How are inner-city population densities affected by freeways?

A study of eight Canadian cities

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A Thesis
in
The Department
of
Geography, Planning and Environment

Presented in Partial Fulfillment of the Requirements
for the Degree of
Master of Science (Geography, Urban and Environmental Studies) at
Concordia University
Montreal, Quebec, Canada

September 2013

CONCORDIA UNIVERSITY

School of Graduate Studies

This is to certify that the thesis prepared

By: Rushdia Mehreen

Entitled: How are inner-city population densities affected by freeways?
A study of eight Canadian cities

and submitted in partial fulfillment of the requirements for the degree of

Master of Science (Geography, Urban and Environmental Studies)

complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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ABSTRACT

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Freeways (limited-access high speed roadways) have long been considered as contributing to low density housing and dispersed urban development (sprawl). Sprawl is known to be unsustainable for the environment, biodiversity and energy use. Metropolitan areas in Canada differ in the level of sprawl, in growth and decline in central city population as well as in the level of freeway provision. This study analyzes census data and the level of freeway provision to explore to what degree the change in inner-city population density between 1956 and 2006 in Canada can be explained by freeways. This research examines changes in inner-city densities in over 200 census tracts in the eight inner-cities of Toronto, Montreal, Vancouver, Quebec City, Ottawa, Edmonton, Winnipeg and Victoria. The results show that over a fifty year period, inner-city population densities declined in 74% of the census tracts. The census tracts where densities declined strongly were overwhelmingly located within a four-kilometre distance from freeways, a threshold identified by the present study. Beyond the four-kilometre threshold, a pattern is observed where census tracts at a moderate distance from freeways gained in population density and those further away from freeways lost. Additionally, aggregate inner-city population densities declined in four cities, barely increased in two, however rose in Vancouver and Victoria, where urban freeways were close to non-existent or not as prevalent. These findings contribute to our understanding of why freeways should not be built in areas where higher densities are desired. The study also contributes to the existing debate on the causes of decline in central city population.

ACKNOWLEDGEMENTS

I would like to start by thanking my family, in particular my mother who has been a constant source of inspiration for me throughout my life. If not for her encouragement and faith in me, I would not have been here today. My husband, Eric, has been a pillar of support for me in good and not-so-good times throughout the (long) time of my masters studies and thesis writing process in particular. Thank you, mon amour, but I know that simply saying thanks won't be enough!

I would like to acknowledge the funding provided by Social Sciences and Humanities Research Council (SSHRC), *Fonds Québécois de la Recherche sur la Société et la Culture* (FQRSC), and by the Concordia University Arts and Science Graduate Fellowship without which this research would not have come to fruition.

I wish to thank my supervisors Dr. Craig Townsend and Dr. Jochen Jaeger for their support, guidance, and belief in me throughout my master's. My gratitude goes out to Dr. Ray Tomalty from McGill University who provided valuable input when this project was in the making. I would also like to thank Dr. Dany Fougères of *l'Institut National de la Recherche Scientifique* (INRS) for sharing extensive historical data on Quebec. Enormous thanks to Rosa Orlandini at Concordia University library and to the staff at McGill University library's government information department for the assistance with collecting historical census data without which this particular project may not have seen the light of the day.

Heartfelt thanks to my "brothers" and "sisters" in research (mostly those under the same supervisors as me). David, thanks for all your help with GIS; Jeff, Tristan, Paul, Magdalena, Rob, Yuseph, and all those who I haven't named here: you've been a great source of motivation for me, particularly on those grey days in the lab and in the "cave". Sincere thanks to the professors in the department and to my friend David, who helped me navigate through the academia as I passed through some tough times in the process of completion of research and the thesis. I would also like to thank GPE department's administrative staff, Annie and Mae Anne for their support throughout my time at Concordia. Thanks for your understanding of my health situation and for accommodating me.

The historic Quebec student movement helped me get a better perspective not only towards my thesis completion but also with respect to my outlook on life. I thank all my friends and the new comrades and friendships that were made during the historic seven-month long strike. Your presence also helped me during the transition back to thesis after the long hiatus. In particular, I would like to thank Ryan T., Stéphanie, Guy-Robert, Roy, Nadia and Stefan for their friendship, encouragement and understanding throughout the challenging times.

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1 INTRODUCTION

Spatial distribution of population, an important aspect of cities, has been changing in different directions in Canadian cities over the past several decades. Population density, defined as the number of people living in a unit area of land, has fluctuated over the last 35 years; it has declined in most established cities, such as Toronto, Montreal and Ottawa, and has increased in Vancouver (Filion et al., 2010; Taylor & Burchfield, 2010). The subject of declining densities is of particular interest because low density -- dispersed urban development (urban sprawl) is argued to be unsustainable because of its vast consumption of land with adverse effects on the environment and biological diversity, and due to its excessive energy requirement, and high automobile and resource use (Newman et al, 2009; Greene, 2004; Newman & Kenworthy, 1989a). High density (Figure 1, Compact scenario), on the contrary, is beneficial because human activity is close together, leaving a larger proportion of land available for biodiversity and environmental well-being. While lowering energy use and reducing the extent of infrastructure requirement, such as roads and sewage, high density promotes transit use and an active lifestyle -- more walking and cycling due to general proximity of resources in a high density setting (Pushkarev & Zupan, 1977; Burchell et al., 2005).

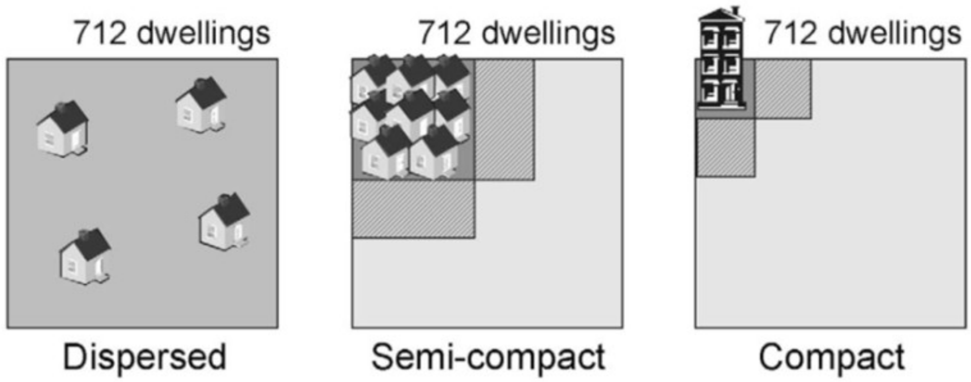

Figure 1. Density levels. Source: Gagné and Fahrig, 2010.

In Canada, variations are found between metropolitan areas[1] in the degree of sprawl, and the growth or reduction of central city populations. In addition to the uneven levels of population growth or decline between central cities, the patterns of change within the central cities differ between central (commercial) core and surrounding residential areas (Bunting et al. 2002). Overall, densities in Canadian metropolitan areas have been decreasing during the last several decades (Bunting et al., 2002; Edmonston, 1983; Latham & Yeates, 1970), and substantial losses are observed in central city population densities (Filion et al., 2010; Taylor & Burchfield, 2010).

Declines in population density are broadly attributed to suburbanisation, a process involving dispersed urban development featuring mono-functional land use, mostly initiated in the 1950's and 1960's both in the US and Canada (Gillham, 2002; Bunting et al., 2002; Gutfreund, 2004; Baum-Snow, 2007; Filion et al., 2010). The introduction of high speed roadways facilitating the use of automobiles further helped suburbanization. In Montreal, for instance, without the automobile post-second world war suburbanization

[1] A (census) metropolitan area (CMA), as per Statistics Canada, is defined as one or more adjacent municipalities with a population center (also known as core, or central city) in the center. For a group of municipalities to be a CMA, the population of the group as a whole must be at least 100,000 and that of the core must be at least 50,000. The municipalities around the core must highly be integrated with the core as can be measured by the commuting flow, which is arrived at by the Place of Work census of the previous year (Statistics Canada, 2010).

would not have been possible (Bussière, 1989). An interdependence can thus be derived between suburbanization, automobile and the roadways, "[a]s the states and the federal government invested in streets, roads, highways, and bridges, the citizenry simultaneously flocked to the open land on the urban periphery" (Gutfreund, 2004, p. 1).

Land-use theory predicts that with improvements in transport technology (such as freeways[2]) that reduce travel times, the demand for suburban land increases compared to that in central city (Alonso, 1964). The theory assumes monocentricity whereby all employment is found in the central city, and that the land rent at a given location is a function of its distance to the central city as it takes into consideration the transportation time. "One basic implication of this model is that a higher commuting speed implies lower population density" (Baum Snow, 2007, p. 785). Thus, freeways connecting the urban core to the suburbs have been considered to contribute to sprawl (Gillham, 2002; Gutfreund, 2004; Solomon, 2007). In Montreal, for example, the decline in central city population and the growth of suburbs were largely attributed to the construction of freeways (Charbonneau et al., 1994). While the introduction of freeways in and near the central cities of Toronto and Montreal in the mid-1950s was considered to have propelled the suburbs at the cost of deterioration of central city/decline of central city population (Sewell, 2009; Solomon, 2007; Charbonneau et al., 1994), the increasing population density in Vancouver over the past 35 years (Filion et al., 2010; Bunting et al., 2002) and the lack of inner-city[3] freeway therein is conspicuous (Harcourt et al., 2007; Punter, 2003; Tomalty, 2002). The relationship between freeways and the spatial distribution of

[2] The term freeway is used in this thesis to denote 'limited-access high speed roadways'. Elsewhere the same type of roadways maybe referred to as highways and such.

[3] The term inner-city refers to the inner core of the central city, which is larger than the central business district. The term in general is used to denote an area that is smaller than and within the central city.

population is, then, worth examining. Although, some theorists argue that the population decline is brought about by people's personal preference, such as the desire for larger space and suburban living with its perceived benefits (Bunting et al. 2002, 2000; Gillham, 2002).

The construction of freeways in Canada was not widespread at its onset. The first "superhighway" (provincial road) of Canada was built in Toronto in the 1930's, which was later extended and became a freeway in the 1950s (during the post-second world war boom); at around the same time (in 1950s) the urban freeways were constructed in Montreal. By 1968, freeways in the central city were only found in Toronto, Montreal and Ottawa (Lea et al., 1968). In the United States, however, the 1947 federal highway plan proposed almost 40,000 miles (64,000 kilometres) of inter-state freeways with the intention of connecting the population centers, i.e., central cities (Baum-Snow, 2007).

A study modelling the relationship between inter-state freeways, essentially rays of freeways (sections of freeways linking the central business district of the central city to a suburb) and decline in central city population in the United States concludes that the inter-state freeways contributed to reducing aggregate central city population. (Baum-Snow, 2007). The central city population declined by 17 percent between 1950 and 1990 where a third of the decline was attributed to the freeways. Also, each new ray added to the freeway system was found to reduce central city population by 9%. Using an econometric model, Baum-Snow (2007) made a causal link between the inter-state freeways and suburbanisation. Such an extensive quantitative study testing the impact of freeways on population in central cities has not been conducted in Canada, where variations are found between metropolitan areas in the level of freeway provision.

1.1 Research Objectives

The present study seeks to assess the extent to which the change in inner-city population density in Canadian cities between the pre-urban freeway period (1950s) and the present can be explained by proximity to freeways.

The main objective of the study is to find the relationship between the change in population density and the distance to closest freeways. The study also looks at how the change in population density relates to the initial density from the pre-urban freeway period. The study further examines how the cities differ with respect to the aforementioned parameters and explores the difference between the core, where mostly commercial activity is found, and the residential areas within the inner-city.

The primary hypothesis was that loss in population density over the period in which freeways were built would be negatively correlated with distance to freeways. In other words, the closer to the freeway, the higher the loss in population in the inner-city. In addition, it was hypothesized that higher losses in density would be expected in areas that had higher initial density, consequently higher losses were expected in Montreal and Quebec City and higher gains in Vancouver.

The research contributes to our understanding of the relationship between freeways and population density in the inner-cities and further informs the debate surrounding the reasons for decline in central city populations.

The thesis proceeds as follows: Chapter 2 provides a comprehensive literature review, Chapter 3 details methods used for the research, Chapter 4 includes results, and Chapter 5 presents the discussion, and Chapter 6 concludes the thesis.

2 LITERATURE REVIEW

The literature review covers four main topics (Figure 2): 1. causes and consequences of low density development (sprawl), the source and propagation of sprawl, the problems associated with it, and the process of de-concentration; 2. benefits of high density, briefly looking at the other end of the spectrum; 3. population density, the causes of the changes in spatial distribution of population; 4. impacts of freeways (transport infrastructure) on population density in the inner-city and in the outer areas, and includes environmental and social impacts of freeways.

The two last sections of the literature review provide an overview of the structure of Canadian cities and a brief historical overview of urban freeways in Canada.

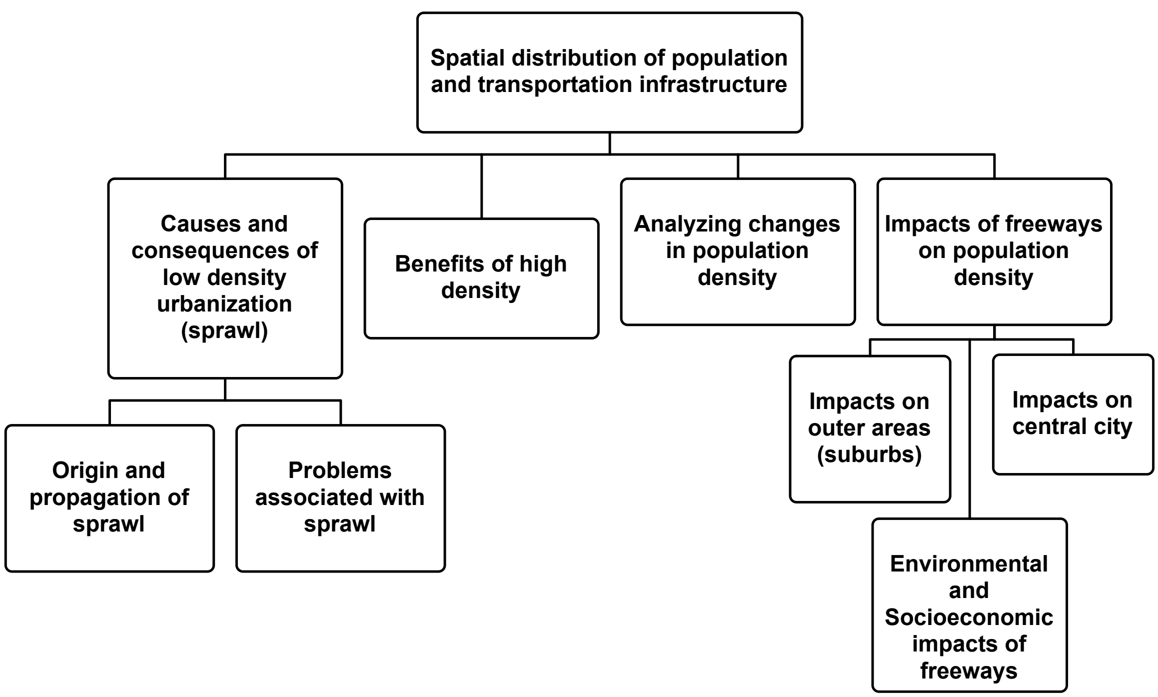

Figure 2. Literature Map

2.1 Causes and consequences of low density urbanisation (sprawl)

2.1.1 Origins and propagation of sprawl

Although there is a consensus that suburbanisation[4] in North America was generally brought about as a result of post-war boom, theories about the origins of sprawl as it relates to the emergence of urban freeways can be contradicting. On one hand, some authors attribute it to people's choice, i.e., a people-first approach (people, for various reasons, moved to the outer areas of the city and the urban freeways followed) (see Gillham, 2002). On the other hand, other authors insist that different levels of governments, for various reasons, built the roads, bridges, and freeways towards the periphery of the city, which gave people the means to establish themselves in the suburban areas (Gutfreund, 2004). The argument of sprawl as a means to absorb the prosperity resulting from the post-war economic boom fits with this perspective:

> "Beginning especially in the post-World War II period, diffuse urban development in the United States became the means to absorb the increasing productive capacities of the world's industrial base. Urban sprawl aides in the consumption of industrial output, because it increases demand for automobiles" (Gonzalez, 2006, p. 1).

