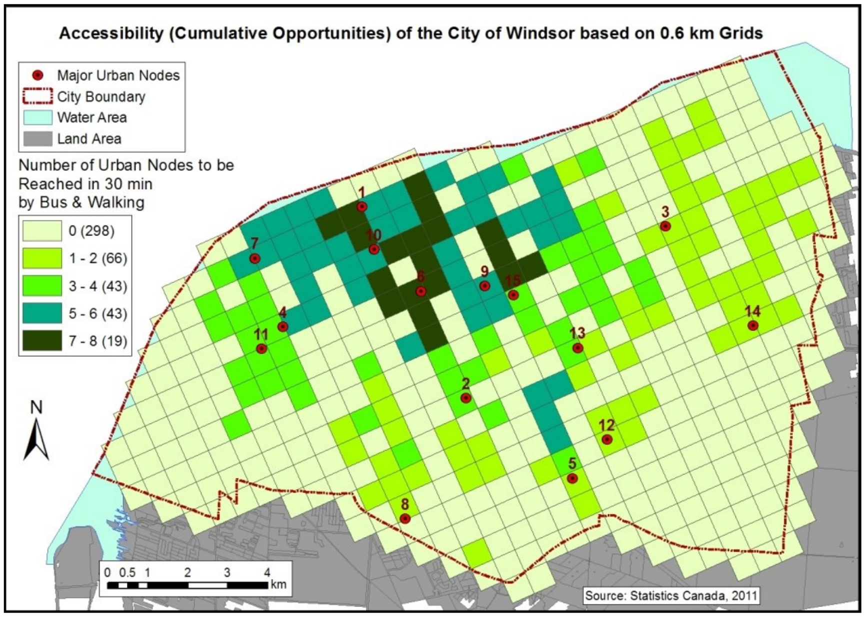


Figure 4. Accessibility in the City of Windsor based on 0.6 km Grids

Appendix C

Differences of accessibility score based on zones at different scales or zoning schemes.

FID is the unique identifier of each area in GIS.

DA versus DB

FID	Difference in number	Difference in percentage	Size of area
0	-8	-100%	0.018
1	-7	-100%	0.256
2	-6	-100%	0.745
3	-5	-100%	0.678
4	-4	-100%	1.051
5	-4	-80%	0.210
6	-4	-57%	0.027
7	-3	-100%	1.212
8	-3	-75%	0.091
9	-3	-50%	0.029
10	-3	-37.50%	0.087
11	-2	-100.00%	1.942
12	-2	-67%	0.535
13	-2	-40%	0.023
14	-2	-33%	0.260
15	-2	-28.57%	0.168
16	-2	-25.00%	0.076
17	-1	-100.00%	5.563
18	-1	-50.00%	0.101
19	-1	-33%	0.321
20	-1	-25%	0.150
21	-1	-20%	0.244
22	-1	-16.67%	0.186
23	-1	-14.29%	0.793
24	-1	-12.50%	0.041
25	0	0%	108.694
26	1	14.29%	0.082
27	1	16.67%	1.243
28	1	20%	0.655
29	1	25%	0.974
30	1	33.33%	0.646
31	1	50.00%	0.651
32	1	100%	7.216
33	2	33%	0.054

34	2	40%	0.382
35	2	50.00%	0.454
36	2	67%	0.191
37	2	100%	0.071
38	2	200%	2.857
39	3	100%	0.024
40	3	150%	0.050
41	3	300%	4.133
42	4	400%	0.678
43	5	500%	0.723
44	6	600%	1.195
45	7	700%	0.605

CT versus DB

FID	Difference in number	Difference in percentage	Size of area
0	-8	-100%	0.017
1	-7	-100%	0.522
2	-6	-100%	1.386
3	-5	-100%	0.604
4	-5	-71%	0.006
5	-5	-63%	0.019
6	-4	-100%	1.785
7	-4	-67%	0.018
8	-4	-57.10%	0.078
9	-3	-100%	0.938
10	-3	-60%	0.414
11	-3	-50%	0.640
12	-3	-37.50%	0.076
13	-2	-100.00%	2.736
14	-2	-66.70%	0.234
15	-2	-50.00%	0.428
16	-2	-40%	0.457
17	-2	-33%	0.688
18	-2	-29%	0.186
19	-2	-25.00%	0.093
20	-1	-100.00%	6.832
21	-1	-50.00%	1.014
22	-1	-33%	1.369
23	-1	-25.00%	1.774

24	-1	-20.00%	0.136
25	-1	-17%	0.378
26	-1	-14%	1.354
27	-1	-12.50%	0.034
28	0	0.00%	81.667
29	1	17%	1.769
30	1	20%	0.902
31	1	25%	0.760
32	1	33%	0.142
33	1	50.00%	0.902
34	1	100%	12.151
35	2	40%	0.473
36	2	50%	0.272
37	2	67%	0.089
38	2	200.00%	5.748
39	3	100%	0.133
40	3	300%	9.388
41	4	200%	0.050
42	4	400%	4.007
43	5	500%	0.913
44	6	600%	2.218
45	7	700%	0.584