Similarly, Gutfreund (2004) argues that highways[5] were built in order to accommodate the automobile and that suburbanization was a simultaneous phenomenon. People chose to move to more spacious outer areas given that there were means available

[4] The first wave of suburbanization i.e., the suburbs referred to in the present literature review, were low density development. Thus, a suburb by default is assumed to be sprawling.

[5] The distinction between highways and freeways will be discussed in the methods section. For now, it is suffice to say that the terms are used interchangeably in the literature reviewed.

to get out of the city. Gutfreund adds that government policies and subsidies played a major role in developing and propelling the dual phenomena of road building and suburbanization (also see Burchell et al., 2005). By using three distinct types of American cities as case studies, Gutfreund ascertains that it was not the size or the location of the city but the federal and state policies and corresponding incentives that allowed the development of suburban low density housing.

Canada followed the United States closely in the growth of suburban development. The federal government created agencies such as the Central Mortgage and Housing Corporation (CMHC) to help people buy a house in the newly developing suburbs (Solomon, 2007; Charbonneau et al., 1994). The houses in the suburbs were spacious allowing for increased demand for household goods (Gonzalez, 2006). Particularly in Toronto, new suburban housing was meant for the millions of soldiers returning after the Second World War. Solomon (2007) sheds light on the reasons why the Canadian government was inclined to promoting the low density housing at the fringe of the urban core: the government wanted "to steer settlement away from cities to more placid setting" (p. 76) particularly for the soldiers returning from the War.

Similar to the process in the US mentioned earlier (Gutfreund, 2004), the population in Toronto, one of the first cities to sprawl in Canada, was dispersed to the suburbs with government's carrot and stick approach (subsidies in the suburbs and prohibitions within the city) (Solomon, 2007). Contradicting the popular myth that people who would like larger houses tend to move out to the suburbs, S. D. Clark's (1966) surveys illustrated that people moved to suburbs for cheaper housing and not for superior lifestyle (larger space, front and back yards) (as cited in Solomon, 2007, p. 73).

2.1.2 Problems associated with sprawl

The problems associated with sprawl can be broadly classified into two main types: (1) the direct consequences that can be seen and felt in the sprawled area itself (e.g., increased automobile use), and (2) indirect effects on the central cities as a result of the growth of the suburbs (e.g. deteriorated central cities) (Burchell et al, 2005). This second aspect is the subject of the present thesis.

1) Direct effects of sprawl

The separation of land uses (residential, shopping, business), which results in high dependence on the automobile, is an important problem associated with sprawl as it makes the suburbs less friendly to walking or cycling (Burchell et al., 2005). The lowered housing density in fact increases automobile use while lowering population density (Gutfreund, 2004). The gasoline used in the automobile travel is a constant source of concern, for the reasons of finite supply of oil as well as for its environmental consequences related to greenhouse gas emissions and climate change (Newman & Kenworthy, 1989a, 1999; Greene, 2004). A case study of sprawling parts of Denver shows that in the sprawling areas the commuting time is higher and carpooling and bus ridership (number of people riding in buses) are lower compared to denser areas (Gutfreund, 2004). The low housing density also makes public transit inefficient and ineffective (Burchell et al., 2005; Pushkarev & Zupan, 1977; also see Filion et al, 1999).

One of the main direct costs linked to the development in the outer areas is its excessive use of land, which threatens and takes away the agricultural and environmentally fragile land (Burchell et al., 2005; Cieslewicz, 2002). Other direct issues associated with low density, spread out housing, are related to the cost of infrastructure:

water and sewer hook-up, maintenance and repair, and demand for water (mainly for watering the lawns) (Burchell et al., 2005).

In addition to the environmental and economic costs of high automobile use, personal and public costs of sprawl are considerable. For instance, the effects of sprawl include higher burden on the health system: obesity is one of the main issues associated with low physical activity as reliance on automobile encourages sedentary lifestyle (Burchell et al., 2005; also see Frank & Engelke, 2001; Lee & Moudon, 2004; Crane, 2000).

2) Indirect costs of sprawl (effect on the central cities)

Gillham (2002) summarizes one of the main issues that is subject of the present research:

> "The rapid expansion of suburbs quickly drained the older center cities, which were the nation's dominant centers of population and commerce" (p. 46).

It was in response to this outward movement of people towards the suburbs that the cities took up "urban renewal" projects to revive the economic condition of the cities (Gillham, 2002). Indirect costs of sprawl also include urban decline and concentration of poverty in the declining central city neighbourhoods due to disinvestment in the urban core, lowered tax revenue to the city given that affluent individuals would move to suburbs (Jargowsky, 2002; Burchell et al., 2005). Societal costs of sprawl include pollution of common goods, namely air, land and water, both in the suburbs as well as the central cities, in addition to the environmental cost discussed earlier (Burchell et al.

(2005); see the same for a detailed account of both direct and indirect costs associated with sprawl).

2.2 Benefits of high density

High density housing has been hailed by many scholars and researchers for almost half a century for various reasons. This section presents a brief overview. One of the main benefits of high density housing or compact form is its suitability for walking and cycling (non-motorised transport) and for public transit use. The advantages in turn are to public health as increased physical activity can translate into lower obesity and heart related problems (Lee & Moudon, 2004; Newman & Kenworthy, 1999; Bedsworth, 2010; Pushkarev & Zupan, 1977).

Transit use correlates positively with population density, thus high density makes transit more efficient and effective (Pushkarev & Zupan, 1977). Higher non-motorised transport and transit use also lower automobile use -- on an average one bus replaces fifty personal cars (STM, 2010). Therefore, another major benefit of high density is to the environmental health - lower car use translates into lower air and noise pollution as well as reduced greenhouse gas emissions. All of this, ideally, could mean lower burden on the road network and infrastructure. A compact urban form, in addition, allows more people to own houses within a given area, thus reducing usage of farmland and/or environmental fragile land (Burchell et al, 2005; Newman & Hogan, 1981).

In addition, higher community interaction is associated with high density living (Jacobs, 1961; Newman & Hogan, 1981). Churchman (1999) summarizes various reasons, such as lifestyle, life stage, cost, and location, that might be factors that make high density living inviting.

2.3 Analysing changes in population density

A first step in the process of analysing changes in population density would be to define density. Table 1 provides a review of density measurements from various literature. Population or residential density is often calculated as total population in a census tract (or central city) divided by the total area of the census tract (Filion et al., 2010; Baum-Snow, 2007). Forsyth (2003) refers to this measurement as gross census tract density. In such a measure of density no exclusions of geographical features such as water bodies and parks are made in the calculation of area. Net density measurements (Table 1) often exclude non-residential land uses including mountains, water bodies, open spaces and recreation parks. Non-exclusion of such non-residential land use from the density calculation lowers the density measured as the area in question (the denominator) increases (Burton, 2002; Table 1). Density calculation based on administrative boundaries is cautioned against since the boundaries can be arbitrary, which could lead to inaccurate measurements and comparisons (Fooks, 1946; Mees, 2010).

Various studies have defined areas such as core, inner-city and suburbs and seldom rely on administrative boundaries. A review of these definitions is presented in Table 2. Central business district is often considered the core, and the area built up before 1946 is considered inner-city by some studies. The distinction of pre- versus post-war (Second World War) also defines what is considered as inner-city and suburb (see Table 2 for a complete list of definitions).

Table 1. Various definitions and measurements of population and other relevant densities

Definition (*The denominator [area] for the calculation of the density is the aspect that differs often from a study to another. The numerator [population, residents, etc] is the figure that follows the choice of the area and the type of density being calculated, thus is straightforward).*	**Source**
Population density is defined as the total population in a census tract divided by the total area of the census tract. Also referred by the authors as residential density.	Filion et al., 2010
Gross urban density is defined as "the population or number of dwelling units relative to the total urbanized land area (in the continuous land base in this study) of a city or metropolitan region." (p.116)	Taylor and Burchfield, 2010
Population density is the total population of the census tract (central city in some cases) divided by the total area of the relevant unit.	Baum-Snow, 2007
Average density, defined as total population divided by the area of concentric circles of one mile radius around the city center. Open spaces, such as parks and mountains were excluded from the area calculation. This approach to density calculation allowed for cross-continental comparisons.	Clark, 1951 (also used by Edmonston, 1983)
Density is calculated using a common definition of urbanized land that was applicable to all the cities in their study. Large water bodies were excluded.	Newman & Kenworthy, 1989a
Regional density is population divided by the region's land area. The region could be the municipal boundary including both developed and undeveloped land.	Cheng, 2010
Net residential density is the ratio of population to the area occupied by the residential use. Non residential land uses such as parks and roads are excluded from the area calculation.	Churchman, 1999, as cited in Cheng, 2010
Gross residential density: same as above except that it considers the residential area in its entirety, that is, land use that serves the local community are considered. However delineating the use for local communities or not is difficult to ascertain.	Cheng, 2010
Occupancy density measures the ratio of number of people occupying a given floor area or habitable area. This is used for smaller scope projects such as calculation of building occupancy rates.	Cheng, 2010
Gross census tract density is the ratio of the residential population in the census tract to the total area of the census tract without any exclusions. This is the density often found in US census information.	Forsyth, 2003
City (or urban) density (also referred to as urbanized area density) is defined as the residential population divided by the city limits (the administrative or the local boundaries) and includes only the urban (developed) area. This is also termed gross density at city level.	Forsyth, 2003

Metropolitan density is similar to the one above but the area is for the whole metropolitan region and includes undeveloped land as well. Also termed as gross density at metropolitan level, data for which is provided in census information.	Forsyth, 2003
Net density is calculated using total number of population or total number of households in a given district or such. The denominator, area, excludes open spaces namely parks, recreation grounds, school playing fields, and open spaces around public buildings such as hospital and educational institutions.	Burton, 2002
NOTE: Density calculation based on administrative boundaries give rise to arbitrary measures as the boundaries can be arbitrary, and inaccuracies can seep in as the area in question (the denominator) increases. The main reason for this caution is because the municipal or other administrative boundaries do not always (even seldom) correspond to urbanized area.	Fooks, 1946; Mees, 2010

In their study on residential density (see Table 1 for density definition) in Montreal, Toronto, Ottawa-Hull and Vancouver, the four largest metropolitan regions in Canada, Filion et al. (2010) conclude that over a 35-year period (between 1971 and 2006), cities have become more alike in terms of population density mostly due to the use of automobiles. Filion et al. (2010) found that the metropolitan area of Montreal, which was the densest in 1971, experienced the highest loss in density over the 35-year period. However, it remained the densest of the four regions in 2006. The authors looked at four zones in the metropolitan regions (core area, inner city, inner suburb and outer suburb; see Table 2 for definitions) and found that the population loss in the inner city is clearly marked in all four cases, while there is a consistent increase in the population of the outer suburbs (but not the density). Hinting on the reasons for the fall in density in the inner city, the authors cite:

> "The development of expressway network in the 1960s [in Montreal, similar to Toronto] played a role in the depopulation of the inner city and the outward expansion observed between 1971 and 1986"

(Bussière, 1989, Charbonneau et al., 1994, as cited in Filion et al., 2010, p. 560).

As discussed earlier, freeway was identified as one of the reasons why central city population deteriorated to the benefit of suburbs, particularly in Montreal. In addition to freeway, Charbonneau et al. (1994) identified two other factors that could explain the lowering of population in the central city and the growth of urban sprawl. First, the introduction of the mortgage programs by Central Mortgage and Housing Corporation (CMHC) in the late 1940s that allowed development and growth of the suburbs. Both the federal and Quebec governments facilitated and encouraged sprawl ("dispersed and sporadic" development) by not only providing mortgages but also by providing subsidies to the developers (Charbonneau et al., 1994, p. 464). Thus houses in the suburbs were cheaper for young middle class couples than new houses in the central city, which encouraged people to relocate (also see Solomon, 2007 and Sewell, 2009). The new housing in the suburbs was often located along the freeways. Second, Montreal lost many jobs due to a de-industrialization process that started in the 1960s. Similar phenomena could be observed in other North American metropolitan areas. In effect the manufacturing jobs declined in the central city areas due to competition from international manufacturers or the relocation of the these jobs to the suburbs. These two factors along with freeways could explain the spatial distribution of population and more specifically urban sprawl (Charbonneau et al., 1994).

In addition, Filion et al. (2010) considered seven factors influencing density patterns in their analysis of varying density trajectories in the four largest Canadian metropolitan areas: 1) "Topography" of the metropolitan area, such as flat/open land or islands, presence of bridges, physical constraints to growth such as borders or ocean; 2) "Inherited built environment", such as high density housing like duplexes and triplexes versus single family housing; 3) "Urban culture", such as trends associated with low density living or the presence of opposing forces of conservation and development that shapes the density; 4) "Demographic and market trends" related to the population and economic growth defining any redevelopment and outward expansion; 5) "Political institutions", such as the presence or absence of a regional planning organizations that cover the metropolitan area; 6) "Land-use policies and patterns" that can determine density patterns, such as provision of public transit or designation of greenbelt areas, or zoning allowing or inhibiting urban development; and 7) "Transportation" policies such as presence and development of public transit/rail versus expressway and the amount of car use both in the central areas and the suburbs (p. 556).

Table 2. Various definitions of inner/central city and other relevant areas

Definition	**Source**
Core area is composed of census tracts within 2km radius from the intersection that had the highest land value traditionally. 1946, the beginning of post-war boom, is considered a key period - census tracts with a majority of the housing stock built before then is considered inner-city. Census tracts that has a majority of the housing stock built in 1946 are defined as inner suburbs, and those built after 1946 are termed as outer suburbs.	Filion et al., 2010
Core area is the area with construction that is largely completed before 1951, while older suburbs are areas with construction largely between 1951 and 1970, and newer suburbs are those that were constructed since 1971.	Taylor and Burchfield, 2010
Central city is defined by the 1950 central city geography/political boundary.	Baum-Snow, 2007
Functional definition, based on the urban form and lifestyle: inner-city is all the area that was built up before 1946, the rest is suburb. Distinction of what was developed post-war versus pre-war.	Walks, 2007; Skaburskis and Moos, 2008
Jurisdictional definition: census metropolitan area (CMA) is split in three zones. Central city is the old (pre-amalgamation) city. The rest of the CMA is suburbs. The suburbs are then split into inner and outer suburbs. The differences are defined based on types of municipality and governance structures.	Walks, 2007
Central (or inner) city is composed of the central business district (CBD) and a ring of residential neighbourhood. The latter is one census tract thick around the CBD.	Triggs, 2007
Central core of the city is defined as the central business district of the city by the same name as the CMA and the surrounding residential districts. Suburbs are zones outside the city's central core or further than a certain distance from the core.	Turcotte, 2008; Ley & Frost, 2006.
Inner-city consisting of CBD and the ring of old neighbourhoods (dwellings mostly constructed in 19th century).	Ley and Frost, 2006
Inner-city has a cosmopolitan character with "old buildings, social and land-use diversity, ethnic neighbourhoods, pedestrian travel and public transportation, urban parks and waterfronts […] as opposed [to] the blandness of the freeway, high-rise city of the renewal planner, or indeed suburban conformity" (p. 193).	Jacobs, J. (1971) as cited in Ley and Frost, 2006
Inner-city is defined as the census tracts that are dominated by pre-1946 housing; Core area is composed of the CBD and 1.5km to 2km of area (defined based on the size of CMA) around it.	Bunting et al., 2002

Taylor and Burchfield (2010) compare urban growth patterns and policies in the census metropolitan areas (CMA) of Calgary, Toronto and Vancouver between 1991 and 2001.

The growth of these three cities took different routes as a result of “varying social, physical, economic, and political contexts, and complex internal dynamics” (p.1). Vancouver for instance faces physical barriers to growth, such as the ocean, mountains and the United States' border. In addition, the provincial Agricultural Land Reserve (ALR) (1973) and the Green Zone (1996) designated by Vancouver's regional government paved way for contained urban growth.

Going beyond physical barriers, gains in Vancouver have been attributed to planning and policies to intensify population and activity coupled with participatory processes that employed neighbourhood visioning and community decision making model. These practices allowed for a mixed-use downtown with a high residential component (Filion et al., 2010; Taylor & Burchfield, 2010; Harcourt et al., 2007; Punter, 2003; Tomalty, 2002). Toronto and Calgary did not follow this route. Taylor and Burchfield (2010) propose that population of the three cities (Vancouver, Calgary and Toronto) grew at the same rate over the study period, providing an "apples-to-apples" comparison, even though each one of them had different forms of provincial, regional and municipal government that controlled the land use planning and policies.

Taylor and Burchfield (2010) investigate *how* and *why* these three metropolitan regions grew between 1991 and 2001, and whether planning and policies by regional governments played a role in the growth. Data for the study included changes in metropolitan population, number of dwellings, amount of urban land, gross density, and mix of housing stock. The source of the growth is then traced to urban intensification or greenfield development. Of the three regions, Toronto saw highest increase in population and dwelling units over the study period. Vancouver and Calgary did not grew as much in absolute terms but they did so at a higher rate.

The Taylor and Burchfield (2010) study concludes that the three regions differed in the percentage of growth that occurred in greenfield (undeveloped land). The rate of urban area expansion in Calgary and Toronto was higher than the rate of population growth [higher in Calgary (43% vs. 24%) than in Toronto (28% vs. 19%)]; in Vancouver, however, the rate of urban area growth was two-thirds that of the population growth rate (16% vs. 24%). Since "one classic definition of "sprawl" is that the rate of urban area expansion is greater than the rate of population growth" (p. 27), it can be concluded that during the study period Calgary and Toronto sprawled while Vancouver did not. As for regional planning and policies, they affirm that the growth patterns reflect the regional plans and policies. They elaborate that:

> "local governments and decision-makers have the autonomy and capacity to chart distinct growth paths, even constrained as they are by provincial and national governments, as well as powerful economic, social, and geographic factors." (p. 90)

Both Taylor and Burchfield (2010), and Filion et al. (2010) clearly identify the importance of high density (although exactly what constitutes "high" is not specified) and find that intensification strategies need to be adapted to the specificities of each region. They warn that the housing and population densities would most likely decline in the future as available open spaces in the urban areas would have been used for residential and other projects.

Highly dense inner-cities and dispersed (lower density) outer suburbs, as observed by Filion et al. (2010) (discussed above), were theorized and tested by Clark (1951) in his seminal work, *Urban Population Densities*. He illustrated that as we move away from the city center towards outer suburbs, density declines, in accordance with the formula:

$$y = Ae^{-bx}$$

Where y is the population density (persons per square mile) at census tract level;

x is distance in miles from city center (this would be zero in central business district);

A is the degree of "over-crowding" – the amount of density the city can tolerate;

b is the measure of compactness of the city, which depends on the cost of intra-urban travel relative to average income.

Using density distance-decay curves (by deploying the above formula) of nearly twenty international cities, dating as far back as the year 1801 (for London), Clark (1951) illustrated that the slope of graphs are always negative, indicating that as the distance increases from the center densities decline. The value of A is the y-intercept (where the line cuts the vertical axis) and b is the slope of the line. An excerpt of the graphs is shown in Figure 3.

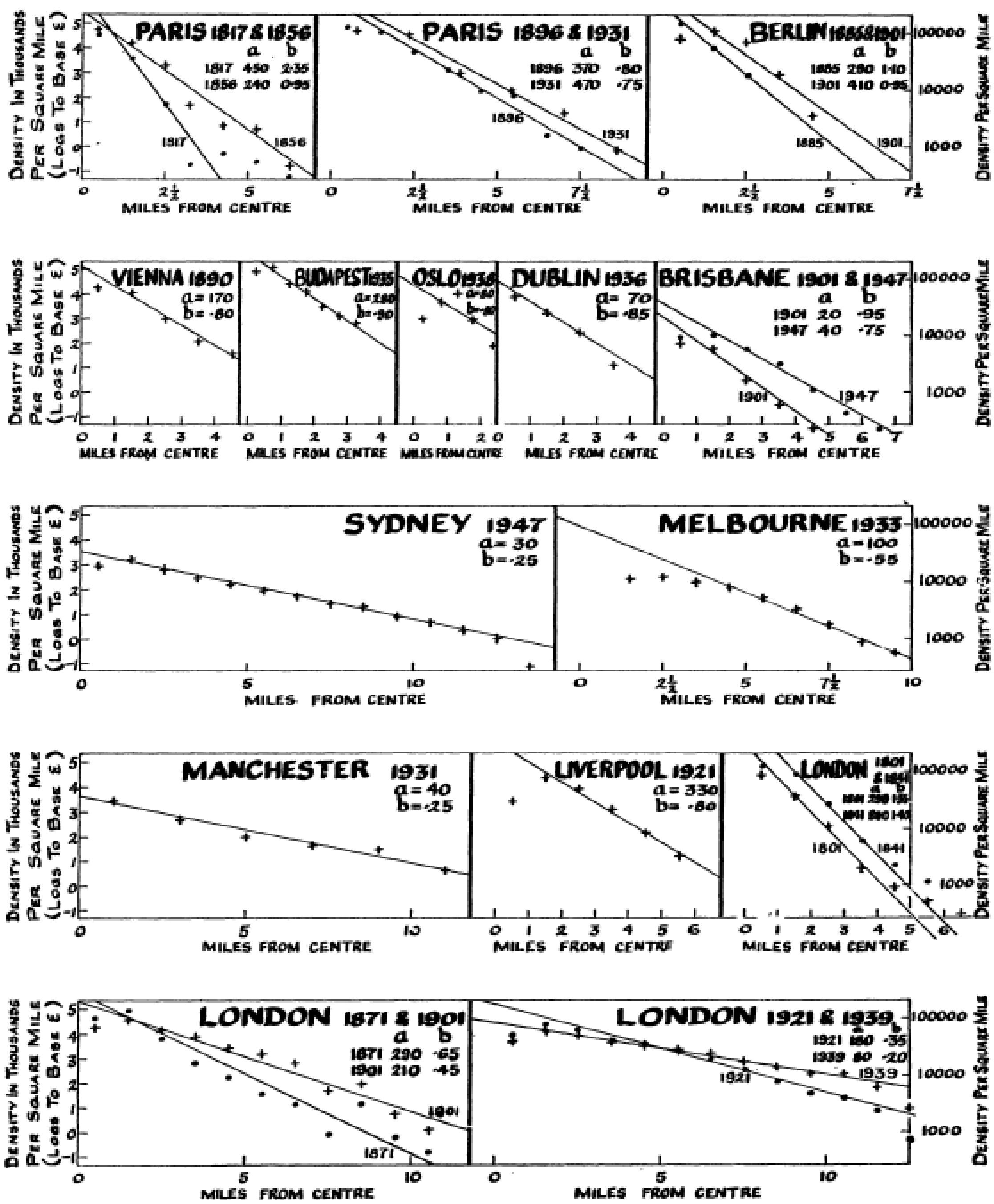

Figure 3. Density distance-decay curves. Source: Clark, 1951.

Clark (1958) and Muller (2004) also illustrate the density gradients whereby the density is higher in the inner-city and declines as the distance from the centre grows.

Muller also shows that over time the density distance-decay curve flattens in North American cities, i.e., in more recent periods, the density is much lower in the central cities, as well as in the suburbs, than it was a decade or so earlier. Thus a "progressive deconcentration" is observed (Muller, 2004, p.61).

Confirming Clark's (1951) projection, a recent Statistics Canada study (Heisz, 2005) shows that between years 1991 and 2001 population in almost all Canadian cities grew at a higher rate at a distance beyond 5km from the city center than within that distance.

2.3.1 Levels of density

Density calculations by various scholars may or may not be comparable between each other as the area used to calculate population density may differ from one study to another (see Table 1), such as the inclusion or exclusion of parks and open spaces in the calculation of area that lower or increase the density calculated (also see Burton, 2002). However, as a means of determining rough values of high, medium and low densities, Table 3 lists some densities found in the literature.

The inner area of New York had the highest density (10,700 persons/km^2) and Phoenix, both inner and outer areas, had the lowest density (1,903 and 791 persons/km^2 respectively) in Newman and Kenworthy's (1989a) study of global cities. Filion et al. (2010) found the highest density in the core area of Vancouver (11,198 persons/km^2) in 2006, and lowest in the inner-city of the same city (2,681 persons/km^2) in 1986.

Table 3. High and low densities from various studies

Newman & Kenworthy (1989a)[a]	**1980**					
	Inner area	**Outer area**				
New York	**10,700**	1,310				
European Cities	9,093	4,300				
Toronto	5,708	3.410				
Phoenix	1,903	791				
Filion et al. (2010)	**1971**		**1986**		**2006**	
	Core area	**Inner city**	**Core area**	**Inner city**	**Core area**	**Inner city**
Toronto	5,119	7,495	6,352	6,436	10,224	7,001
Montreal	6,192	11,106	4,688	7,785	5,724	7,886
Vancouver	5,201	2,759	5,516	2681	**11,198**	3,664
Ottawa-Hull	6,719	4,944	5,099	3,828	5,349	4,002

All densities in persons per square kilometre; Bunting et al. (2002) also contains density figures for Canadian Cities, however the years overlap with that of Filion et al. (2010) study and the high and low density remain as presented above in Filion et al. (2010) study.
a. Density converted from persons per acre to persons/km^2.

2.4 Impacts of freeways on population density

This section reviews literature that deals specifically with analysing the impacts of freeways on population densities and other related factors. In the same vein as Clark (1951, 1958), Filion et al. (2010) and Muller (2004) discussed above, Giuliano (2004) argues that the further from the city center, the lower would be the density. Land value decreases as one moves outwards from the city center, thus plays a major role in lowering of the density. High-speed roads, a freeway for example, enable accessibility to areas located further from the central city (Giuliano, 2004; Burchell et al., 2005) making them more desirable. Rail transit is another example of transportation technology that makes areas further from the city center more accessible; however, this literature review focuses on the impact freeways may have on population density.

Giuliano (2004) reviews the theories of land use and transportation, such as theory of agricultural land rent and use [von Thunen's (1826), later developed by Alonso (1964) among others] and residential location theory. These theories rely on residential location choice, whereby people would choose to live at a location where the savings in the cost of housing outweigh the additional cost of commuting (in time and money) if living at a longer distance from the location of work. Since the cost of land (rent) declines as we move further away from the city center (see Figure 4) (as more would have to be paid in commuting cost), people consume more housing per capita (larger houses, with larger yard spaces around) in the outskirts compared to the center. Thus population density declines with distance from the center (Giuliano, 2004; also see Alonso(1964), Mills (1967), and Muth (1969)). In addition to the lowered cost of housing, any reduction in commuting cost (in time and/or in money) would contribute to further lowering of population density as it would encourage housing location further from the central city (Giuliano, 2004).

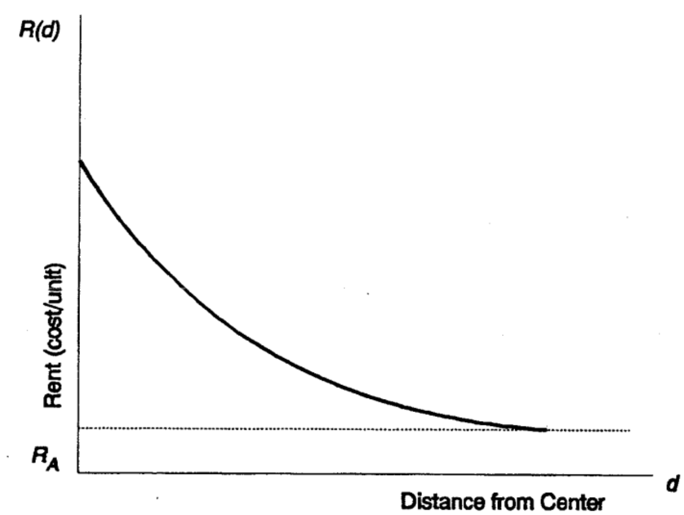

Figure 4. The relationship between rent and location. Source: Giuliano, 2004, p. 243.

Improvements in transportation, particularly in freeways (and high-speed transit), reduce commuting cost, in time and money. Figure 5 illustrates the effect of introduction of freeways or expressways, which lowers the transportation cost, particularly in time. Line 1 in the figure represents land rent gradient before transportation improvement; improvement in transport facilities flattens the land rent gradient, as seen in line 2. Improved access to areas further away from the city center with lower transport cost makes such areas more attractive. As a result, the "location advantage" of the center declines lowering the rent at the center, as can be seen in b (compared to a), the vertical-intercept of line 2 (Giuliano, 2004).

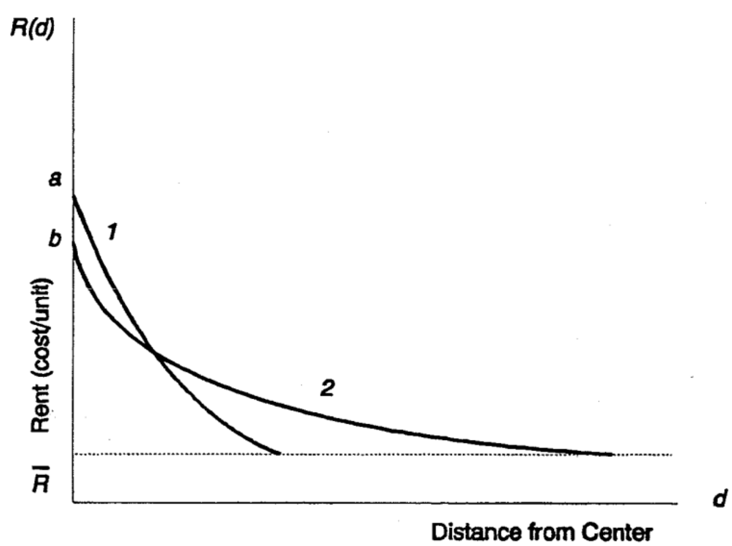

Figure 5. Response of rent function to a transport cost decline. Source: Giuliano, 2004, p. 244.

The residential location model explains the phenomenon discussed earlier, and defines demand for housing (D) to be:

$$D = f(P_h, P_t, P_g)$$

The demand for housing is a function of Price of housing (P_h), Price of transportation (P_t), Price of all the other goods used by the household (P_g). It is important to note, however, that the model assumes identical preferences among all households, whereas the preference for housing may change depending on the socioeconomic situation (Giuliano, 2004).

Land use impacts of freeways, i.e., development brought about as a result of freeway construction, can be seen more in the places where there is developable land, rather than where the land is already developed (Giuliano, 2004). Therefore, impacts of freeways can be seen more in the outer areas, suburbs, and not so much in the central city. In the next section, I review literature that deals specifically with the impact of freeways in the outer areas of the city, followed by the impacts on the inner-city.

2.4.1 Impacts of freeways on outer areas (suburbs)

Funderburg et al. (2010) studied three counties in California to examine the amount of growth that can be attributed to new freeways. They tested the results of Baum-Snow's (2007) study 'Did highways cause suburbanization', which concluded that the interstate freeways contributed heavily to the creation of suburbs and lowered the central city population. (A detailed review of Baum-Snow's (2007) study is included in the next section).

The study by Funderburg et al. (2010) consisted of comparison between counties that received recent freeways and a control group of "no-build" counties. The method involved analysing a 3-mile (4.83 km) corridor around the new freeways for new growth as a result of new freeway construction. Their results show that more jobs were added within 2 miles (3.22km) of a new freeway, nonetheless they did not find the effect to be uniform throughout the study areas. Smaller counties were comparatively much less impacted than larger ones such as Orange County. The impact, where it is found, was mainly in employment. Funderburg et al. conclude that the general growth patterns cannot be solely attributed to freeways (also see Boarnet & Haughwout, 2000), and they qualify:

> "[W]hile improvements in surface transportation tend to have large impacts on growth patterns, the nature of the effects is materially dependent on the context [type of highway improvement and characteristics of the location] of the highway investment" (Funderburg et al., 2010, p. 94).