0.15 km Grids versus DB

FID	Difference in number	Difference in percentage	Size of area
0	-7	-100%	0.053
1	-6	-100%	0.417
2	-5	-100%	0.371
3	-4	-100%	0.383
4	-4	-80%	0.008
5	-4	-67%	0.005
6	-4	-57%	0.003
7	-4	-50%	0.001
8	-3	-100%	0.578
9	-3	-75.00%	0.000
10	-3	-60.00%	0.017
11	-3	-50%	0.017
12	-3	-42.86%	0.002
13	-3	-38%	0.019

14	-2	-100%	0.649
15	-2	-67%	0.087
16	-2	-50%	0.018
17	-2	-40.00%	0.012
18	-2	-33%	0.099
19	-2	-28.57%	0.080
20	-2	-25.00%	0.006
21	-1	-100.00%	2.136
22	-1	-50.00%	0.349
23	-1	-33%	0.361
24	-1	-25%	0.506
25	-1	-20%	0.536
26	-1	-16.67%	0.285
27	-1	-14.29%	0.434
28	-1	-12.50%	0.032
29	0	0%	117.791
30	1	14.29%	0.347
31	1	16.67%	1.725
32	1	20%	0.632
33	1	25%	0.510
34	1	33.33%	0.619
35	1	50.00%	0.898
36	1	100%	9.119
37	2	33%	0.152
38	2	40%	0.209
39	2	50%	0.465
40	2	66.67%	0.124
41	2	100%	0.365
42	2	200%	2.383
43	3	60%	0.039
44	3	75%	0.048
45	3	100%	0.030
46	3	150.00%	0.182
47	3	300%	2.586
48	4	100%	0.015
49	4	133%	0.009
50	4	400%	2.226
51	5	500%	1.107
52	6	600%	1.587
53	7	700%	0.374
54	8	800%	0.033

0.3 km Grids versus DB

FID	Difference in number	Difference in percentage	Size of area
0	-7	-100%	0.089
1	-6	-100%	0.744
2	-5	-100%	0.506
3	-4	-100%	0.453
4	-3	-100%	0.869
5	-3	-60%	0.009
6	-3	-50%	0.044
7	-3	-42.86%	0.011
8	-2	-100%	0.791
9	-2	-67%	0.055
10	-2	-50%	0.055
11	-2	-40%	0.021
12	-2	-33.33%	0.244
13	-2	-29%	0.074
14	-2	-25.00%	0.022
15	-1	-100.00%	2.268
16	-1	-50.00%	0.415
17	-1	-33%	0.411
18	-1	-25%	0.588
19	-1	-20%	0.414
20	-1	-16.67%	0.276
21	-1	-14.29%	0.608
22	-1	-12.50%	0.134
23	0	0%	119.452
24	1	14.29%	0.274
25	1	16.67%	1.915
26	1	20%	0.779
27	1	25%	0.716
28	1	33.33%	0.598
29	1	50.00%	0.937
30	1	100%	9.450
31	2	33%	0.147
32	2	40%	0.556
33	2	50%	0.315
34	2	66.67%	0.102
35	2	100%	0.303
36	2	200%	3.067
37	3	60%	0.055

38	3	75%	0.107
39	3	150%	0.202
40	3	300%	3.118
41	4	100%	0.000
42	4	200%	0.089
43	4	400%	2.392
44	5	500%	1.110
45	6	600%	2.302
46	7	700%	0.432
47	8	800%	0.072

0.6 km Grids versus DB

FID	Difference in number	Difference in percentage	Size of area
0	-8	-100.0%	0.042
1	-7	-100.0%	0.204
2	-6	-100.0%	1.212
3	-5	-100.0%	0.829
4	-4	-100.0%	1.020
5	-3	-100.0%	0.929
6	-3	-60.0%	0.121
7	-3	-37.5%	0.077
8	-2	-100.0%	1.281
9	-2	-66.7%	0.032
10	-2	-40.0%	0.024
11	-2	-33.3%	0.120
12	-2	-28.6%	0.249
13	-2	-25.0%	0.017
14	-1	-100.0%	4.764
15	-1	-50.0%	0.741
16	-1	-33.3%	0.381
17	-1	-25.0%	0.730
18	-1	-20.0%	0.357
19	-1	-16.7%	0.336
20	-1	-14.3%	0.898
21	-1	-12.5%	0.052
22	0	0.0%	122.891
23	1	14.3%	0.120
24	1	16.7%	1.955
25	1	20.0%	0.381

26	1	25.0%	0.791
27	1	33.3%	0.519
28	1	50.0%	1.108
29	1	100.0%	9.597
30	2	33.3%	0.314
31	2	40.0%	0.664
32	2	50.0%	0.344
33	2	66.7%	0.165
34	2	100.0%	0.112
35	2	200.0%	3.618
36	3	60.0%	0.033
37	3	75.0%	0.180
38	3	100.0%	0.064
39	3	150.0%	0.026
40	3	300.0%	4.083
41	4	133.3%	0.049
42	4	400.0%	2.192
43	5	500.0%	1.559
44	6	600.0%	2.891
45	7	700.0%	0.567
46	8	800.0%	0.202