Overall, Funderberg et al. find it difficult to establish a clear and unambiguous connection between freeways and land use change (in terms of change in employment). A land use change can potentially change the population density if the change involved housing.

Based on a review of eighteen studies that looked at the impacts of freeways on growth, Ewing (2008) concludes that highways in general do not have a high net effect on overall growth and development of a metropolitan area and that any development is a result of investment that was moved around within the metropolitan area. However, one of the conclusions of Ewing's review is that highway investments generally favour development in the suburban areas resulting in decentralisation and lowering of density. Overall, the effect of freeways can be considered negative since they encourage low-density development (Ewing, 2008).

Increasing freeway capacity is also counter-productive from a welfare point of view, as it "worsens the existing urban transportation problem" (Zhang & Xu, 2011, p. ii). Often times cost-benefit analysis of a new freeway does not take into account the induced demand (more people using automobile because of newly available higher capacity), and future land use changes (more housing further away from the city center). Thus, freeways, that cost significantly more than the improvement work on the urban arterial system, end up benefiting the suburbs more than the core (Zhang & Xu, 2011).

2.4.2 Impacts of freeways on central city

The classic land use theory proposed by Alonso (1964) and developed by Mills (1967) and Muth (1969) suggests that the investments allowing higher speed transportation, which lower transportation costs, promote decentralisation and can even cause suburbanization.

> "It is clear that the existence, size, and structure of cities are closely related to transportation costs" (Mills, 1967, p. 198).

Higher speed reduces commuting times increases the distance people are able to travel on a regular basis, as discussed earlier. Therefore, more people can live further and further away from the central city. Further, the model developed by Alonso (1964) and Mills (1967) predicts that with faster, non-mass transit commuting, more pressure is exerted to expand into the suburbs. Thus land in the suburbs is more demanded compared to that in central cities. In the above models, employment is assumed to occur in the central city, i.e., the land use models assume a monocentric city.

On the basis of the monocentric city model and the classic land use theory, Baum-Snow (2007) conducted a study to determine the impact of interstate highway (freeway) system on the central cities in United States. Through a series of econometric analysis and tests, he concludes and asserts that freeways led the way for suburbanisation. His quantitative research examines the rate of suburbanization among cites that received a number of new freeways between 1950 and 1990 and those that received far less during the same period, and establishes that freeways did cause suburbanisation. The results of his study confirm the classical models of land use theory discussed above:

> "[I]nnovations to the urban transportation infrastructure played a key role in influencing changes in the spatial distribution of the population in US metropolitan areas between 1950 and 1990" (Baum-Snow, 2007, p. 776).

Figure 6 shows that despite an aggregate increase in the metropolitan and central city populations, the population of the constant geography central city lowered. Note that Baum-Snow (2007) used 1950's central city constant geography, that is, the 1950 boundaries of the central city were maintained even if the actual central city boundary in 1990 changed. In all large MSAs and inland MSAs, the total central city population increased by 14 and 38 percent respectively and the MSA population increased by 72 and 88 percent respectively. However, the constant geography central city population declined in both cases by 17 and 26 percent respectively.

Aggregate Trends in Suburbanization, 1950–1990

	1950	1960	1970	1980	1990	Percent change 1950–1990
Panel A: Large MSAs						
MSA population	92.9	115.8	134.0	144.8	159.8	72
Total CC population	44.7	48.5	51.3	49.2	51.0	14
Constant geography CC population	44.7	44.2	42.6	37.9	37.1	−17
N for constant geog. CC population	139	132	139	139	139	
Panel B: Large Inland MSAs						
MSA population	39.2	48.9	57.0	65.0	73.5	88
Total CC population	16.8	19.7	22.1	22.1	23.2	38
Constant geography CC population	16.8	16.5	15.4	13.3	12.5	−26
N for constant geog. CC population	100	94	100	100	100	
Total U. S. population	150.7	178.5	202.1	225.2	247.1	64

Notes: All populations are in millions. CC stands for central city. The sample includes all metropolitan areas (MSAs) of at least 100,000 people with central cities of at least 50,000 people in 1950. The sample in Panel B excludes MSAs with central cities located within 20 miles of a coast, major lake shore, or international border. MSA populations are for geography as of year 2000. Constant geography central city population uses 1950 central city geography. Census tract data are not available to build constant geography central city populations for some small cities in 1960. These cities are assigned a population of 0 for constructing the aggregates. Reported total U. S. population excludes Alaska and Hawaii.

Figure 6. Aggregate trends in suburbanization. Source: Baum-Snow, 2007, p. 777

Note: rectangles added for pointing out the data.

An adapted version of the classic distance decay curve (Clark, 1951; also see McDonald, 1989) can be seen in Baum-Snow's (2007) spatial distribution of metropolitan population model:

$$\text{Log } PD_{ij} = \alpha_i + \beta D_{ij}^{cbd} + c D_{ij}^{hwy} + \varepsilon_{ij},$$

where β turns out to be negative and values of *c* range from negative to positive.

Population density (PD_{ij}, measured as population per square mile) in census tract i in MSA j is defined as a function of distance from a given census tract centroid to the CBD (D^{cbd}), and from centroid to the nearest interstate highway (D^{hwy}). For the years 1970 and 1990, for a total of 36,250 census tracts in 139 MSAs, Baum-Snow’s (2007) model concludes that depending on distance to the CBD, population density is higher near[6] the highways and that the density lowered on an average by 1 to 2 percent with each additional mile away from the highway. The results show consistent pattern between highway and residential location, which in turn is influenced by highways.

Baum-Snow (2007) takes the traditional land use model further to incorporate various other predictor and explanatory variables. The long difference estimate or long difference regression using ordinary least squares and instrumental variables estimates forms the basis of his conclusion that the inter-state highways *cause* suburbanization (further details on this follow). The instrumental variables method is used to estimate causal effect between response and predictor/explanatory variables (Steiger, 2009; also see Angrist et al., 1996)[7]. The main specifications used in the estimates are:

$$\Delta \log N^{c}_{i} = \alpha_0 + \alpha_1 \Delta ray_i + \alpha_2 r_{ci} + \alpha_3 \Delta w_i + \alpha_4 \Delta \log N^{MSA}_{i} + \alpha_5 \Delta G_i$$

The change (between 1950 and 1990, applies to all the variables) in constant-geography central-city population in a MSA i (N^{c}_{i}) is a function of change in ray_i, number of "rays" (roads with higher speed than regular surface streets, connecting the central business district to a highway in the outer area of the city[8]) in a given MSA, i; r_{ci}, the radius of the constant-geography central city; w_i, change in the mean log annual income – adjusted (balanced and controlled) to counter the differences in income between suburban residents and generally less rich central city population; and N^{MSA}_{i}, MSA population, whereas Gi is the Gini coefficient of income distribution (Baum-Snow, 2007).

[6] How near is "near" is not specified.

[7] Detailing further the method used in an econometric study by Baum-Snow, an economist, is beyond the scope of the present literature review.

[8] For detailed methods see Baum-Snow (2007a), the separate methodology paper.

TABLE IV
LONG-DIFFERENCE REGRESSIONS OF THE DETERMINANTS OF CONSTANT GEOGRAPHY CENTRAL CITY POPULATION GROWTH, 1950–1990

Large MSAs in 1950						
		Change in log population in constant geography central cities				
	OLS3	IV1	IV2	IV3	IV4	IV5
Change in number of rays	−.059 (.014)**	−.030 (.022)	−.106 (.032)**	−.123 (.029)**	−.114 (.026)**	−.101 (.046)*
1950 central city radius	.080 (.014)**		.111 (.023)**	.113 (.023)**	.106 (.023)**	.125 (.021)**
Change in simulated log income	.084 (.378)			.048 (.417)	−6.247 (6.174)	−.137 (.480)
Change in log of MSA population	.363 (.082)**			.424 (.094)**	.374 (.079)**	.405 (.108)**
Change in Gini coeff of simulated income					−23.416 (23.266)	
Log 1950 MSA population						−.062 (.062)
Constant	−.640 (.260)*	−.203 (.078)*	−.359 (.076)**	−.588 (.281)*	4.580 (5.091)	−.611 (.265)*
Observations	139	139	139	139	139	139
R-squared	.39	.00	.01	.30	.33	.37

Notes: In columns IV1–IV5, the number of rays in the 1947 plan instruments for the change in the number of rays. Standard errors are clustered by state of the MSA central city. Standard errors are in parentheses. ** indicates significant at the 1 percent level, * indicates significant at 5 percent level. Summary statistics are in the Appendix Table. First stage results are in Table II.

Figure 7. Long-difference regression using ordinary least squares (OLS). Source: Baum-Snow, 2007, p. 791

Note R-Squares (rectangles added for pointing out the data).

Figure 7 shows the results of the long difference regression, partly based on which Baum-Snow concludes that a third of the decline in the central city population in the United States can be attributed to the freeways. Each new freeway reduces the constant geography central city population by about 18%, and each additional “ray” contributes to approximately 9% decline in central city population. Moreover, population in major central cities declined on average by 28% between 1950 and 1990. These declines came about despite net migration in the MSA. Furthermore, the highways built specifically to link CBD to the outer areas had a higher impact on lowering the central city population density than otherwise. Based on his model, Baum-Snow (2007) estimates that without the interstate freeways, aggregate central city population would have increased by 8%

instead of falling by 17% over the four decades between 1950 and 1990 (Baum-Snow, 2007).

Similar to the observation of Taylor and Burchfield (2010) in the case of Vancouver's growth discussed above, the study by Baum-Snow (2007) clearly finds a difference between coastal cities[9] and the inland cities – the former did not sprawl as much as the latter given the geographical constraints they faced. Baum-Snow (2007) explains: "this is consistent with predictions from a land use model in which the space into which the metropolitan area can expand is exogenously restricted" (p. 793).

While reviewing the seminal work by Baum-Snow (2007), it is important to note that Cox et al. (2008) criticise the study by Baum-Snow on various counts. Their critique is based mainly on self-selection theory and on 'what is generally known today': that Baum-Snow's study does not take into consideration that the suburbanization is related to consumer preference, and that Baum-Snow's study ignores larger trends of rising wealth, and improvement in transportation and communication technologies. Cox et al, referring to Jackson (1985) on streetcar suburbs, also note that the growth of the suburbs relative to central city was seen well before 1950's, thus refuting the conclusion of Baum-Snow (2007) that the interstate-highway construction caused the suburbanisation. Streetcars did allow for growth around the central city beginning in the late nineteenth century (see Cervero & Radisch, 1996 and Wheeler, 2010). These areas were known as streetcar suburbs and had relatively high or medium population densities (Newman & Kenworthy, 1999). What is significant, however, about the Baum-Snow (2007) study is that it shows that highways contributed to a *third* of the decline in aggregate central city population relative to population in the overall metropolitan area. Cox et al. (2008) maintain,

[9] These were the MSA's within 20 miles from a coast, major lake shore, or international borders.

however, that people moved out to the suburbs simply because they could – as income rise, people can afford to choose mobility by automobile and commute larger distances without a problem. Cox et al. assert that the public sector infrastructure (freeways and such) follows people, and does not lead them to the suburbs.

2.4.3 Environmental and socioeconomic impacts of urban freeways

2.4.3.1 Environmental impacts of urban freeways

The literature in this area is vast with many studies pointing to the adverse effects of freeways on the environment. Since this is not the immediate subject of the thesis, this section presents a brief summary of the impacts of freeways on the environment.

Combustion of fossil fuel in internal combustion engines in automobiles is the main source of environmental impact of freeways (Greene, 2004; Kenworthy, 2008). Passenger transportation accounts for 70% of transport emissions (Environment Canada, 2009; Schipper & Fulton, 2003). 40 – 50% of a Toronto household's emissions are from transportation (Norman et al., 2006). Urban freeways providing platform for higher driving exacerbate the pollution and greenhouse gases generated by transportation. Figure 8 shows the inverse relationship between population density and the greenhouse gas emissions for major international cities (Kennedy et al., 2009).

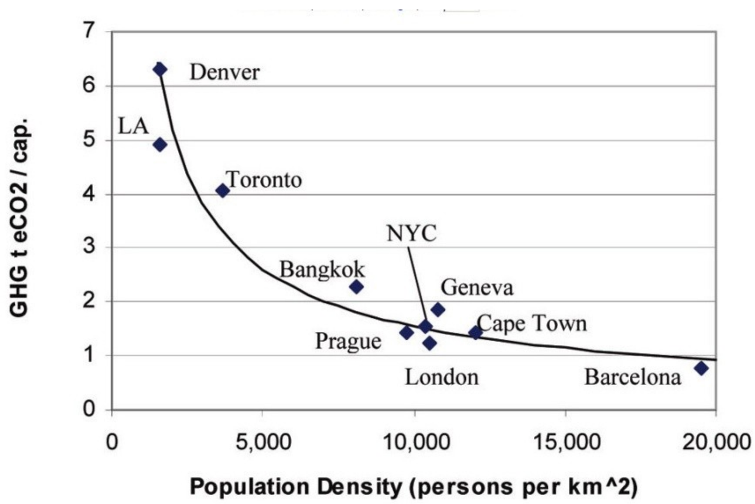

Figure 8. GHG emissions from ground transportation fuels and population density. (Source: Kennedy et al., 2009)

Similar to Kennedy et al., Newman and Kenworthy (1989a and 1989b) in their seminal work on correlating density and gasoline consumption show that the lower the density, the higher would be the gasoline consumption and vehicle kilometre travelled (VKT). High VKT contributes to environmental degradation through greenhouse gas emissions (Greene, 2004; Kenworthy, 2008; also see Newman & Kenworthy, 1999).

2.4.3.2 Socioeconomic impacts of urban freeways

When the first urban freeways were built (such as, interstate freeways in 1940s and 1950s in the US), the engineers did the planning and were focused on the traffic related aspects and were not bothered by other issues. Consequently, social impacts on the communities were ignored (Altshuler, 1965). Construction of freeways in already built areas have high social impacts as they often displace and disperse communities (Harvey, 1996; Gauthier, 2009). The chief planning engineer of St. Paul, US, George Herrold, who was in his eighties in 1940's, had opposed the freeway that were to cut through a traditionally black community. He described the socioeconomic impact as "[it] requires the moving of thousands of people, who must give up their homes, churches, schools, neighbours and valued social contacts, who lose the institutions they have built for their pleasure and profit" (as cited in Altshuler, 1965, p. 43).

Similar (more successful) resistance was built to a freeway plan cutting through Chinatown in Vancouver (Pendakur, 1972; Ley et al., 1992). In sum, urban freeways destroy urban fabric and dislocate its inhabitants who are more often than not poor and face difficulties in securing new housing (Altshuler, 1965).

Once the urban freeways are built, they may discourage people to live in surrounding areas due to factors such as increased noise, and worsening air quality. Thus, as freeways are constructed, people would move out of the neighbourhood adding to the lowering of population density, as evidenced by Baum-Snow (2007). In addition to the nuisance aspect of freeways, the noise and air pollution caused by the automobile traffic of the freeway degrades the quality of life (Newman & Kenworthy, 1999; Altshuler, 1965).

2.5 Structure of Canadian Cities

Various studies explore the extent to which the concept of monocentric city is applicable to Canadian cities, and results vary depending on the context and the cities studied. Shearmur et al. (2007) concluded that metropolitan areas of Montreal, Toronto and Vancouver are polycentric (or "polynucleated"), although with higher concentration of employment in a small number of centers. Another study on the same cities by Shearmur and Hutton (2010) noted that the employment is concentrated in more or less strong centers followed by fewer jobs in the surrounding areas in a "concentric" manner. Bunting et al. (2002) report that with the exception of Vancouver, Toronto, and Calgary (where a recentralisation trend is observed), Canadian cities have been losing their traditional centrality [also see Edmonston (1983)).

In a study of Quebec City metropolitan area, Vandersmissen et al. (2003) attribute increased commute times between 1977 and 1996 to the lack of monocentricity. In addition to reasons discussed above, sprawled metropolitan areas are more unsustainable because of the increased personal automobile use whether it be to commute in a monocentric or dispersed city situation (Filion et al., 1999).

It is important to note, however, that a consensus is found in the literature that Canadian cities are unlike their counterparts in the United States in many ways. Canadian cities are not as "scattered" or dispersed due to lower levels of urban sprawl, which is also evident in development patterns and employment growth (Schneider & Woodcock, 2007; Filion et al., 2004; Bunting et al., 2002; Edmonston et al., 1985). In addition, the per-capita investments in highways in Canada is considerably lower compared to that in United States (Condon, 2004).

2.6 Urban Freeways in Canada - a brief historical overview

Toronto's Queen Elizabeth Way (QEW) was the first "superhighway" (provincial road) of Canada (Stamp, 1987). It was gradually built starting in 1931 with the first segment opening in 1939. However, its extension to the east in the form of Gardiner Expressway, whose construction began in 1954-55 (and was functional in 1964) came to be the first multilane limited access freeway going through Toronto (Marshall, 2009; Lea et al., 1968; also see Guillet, 1966).

Freeways in the province of Quebec first appeared in the surroundings of Montreal (largest Canadian city up until 1970s) in late 1950s, when *Autoroute des*

Laurentides was constructed in 1958 in the northern part of Montreal. *Autoroute Metropolitain*, the TransCanada highway that passes through Montreal, started functioning in 1959 (Transport Québec, 2007; Lea et al., 1968).

Unlike Toronto and Montreal, Vancouver lacks inner-city freeways thanks to the public uproar against the proposal of a freeway network that was supposed to go through vital urban neighbourhoods. Upon major protests against neighbourhood deterioration which the freeway project would have brought about, the project was cancelled (Hayes, 2005; Ley et al., 1992; Goldberg & Mercer, 1986). The Granville Street Bridge is the "only freeway-style highway" to be ever built in downtown Vancouver; the bridge had eight lanes and opened in 1954, however the idea of downtown freeways was finally dropped after almost twenty years (Hayes, 2005, p. 144). The Trans-Canada Highway (opened in late 1950s) and its northern sections, Upper Levels freeway that exists today circumvents the central city of Vancouver (North and Hardwick, 1992). Other major Canadian cities did not have urban freeways up until the early 1960's.

2.7 Conclusion

A review of the literature has shown that freeways contribute to low density development (sprawl) as well as their resulting environmental and social impacts. In the United States, a third of the decline in aggregate central city population can be attributed to freeways (Baum-Snow, 2007). An extensive study testing the impact of freeways on population in central cities has not been conducted in Canada, where considerable differences are found between cities in terms of trajectories of population growth or decline. Although a few studies point to freeways playing a role in reduction of central city population, much of the variation in population/population densities have been attributed to regional planning and land use policies. To what extent might this variation be due to freeways is not yet investigated.

The following thesis seeks to contribute to the current body of knowledge by analysing changes in population density and its relationship to the freeways in the inner-cities of eight Canadian cities. This research also adds to the debate over the reasons for decline in central city populations.

3 RESEARCH METHODS

3.1 Study period and regions

A study period needed to be defined before selecting study areas. Since the objective of the research was to compare the population density from the pre-freeway period and present, and almost no urban freeways were constructed until the mid to late 1950s, the 1950s was chosen as the starting point.

Eight Canadian cities, Quebec City, Montreal, Ottawa, Toronto, Winnipeg, Edmonton, Vancouver and Victoria were chosen because they were some of the largest cities in 1956 and because the *Atlas of Canada* (Government of Canada, 1957) contained land use maps for all these cities (and only for these cities; for maps see Appendix 1 - Land-use maps used to define inner-city), which included land-use classification that seemed to be consistently done enabling an unambiguous definition of inner-city (further elaborated later). Other maps from the same time frame were available (a number of days were spent in cartographic libraries to find historic maps for all the census metropolitan areas of Canada) but none seemed consistent nor were from the same source.

The year 1956 was chosen to match the year of the land use maps and because it is a census year. Thus the study compares the population density between 1956 and 2006, that is over a 50-year period.

In 1956, the eight cities with the highest metropolitan population from largest to smallest were: Montreal, Toronto, Vancouver, Winnipeg, Ottawa, Hamilton, Quebec City and Edmonton (Statistics Canada, 1956a). Of these cities, the current study includes all but Hamilton, which was left out because of a lack of availability of land use maps.

Victoria was the thirteenth largest city (Statistics Canada, 1956a), yet it is included in the study because it was an interesting case in terms of freeway (non) provision, and because there were land use maps available from the *Atlas of Canada*. Calgary and Halifax (at 9th and 11th position respectively in 1956) were two other interesting cities that could have been included in the study. A lack of maps from the 1950s with consistent land use classification (as discussed above) inhibited their inclusion, however.

Since the cities included in the study are carefully selected, they are not a random nor a representative sample, thus they do not approximate a larger population; any conclusions made would apply to the population itself, that is, to cities included in the study themselves.

Although the present study includes years before and after the urban freeway construction, the before-after-control-impact (BACI) design was not adopted for several reasons. The BACI is a research design that allows for assessing the impact (I) of an intervention such as a road construction before (B) and after (A) the intervention, while facilitating its assessment and arriving at an inference by comparing the impacted sites with control (C) sites that did not receive the intervention or that were not affected by it. The BACI is used to study various interventions such as in medicine for assessing the effect of new medication. In environmental impact studies, BACI has been used to assess human impacts on the environment (Roedenbeck et al., 2007; Gotelli and Ellison, 2013).

The BACI can be used in a manipulative study – forward-looking, where the study is started before the intervention and data is collected several times before and after the intervention -- or in a non-manipulative study, which is retrospective, in which case the availability of data from before the intervention could be limited (Roedenbeck et al., 2007). Additionally control sites would need to be selected carefully, as "the control locations […] must be a representative sample of places of the same general habitat as that in which the impact is expected" (Underwood, 1994, p. 5).

The present study is non-manipulative (that is, retrospective) and only a limited amount of data was available from 1956. The study explores how density has changed between 1956, before the prevalence of urban freeways, and 2006 while the construction of freeways occurred at various times during this fifty year period (Table 6). The research mainly investigates the relationship between the change in density and the distance to closest freeway. The present thesis was thus a before and after study and without controls.

The control site selection for a study such as the present one would be difficult as factors other than freeways that influence density such as land use and other policies, topography, the built environment in the control site would have to be comparable with the impacted site throughout the fifty-year period (Roedenbeck et al., 2007). Also, at least in Canada, no cities can be found without freeways near the major city centres. Vancouver and Winnipeg are the closest to this requirement where freeways are further from the inner city and were included in the study.

3.2 Inner-city definition

The physical forms of the areas close to the centre were all established prior to the freeway era and mass automobile ownership. Thus, a first step was to identify the pre-automobile, pre-freeway "inner-city" to measure population change and the relationship of that change with freeways.

Various definitions have been used to delineate inner-city from the rest of the city and from the suburban areas (see Table 2). For the purpose of the present research to study changes in population density which is closely related to land-use, the inner-city is defined as the commercial core and the surrounding inner residential area (Turcotte, 2008; Triggs, 2007; Ley & Frost, 2006). Administrative boundaries of the central municipality of the census metropolitan area were not used, unlike Baum-Snow (2007), because some Canadian municipalities were larger than others and some included agricultural land (Turcotte, 2008). Therefore, such a research design would not necessarily have compared the change in population in an area with similar base-line land use.

The commercial and inner residential areas were defined using the land use classification from 1956 (for some cities 1955) found in the *Atlas of Canada* land use maps (Figure 9). The inner-city census tracts were visually identified based on the commercial or mixed use land and the ring of exclusively or almost exclusively residential census tracts sharing a border or a vertex with the commercial/mixed use census tracts (see Triggs, 2007). Contiguous commercial activity in residential census tracts extended the inner residential area. Great care was taken to ensure that the same criteria were applied in each of the 8 cases. Table 4 lists the criteria used.

This delineation of the inner-city under study was kept constant even if the site of the commercial core or its size changed during the period of the study, referred to as constant geography (also see Baum-Snow 2007). Therefore, the study compares the population density in 1956 inner-city with the population density in 2006 in the constant geography of 1956. Relevant maps are included in Appendix 2.

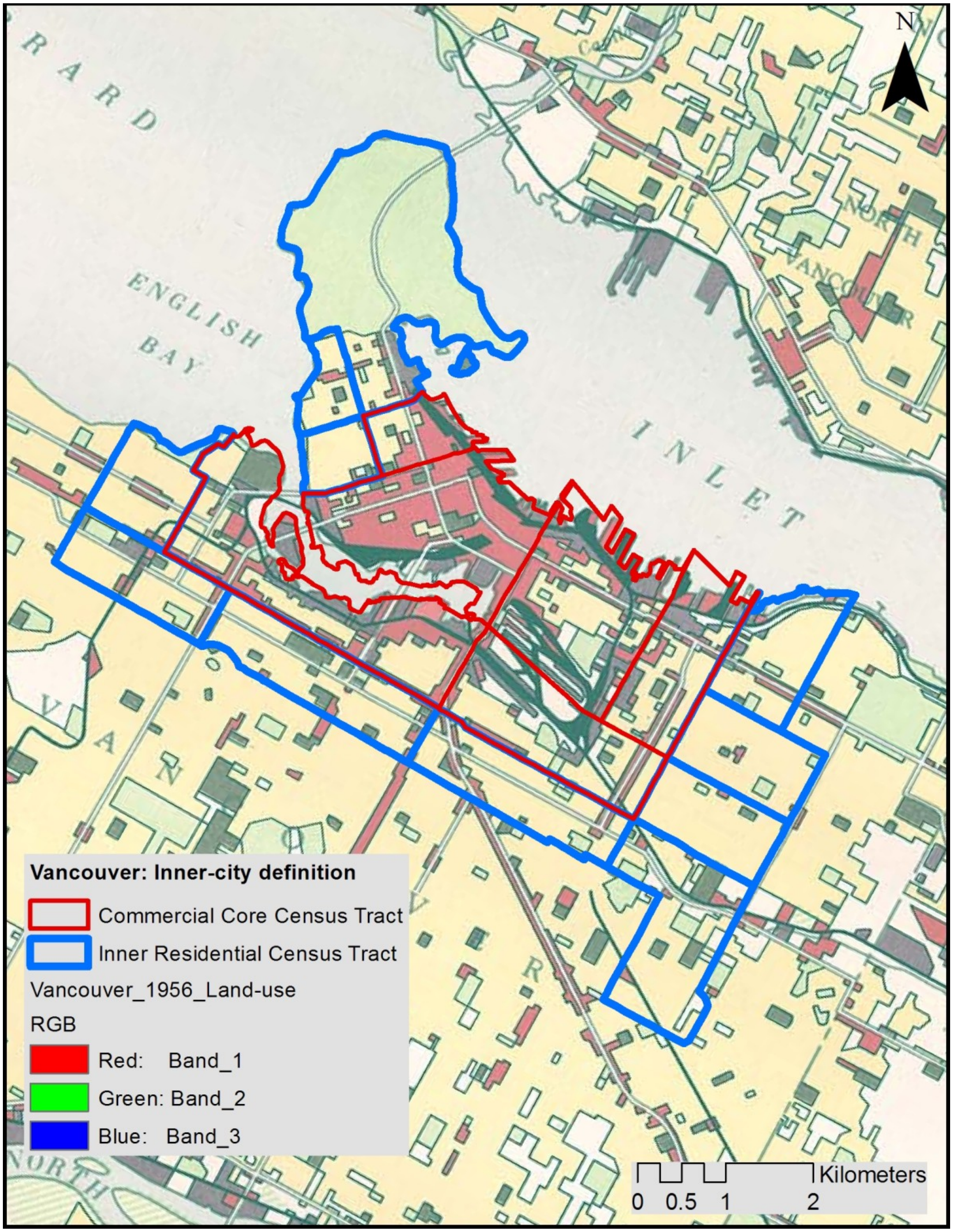

Figure 9. Vancouver: Inner-city definition

Table 4. Inner-city definition - Commercial core and inner residential definition criteria

Area type	Definition
Commercial Core (CC)	a) 40% rule – if almost half of the census tract (CT) is commercial, then the tract is considered commercial core; b) In port cities (Montreal, Quebec and Toronto), the commercial yards are considered commercial activity, thus included in commercial core category (as per rule (a)); c) If one (or more) census tract is enclosed by two CC tracts, then the one in the middle is also considered CC (e.g. Montreal, 1956 CT 121 and 122).
Inner Residential (IR)	d) Census tracts immediately surrounding the commercial core (sharing a boundary or a vertex) that are marked residential are considered inner residential; IR is one census tract thick (one census tract around CC); e) Normally IR is only one census tract thick, but if there is some commercial activity in census tracts around those identified in (d) and is contiguous from the core, the census tract is considered part of IR; f) If a CT is enclosed by two IR, then the one in the middle is also considered IR (e.g. Ottawa, 1956 CT 22).

3.3 Study unit

The census tract[10] was the unit of study and a total of 205 census tracts were included from eight cities. A detailed breakdown by city is found in Table 5.

Table 5. Number of census tracts included in the study - summary

	Number of census tracts		
City	**Commercial Core (CC)**	**Inner Residential (IR)**	**Total**
Quebec City	8	13	21
Montreal	29	39	68
Ottawa	2	12	14
Toronto	17	29	46
Winnipeg	5	15	20
Edmonton	3	13	16
Vancouver	4	8	12
Victoria	1	7	8
Grand Total	**69**	**136**	**205**

3.4 Freeways

3.4.1 Background information and various freeway definitions used

A freeway is defined as an expressway with controlled or restricted access, whereas an expressway is a "divided arterial highway for through traffic with full or partial control of access" (Urban Advisors to the Federal Highway Administrator, 1968, p. 136). The British Columbia provincial Digital Road Atlas (DRA) defines freeways as controlled access roads which are typically divided[11], while Desktop Mapping Technologies Inc (DMTI) CanMap road network defines expressways as usually having

[10] A census tract is a geographic area that is relatively small and stable and has a population of between 2,500 and 8,000. Similar socioeconomic conditions are sought at the time of creation of census tract so that homogeneity can be found as much as possible within a tract. More or less similar population size allows for meaningful data comparisons (Statistics Canada, 2012).

[11] Freeways are divided using intermittent barriers or by having a paved or unpaved, or some other means of dividing the opposing directional flows of traffic.

four lanes with very limited access to adjacent land uses (Setton et al., 2005). Google Maps and Google Earth follow extensive guidelines to identify freeways: "No crossroads, stops, or at-grade intersections; Accessible only through Ramps or Highway interchanges; A Freeway ends at the first intersection that allows non-ramp access to the road. Designate all segments before the crossroad as Freeway; Dual-carriage, split road; Minimum of 4 lanes; Walking or biking not allowed, except in rare cases such as California in the U.S. Minimum speed limits that are around 65 mph / 120 kph." (Google, 2011, Priority section).

3.4.2 Freeway definition

Based on the prevailing definitions, freeways, for the purposes of the current study, are defined as limited access high-speed roadways. Such roadways do not have intersections, thus access is provided only via limited entry and exit points. They lack signalized intersections that further increase travel speed. The term freeway is used in the present study for any roadways that meet the above definition, even if they are referred to by other names (expressway, highway and such) in different contexts. Table 6 details the freeways included in the current study. The DMTI classification of expressway fits the definition of freeway defined above for the freeways used in the present study, therefore DMTI spatial files were used to calculate the distance to freeway.

Table 6. Urban freeways included in the study

City	Freeways included in the study (as present in 2006)	Year of opening
Quebec City	Autoroute Charest	1962
	Autoroute Laurentienne	1963
	Autoroute Felix Leclerc	1972
	Autoroute Dufferin Montmorency	1976
Montreal	Autoroute Metropolitain	1959
	Autoroute Bonaventure	1967
	Autoroute Ville Marie	1972
Ottawa	Queensway	1962
	Autoroute de la Gatineau	1964
Toronto	Gardiner Expressway	1964
	Don Valley Parkway	1961-66
Winnipeg	Perimeter Highway (parts)	1955
	Transcanada Highway	1962
Edmonton	Yellowhead highway	1970
	Sherwood Park Freeway NW	Post-1970
	Highway 216	Post-1970
	Whitemud Dr. NW (city)	Post-1970
Vancouver	Trans-Canada Highway (highway 1)	Late 1950s
	Upper Levels Highway (this is a newer segment of the same freeway as above, highway 1)	1975
Victoria	Patricia Bay Highway	1960
	Island Highway	1966

Sources: Montreal, Quebec City & Ottawa: Transport Québec (2007) and Lea et al. (1968); Toronto: Marshall (2009), Lea et al. (1968) and Ministry of Transportation, Ontario (2009); Winnipeg: Lea et al. (1968); Edmonton: Transport Canada (2010) and Alberta Transportation (2011); some freeways included for Edmonton were opened in parts and the latest were opened before 2000. Vancouver: Hayes (2005), Lea et al. (1968) and North and Hardwick (1992); Victoria: Lea et al. (1968); (Some of the years of opening are from Wikipedia and other websites; Freeway names are as indicated in DMTI network shape files used for the study).

3.4.3 Freeways included in the study

Table 6 does not list all the existing freeways in the named cities. Instead, it lists the freeways that passed through or were close to the inner-cities and were therefore included in the present study. While freeways in Winnipeg, Edmonton, Vancouver and

Victoria did not enter or go through the inner city, in the rest of the cities, a couple of freeways penetrate or go across the inner-city while others remain in the periphery. In Quebec City, two out of four freeways -- Autoroute Laurentienne and Autoroute Dufferin Montmorency -- enter the inner-city. Autoroute Bonaventure and Autoroute Ville Marie enter the inner city of Montreal, while Autoroute Metropolitain remains outside the inner-city. Both the freeways included in the study for Ottawa enter the inner-city although the Queensway also passes through it. In Toronto, the two freeways included in the study together go across the city (Figure 10; see appendix 2p to 2w for maps of all the cities).

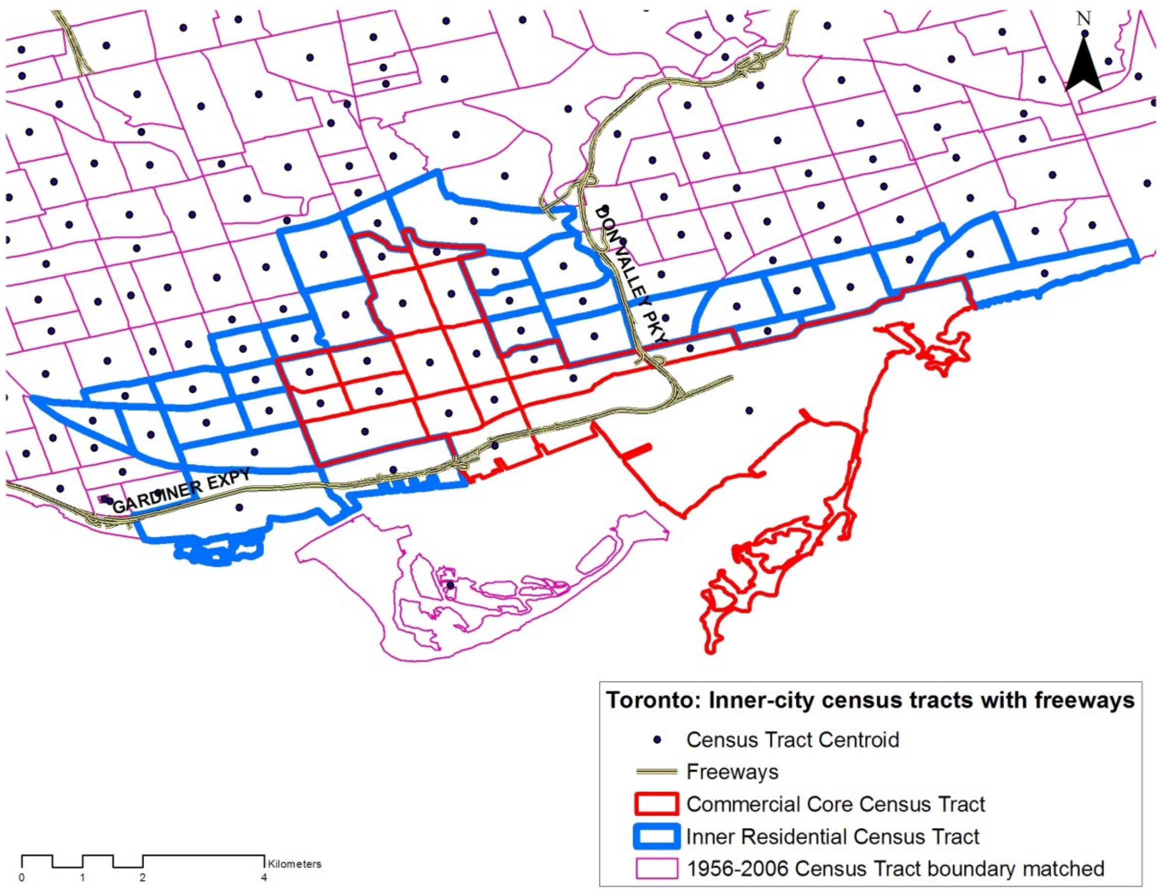

Figure 10. Toronto: Inner-city census tracts with freeways

3.5 Data sources

Population counts were obtained from 1956 and 2006 censuses carried out by Statistics Canada (1956b to 1956i; 2006a). 1956 census information was available only in hard copy therefore the relevant data was transcribed; 2006 Census data was obtained in electronic form. The shape files (ArcGIS format) for census tracts boundaries and water bodies were obtained from Statistics Canada (2006b). The shape files (ArcGIS format) for freeways (also cross-checked with Google Maps), parks and additional data on water were obtained from Desktop Mapping Technologies Inc (DMTI), a recognized geospatial data provider (DMTI Spatial, 2006).

3.6 Distance to closest freeway calculation

Although the study is inspired by Baum-Snow (2007) the measure of the freeways differs between Baum-Snow's study and this one. As mentioned earlier, in 1947 the US federal authorities planned a web of inter-state freeways connecting the population centers, which was not the case in Canada. In the present study, which is much smaller in scope, only four of the eight cities included in the study had freeways entering or passing through the inner-city. The approach of distance to closest freeway was, therefore, adopted for this research. Only the freeways closest to the centroid of a census tract are therefore used in the study (Table 6).

The distance to the closest freeway was measured from the centroid of a census tract to the closest freeway (as present in 2006) using a straight line distance (also see Funderburg et al., 2010) using Analysis tool (Near) in ArcGIS.

3.7 Population density calculation

Population density, defined as population living within a given boundary divided by its area, was calculated for the years 1956 and 2006. Since the 1956 census tracts boundaries were not available in electronic format, Georeferencing in ArcGIS was used to digitize the hard copy maps. The digital 2006 census tract boundaries were then compared with digitized maps of 1956 boundaries; some 2006 census tracts were merged to match the 1956 boundaries, so that the same land areas could be compared. Therefore, the area used for calculation of densities in 1956 and 2006 is the same (i.e., land area from 2006) (see Figure 11; Appendix 2h to 2o for maps of all cities).

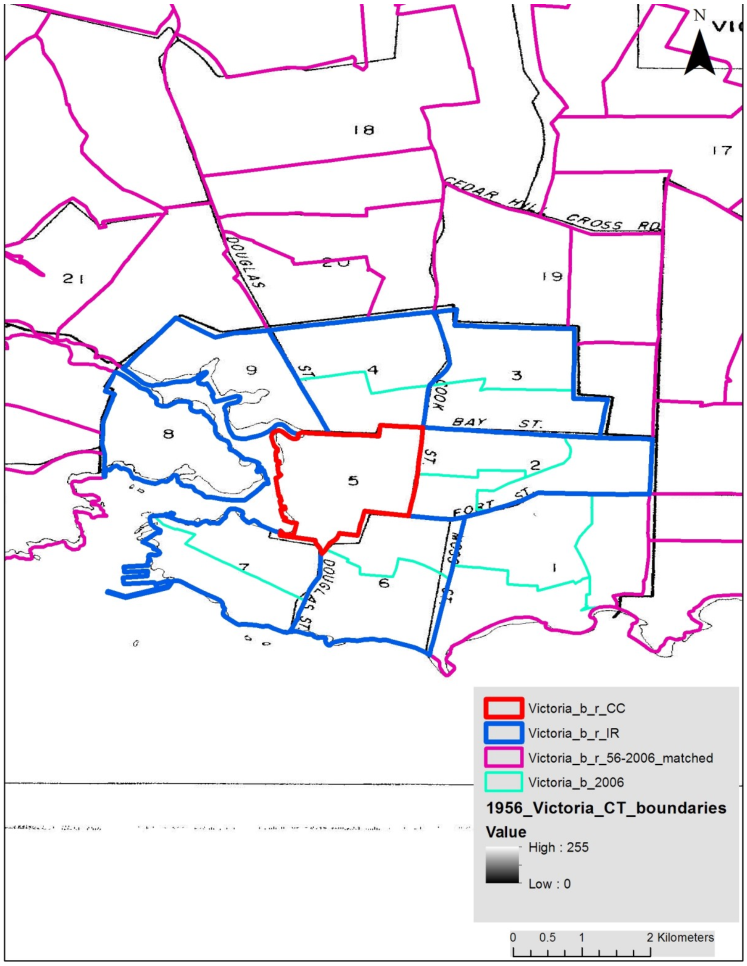

Figure 11. Victoria: 1956 and 2006 census tract boundary matching

Note: Victoria_b_2006 is the 2006 boundary; all other boundaries are the matched boundaries between 1956 and 2006.

Inland water bodies, and parks larger than 10 hectares were removed from the area of the census tracts before calculating the density because they artificially lower density figures (as it was land which could not be built upon in general). Since this research is focused on comparing densities, it was important to take this step in the density calculation. The areas of parks and water bodies were calculated using land use information of 2006.

For cities where highways penetrate the inner-city, it is debatable as to whether the area used by freeways should be excluded from the density calculation. First, calculation of the exact space taken up by freeways is technically very difficult: the number of lanes need to be considered as well as changing number of lanes within a given freeway. An approximation could possibly be made based on approximate length, however. Second, since urban freeways were hardly present in 1956, removal of the area taken up by freeways, as they are in 2006, would inflate the density calculation for 1956 to some extent. Besides, if people were expropriated and houses or entire neighbourhoods were destroyed due to the space taken up by freeways, the effect of freeways would then be reflected, at least to some extent, in the loss in density. For these reasons, the land area taken up by freeways was not removed from the density calculation.

3.8 Statistical analysis

Linear regression was used for the statistical analysis where the response (or dependent) variable was the loss in population density from 1956 to 2006. While absolute loss was used for most of the analysis, relative loss was also employed. Two explanatory (or independent) variables were used: Distance to closest freeway (DCF) and population density in 1956 (PD56).

Variance partitioning, more precisely, commonality analysis was used to partition the variation in the response variable (as calculated by the multiple R^2) among the two explanatory variables (Reichwein Zientek & Thompson, 2006). Variance partitioning allows for interpretation of results when using a multiple regression model by separating the unique (U) and shared (S) (also referred to as intersecting, common or joint) contributions of each of the two explanatory variables. The following formula was used:

$$R^2_{(DCF + PD56)} = U_{DCF} + U_{PD56} + S_{DCF \text{ and } PD56}$$

where:

$S_{\text{DCF and PD56}} = R^2_{(\text{DCF only})} + R^2_{(\text{PD56 only})} - R^2_{(\text{DCF + PD56})}$;

$U_{\text{DCF}} = R^2_{(\text{DCF only})} - S_{\text{DCF and PD56}}$, and

$U_{\text{PD56}} = R^2_{(\text{PD56 only})} - S_{\text{DCF and PD56}}$

Variance partitioning, also referred to as hierarchical partitioning, is considered informative only for predictive or experimental research, as it can allow variable selection based on the unique contribution of a variable. The method is criticized when used in explanatory or causal research, as the level of importance given to the variables by the method can be misleading (Pedhazur, 1982).

Two approaches to variance partitioning can be found: incremental variance partitioning and commonality analysis (CA). The former is criticized when used in a causal model (the increments and the controlling of variables are both criticized). The present research uses the latter, the CA approach, therefore further discussion here will focus for the most part on this approach.

The main points of criticism of variance partitioning in general is its excessive reliance on R^2 , and that the method cannot be relied upon in the presence of multicolinearity -- a high correlation between the predictor (or explanatory) variables. The heavy dependence on R^2 poses a problem because two models can have the same or similar R^2 but the regression equation may not be the same, therefore use of only the R^2 ignores the nature of relationship between the variables.

CA is used to identify unique and common effects of variables in a multiple regression scenario. Multicolinearity between two (or more) variables pose a problem mainly because it could increase the shared (or common) contribution, thus lowering the unique component leading one to erroneously conclude that such a variable is not important. Whether the joint effect is a result of multicolinearity or simply due to the two or more variables being able to explain the variability of the dependent (or response) variable is confounded (Pedhazur, 1982).

The criticism is also related to the problem associated with unique contribution as the uniqueness of a variable depends on the variables present in the model. Any addition or removal of variables changes this uniqueness by varying degrees. It would be better to employ the term usefulness here, as the (unique) component shows the usefulness (rather than uniqueness) of a variable in estimating the dependent variable (Pedhazur, 1982).

Another problem is the negative shared component, which shows up from time to time when a majority of the relationships between the two predictor variables suppress each other. Other reasons for the presence of negative shared component include large variability in the data, presence of outliers and a mix of positive and negative correlations between the independent variables (Chevan & Sutherland, 1991; Pedhazur, 1982).

Variance partitioning, however "is potentially useful in exploring multivariate relationships both within one set of data and between similar sets of data" (Chevan & Sutherland, 1991, p.94). While taking the criticism into consideration, commonality analysis is used in the present study to explore the results and to ascertain the usefulness of the variables included. It is also employed to observe the relationships in a given model (of a city) and between similar models, i.e., comparing results between various cities.

The unit of analysis was a census tract, and a total of 205 census tracts were included in the study. From this point forward, the terms population density is referred to as density, and distance to closest freeway as distance to freeway.

4 RESULTS

This chapter presents the results of the analysis of loss or gain in population densities between 1956 and 2006 in eight Canadian cities[12]. This includes aggregate summaries at the city level. Results of linear regression between loss in population density over the fifty-year period and a) distance to freeway, and b) population density in 1956 follow. These tests were conducted for all the cities together (all the census tracts included in the study) as well as individually for eight cities. The section that follows presents the results of the relationship between loss in density and distance to freeway at different levels of density in 1956. The last section presents the results of multiple regression with distance to freeway as the response variable and loss in density and density in 1956 as explanatory variables.

[12] The analysis of the densities and whether they are "high" or "low" are relative to the cities included in the study and to the figures calculated by the present study, unless otherwise specified.

4.1 Absolute losses in density

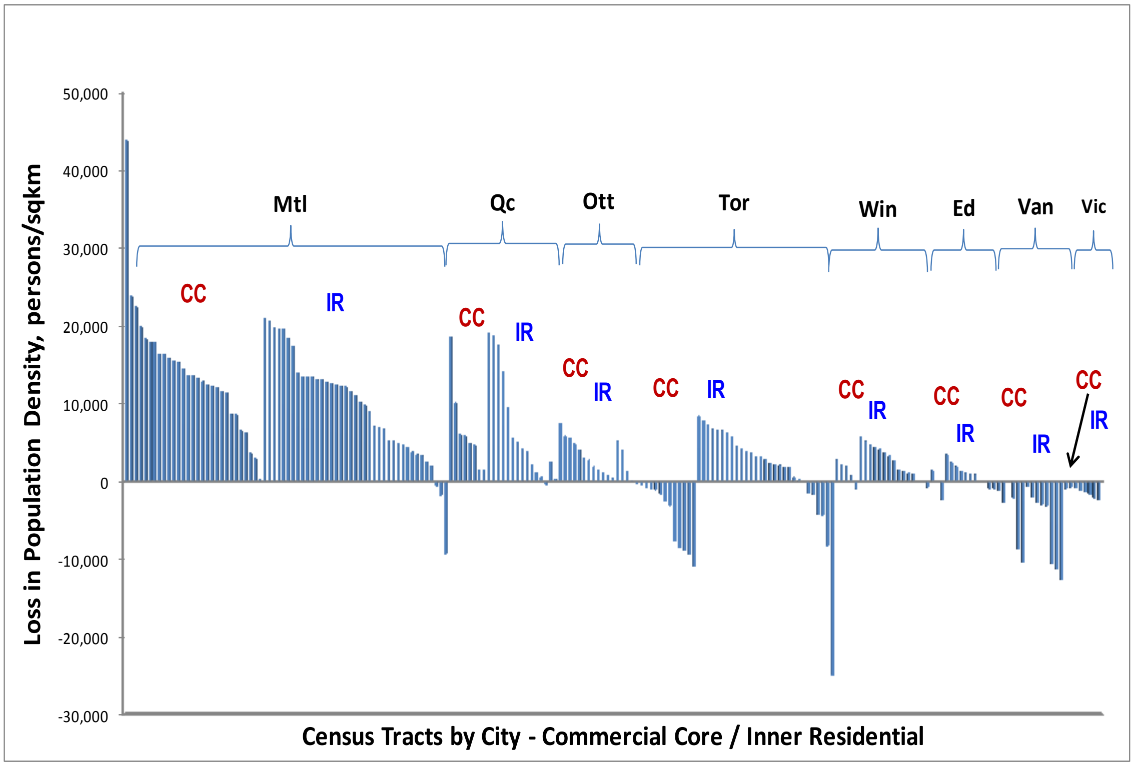

Figure 12. Absolute losses in density between 1956 and 2006 in the eight cities.

Note: The plot is separated by cities, then by Commercial Core (CC) and Inner Residential (IR) in descending order of loss within each category of CC and IR. (Mtl = Montreal, Qc = Quebec City, Ott = Ottawa, Tor = Toronto, Win = Winnipeg, Ed = Edmonton, Van = Vancouver, Vic = Victoria).

Seventy-four percent of all inner-city census tracts in the eight cities combined lost density (152 out of 205) (Figure 12). Higher losses were found in Montreal and Quebec City, followed by those in Toronto. While most inner-city census tracts in Toronto lost density, nearly all of those located in the commercial core and some in inner residential area gained (indicated by negative values for loss in density). On one hand, Vancouver experienced only gains in density (except for slight loss in one commercial core census tract) as well as Victoria although the sizes of gains were smaller than Vancouver. On the other hand, all census tracts of Ottawa lost density (Figure 13; Appendix 3a). The highest loss (of over 43,000 persons/km^2) was in a census tract of

Montreal and the highest gain (of over 25,000 persons/km^2) occurred in Toronto's inner-city.

Appendix 3b includes the graph of level of density per census tract for all the tracts for both 1956 and 2006, and Appendix 4 contains density diagrams for both the years for all the cities.

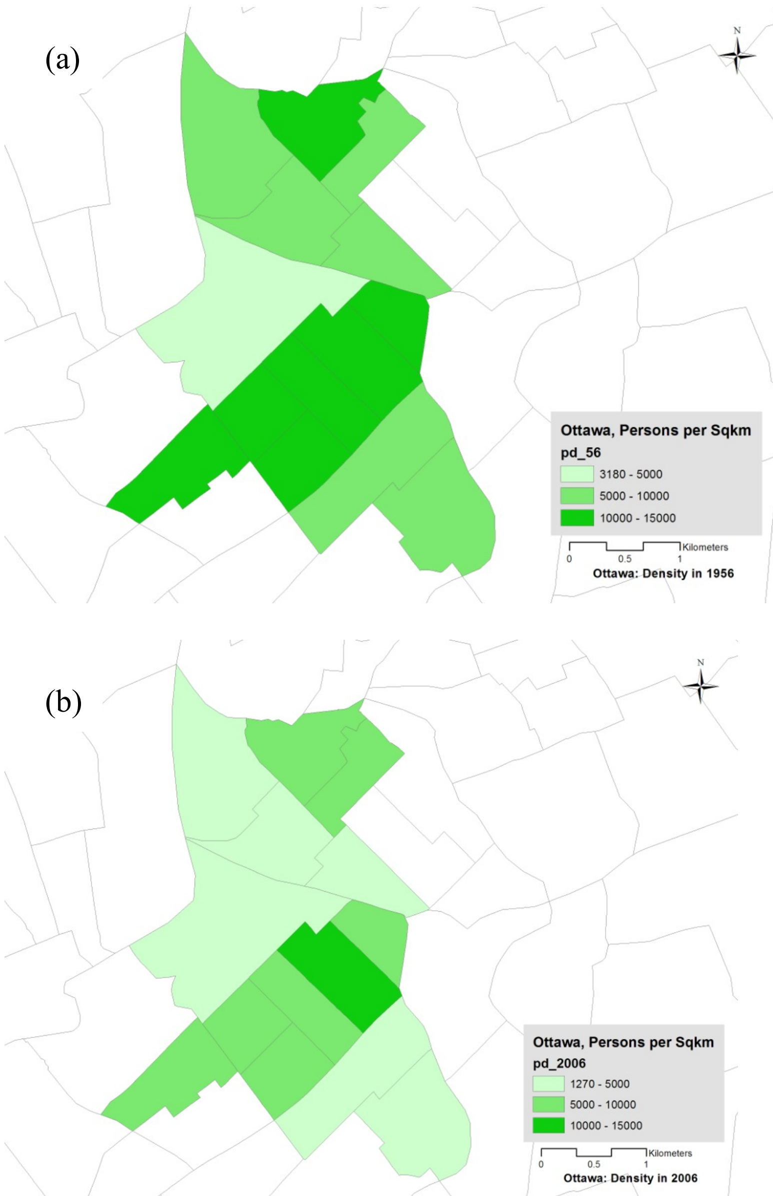

Figure 13. Population Density in Ottawa Inner-City. (a) 1956; (b) 2006

Loss in density is not significantly different in commercial core (CC) than in inner residential (IR) census tracts. A Student's t-test was used to confirm the difference (or not) between these two sets of census tracts, although the data in the present analysis is not a sample. The t-test for all cities together comparing the means of losses in density in commercial core and inner residential census tracts indicated no differences at a significance level of 0.05. The t-tests at the city level indicated the same result, except for Toronto and Montreal where with a significance level of 0.05 the loss in density in the two sets of census tracts was not the same (p = 0.0213 for Toronto, 0.0137 for Montreal).

For all the census tracts together mean loss in density in CC is 5,817 persons/km^2 and that in IR is 4,065 persons/km^2. Similar levels of differences are found for individual cities except for Toronto, where mean loss in density in CC is -2,713 persons/km^2 (negative value indicating a gain in density) and that of IR is 1,592 persons/km^2, and Montreal with mean loss of CC being 14,227 persons/km^2 and 9,730 persons/km^2 for IR.

4.1.1 Aggregate summaries

A loss in aggregate population density at the inner-city level (calculated as total population in inner-city divided by total area) is observed in four cities: Montreal, Quebec City, Ottawa and Winnipeg over the 50-year study period. In Toronto, the aggregate population density increased by a very small amount (9%), Edmonton remained pretty much the same, and Vancouver and Victoria saw gains in density (Figure 14). Density in the inner-city of Vancouver increased by 84% from 1956 to 2006 (Figure 14c) whereas the loss in density was highest in Montreal's inner-city (47%). The table of aggregate population and the aggregate population density is provided in Appendix 5 - Aggregate summaries.

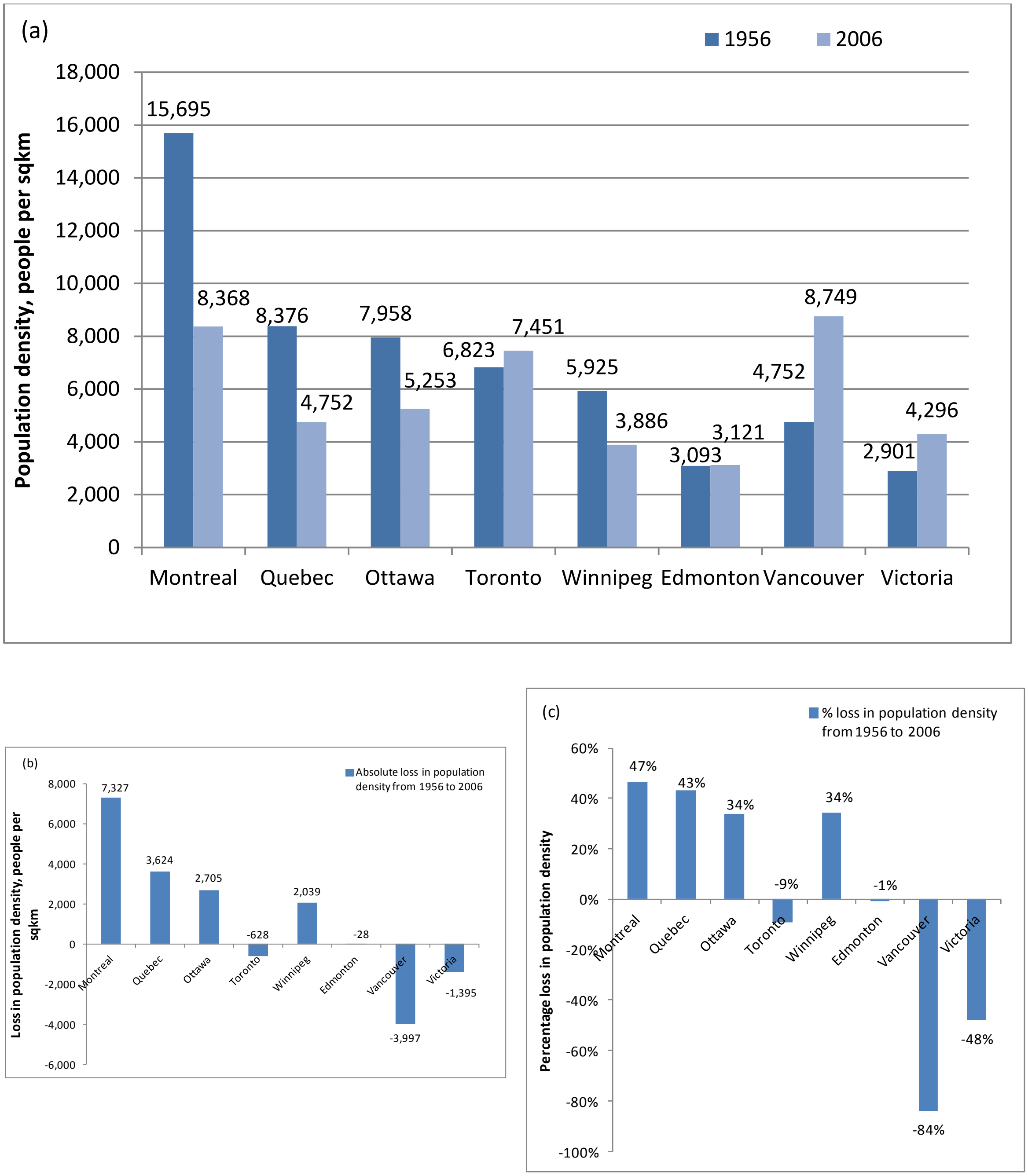

Figure 14. Aggregate population density in inner-cities

a) Inner-city population density in 1956 and 2006; b) Absolute loss in population density, from 1956 to 2006 in the inner-city. Negative numbers signify a gain; c) Percentage loss from1956 to 2006 (percentage values are rounded up for visual simplicity).

4.2 Relationship between Loss in density and Distance to freeway

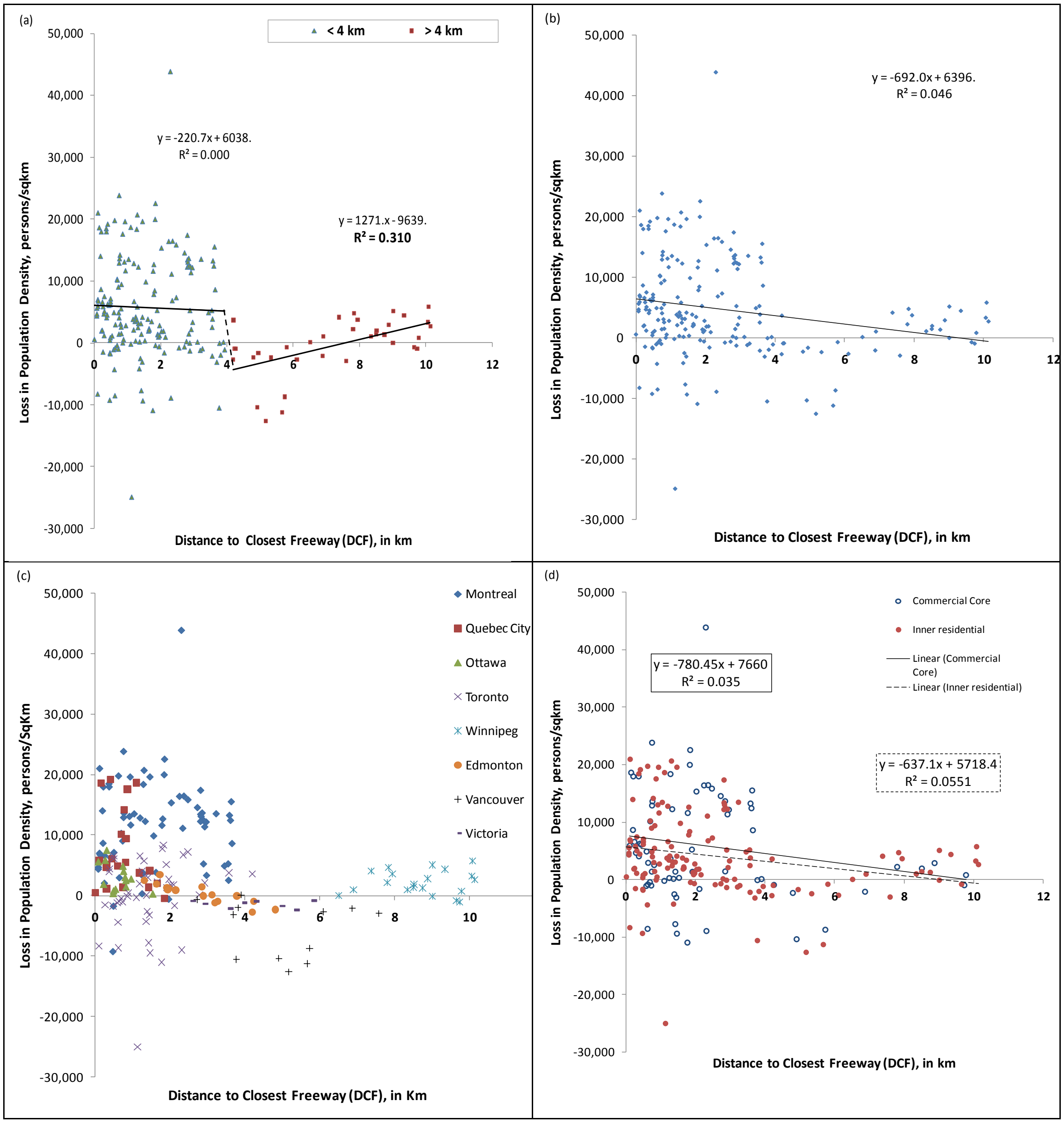

Figure 15. Absolute loss in density as a function of distance to freeway.

Note: Most important losses were seen within a 4 km distance from the freeways. a) A stepped function separates census tracts within 4km from the freeways and those beyond the 4km distance; b) Linear regression model of all the census tracts in the study; c) Cities identified; d) Commercial core and inner residential census tracts distinguished.

Census tracts located within a four-kilometre distance of the freeways have lost a greater amount of density than beyond this distance (Figure 15a and b). Thus the effect of freeways is strong up to 4 km. It is important to note that within the four kilometres of the freeway, the actual distance does not seem to matter – e.g., whether a census tract is one or three kilometre away from the freeway, high losses in density were experienced. Based on this visual observation, it is appropriate to study the census tracts that are within four kilometres and those beyond that distance separately using a stepped function (Figure 15a).

Table 7. Regression results for stepped function, both for DCF <= 4km and > 4km. Response variable: Loss in population density.

R-Squared and N	Variable	Coefficient	t-stat	p value	95% Confidence Interval	
					2.5%	**97.5%**
R^2 = 0.00 N = 170	Intercept	6036.1 persons/km^2	5.487	1.48E-07	3864.58 persons/km^2	8207.71 persons/km^2
	DCF <= 4km	-219.1 persons/km^3	-0.376	0.708	-1370.25 persons/km^3	932.12 persons/km^3
R^2 = 0.31 N = 35	Intercept	-9642 persons/km^2	-3.893	0.00046	-14680.87 persons/km^2	-4603.07 persons/km^2
	DCF > 4km	1271.6 persons/km^3	**3.858**	**0.0005**	601.09 persons/km^3	1942.15 persons/km^3

DCF: Distance to Freeway; N: Number of observations.

There was no correlation between loss in density and distance to freeway for census tracts that are within four kilometres from the freeway. The regression results in Table 7 (upper section) show that within four kilometres of freeway the variable distance to freeway was not statistically significant at 5% level ($p > 0.05$). However, it is important to note that the effect of freeways on density is equivalent within the four-kilometre distance where the losses are prominent and concentrated (Figure 15a). Some gains were also seen within the four-kilometre distance in a few census tracts, predominantly in Toronto. Overall, about 83% (170 out of 205) of the census tracts included in the study are found within the distance to freeway of four kilometres out of which 79% lost density.

A distinct trend is found among the census tracts located beyond four kilometres of the freeway, with a moderately strong R^2 of .31. A low p value ($p<0.05$; Table 7, lower section) indicates high significance level for the variable, distance to freeway greater than four kilometres. In this group of census tracts, gains were observed closer to freeways (between four and six kilometres) and moderate losses (in Winnipeg) further away from the freeway (Figure 15c). It should be noted that the positive slope (coefficient of 1272 persons/km^3) found in the group of census tracts beyond four kilometres is largely because Winnipeg census tracts lost density in almost every case. These tracts were far from the freeways (the freeway was far from the inner city), and therefore represent an exception as no other city in the study lost density beyond four kilometres or so from the freeways (Figure 15a and c).

Losses closer to freeways (within four kilometres) were found in Montreal, Quebec City, Ottawa, and to some extent in Toronto and Edmonton. While Toronto has seen large gains in density closer to freeways, Edmonton and Victoria have experienced moderate gains at a distance of four to six kilometres. At the same distance, Vancouver saw major gains. The inner-cities of Vancouver as well as Victoria, Edmonton and Winnipeg did not have a freeway going through them as opposed to Toronto, Montreal, Quebec City and Ottawa through which freeways pass at varying degrees.

A variation of Figure 15b -- relationship between loss in density and distance to freeway -- was also plotted for only those census tracts that experienced a loss. However the R^2 changes only by a negligible amount (for plots see Appendix 6 - Relationship between loss in density and distance to freeway - only for census tracts that experienced a loss.).

Commercial core and inner residential census tracts are also plotted separately (Figure 15d) with no visible difference between the two sets. The R^2 is also not very different -- 0.035 for commercial core and 0.055 for inner residential census tracts. Later sections include more on this.

4.2.1 Testing for Outliers:

The value of R^2 could potentially be improved without the outliers; therefore, tests for outliers were conducted to determine the presence of data points that may exert high influence. Outlier diagnostics was run using R for distance to freeway as explanatory variable and loss in density as the response variable.

Highest loss and gain in population density identified in the previous section (Section 4.1/Figure 15) were identified as outliers using Cook's D value (for plots see Appendix 7 - Testing for Outliers), and were removed to test if the results would differ. However, no real difference was found in the R^2 without the outliers (R^2 with all data = 0.046; R^2 without the outliers = 0.06).

4.2.2 Commercial core versus inner residential census tracts

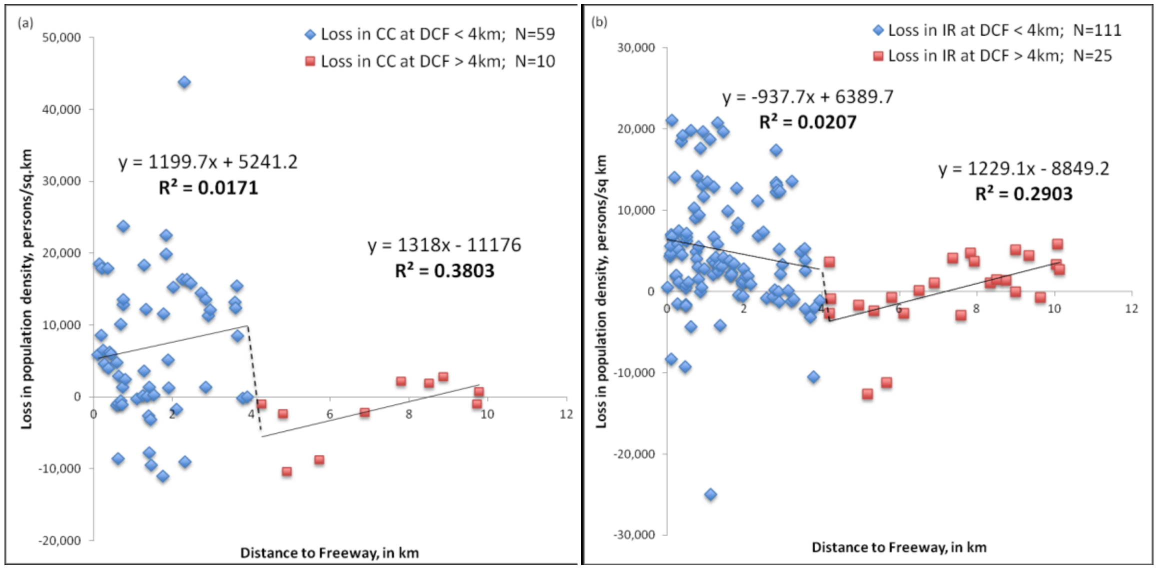

Figure 16. Stepped function separating census tracts within 4km from the freeways and those beyond the 4km distance for a) census tracts in commercial core; b) census tracts in inner residential part of the inner-city.

The two types of inner-city census tracts (commercial core and inner residential) lost (or gained) density somewhat equally (Figure 15d). A stepped function, separating census tracts at a distance to freeway of 4km, for commercial core and inner residential census tracts separately illustrates certain differences between the two groups (Figure 16).

The slopes of the two types of census tracts within 4km of freeways differ: for commercial core the slope is positive whereas for the inner residential census tracts it is negative (Figure 16 a & b, left segment). The negative slope in the latter case indicates that the losses in density are smaller in magnitude near the 4km mark: for IR it is 2,639 persons/km^2 and 10,040 persons/km^2 for CC[13].

At a distance to freeway further than four kilometres, both commercial core and inner residential census tracts show a trend (R^2 = .38, and .29 respectively; Figure 16a and b, right segments). The trend is similar to that seen for all the census tracts (see

[13] Calculated using the equation, see Figure 12: CC = 1199.7*4 + 5241.2; IR = -937.7*4 + 6389.7.

Figure 15a). Even though the commercial core census tracts beyond the 4km distance to freeway correlate more with the loss in density than the inner residential ones (R^2 of .38 versus .29) the two R^2 are not very different. The R^2 is very similar for the census tracts within 4km of the freeways for both commercial core and inner residential areas (0.017 and 0.02) (Figure 16 a & b, left segment).

Thus based on the above results and those in previous sections (that is, for a majority of cities under study the two groups of census tracts were not very different), the data from both groups are pooled in the following analyses.

4.3 Relationship between Loss in Density and Density in 1956

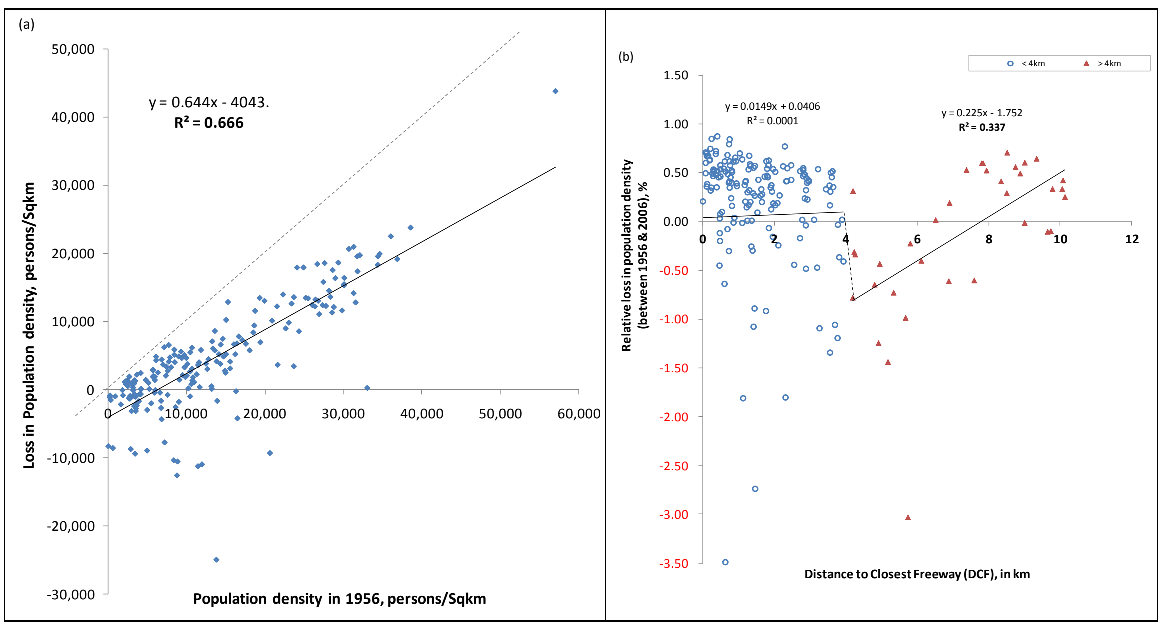

Figure 17. a) Absolute loss in density as a function of density in 1956 showing a positive relationship between the density in 1956 and the loss experienced from 1956 to 2006; b) Stepped function: of the relative loss in density as a function of distance to freeway; note: graph (b) cuts the y-axis at RLPD = -4 to provide a better visual for the majority of the losses.

The positive slope of loss in density as a function of density in 1956 (Figure 17a) indicates that the areas with higher density in 1956 lost more population than other areas over the study period. The dashed line in the figure represents 100% loss (slope = 1) indicating the highest possible loss in any given census tract in the density. Thus no data points can be higher than the dashed line.

To better consider the effect of initial density in 1956, which is reflected in the relative loss in density, distance to freeway as a function of relative loss in density was plotted (Figure 17b). The results are similar to those for the absolute losses in density: census tracts at or below four kilometres distance experienced higher relative losses irrespective of their location within the four kilometre range; beyond this distance, a clear positive trend in the relative loss in density is found, with R^2 of .337, reinforcing the findings of section 4.2.

Highest relative losses (or gains in case of negative values) in population density are seen in Toronto (-349% and -14%); While the graph above (Figure 17b) is drawn without the outlier -349%, the other high relative losses are not shown in the plot area to make the plot more readable (for plots with all data points, see Appendix 8 - Relative loss in population density and distance to freeway). Point to note here is that no real difference in R^2 is observed for all the data points without the outlier ($R^2 = 0.004$) and with it ($R^2 = 0.00005$).

4.4 Individual cities

Variations between cities are prominent both in terms of the loss in density and its relationship to distance to freeway (sections 4.1 and 4.2). Therefore, this section presents a closer look into relationships at the city level.

4.4.1 Relationship between Loss in Density and Distance to Freeway

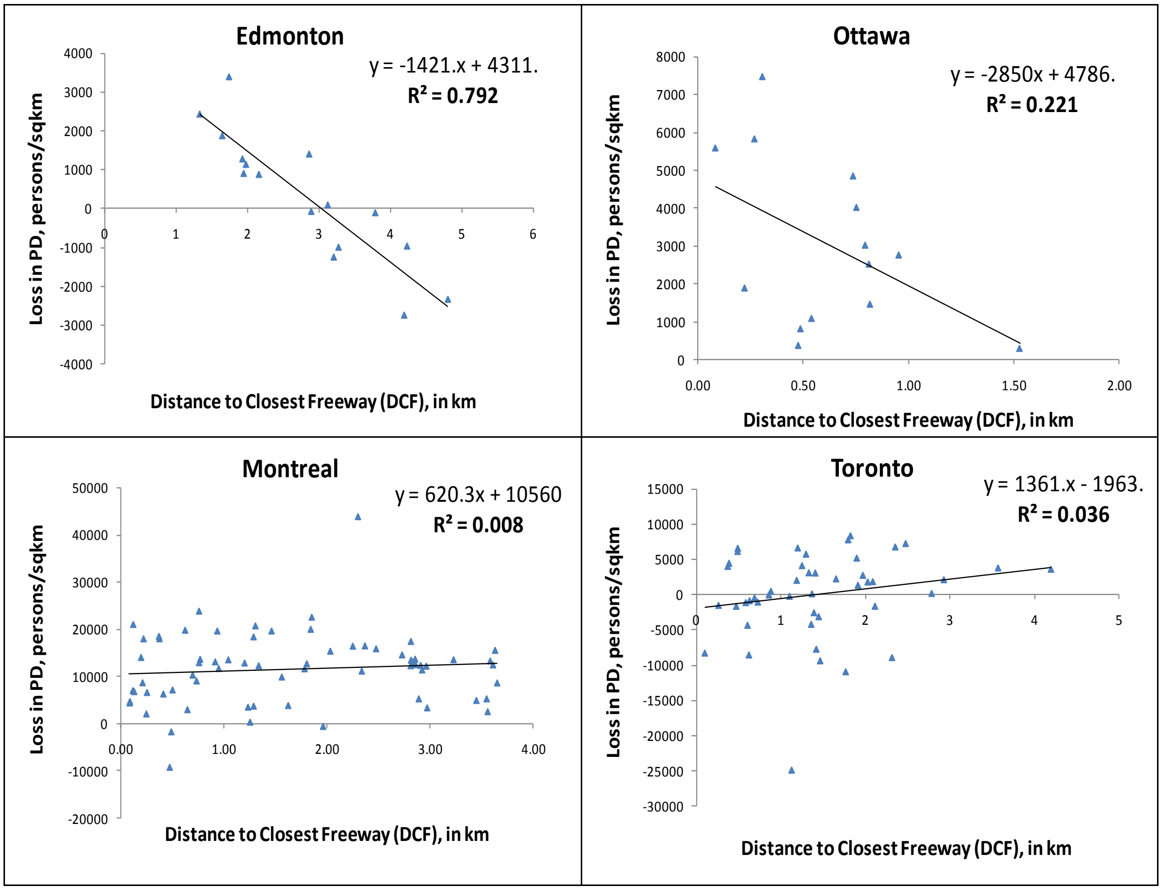

Figure 18. Relationship between loss in density and distance to freeway in individual cities.

Edmonton exhibits the highest correlation between loss in density and distance to freeways among the eight cities with an R^2 of .79 (Figure 18). Census tracts closer to freeways experienced losses and those further away from the freeways saw gains in density. Here, the breakpoint between losses and gains is at three kilometres distance from the freeway.

Ottawa shows a moderate relationship between the two variables with an R^2 of .22. All census tracts included in Ottawa were within approximately 1.5 km of a freeway, and lost density. Montreal and Toronto, although exhibiting almost no relationship with distance to freeway, are interesting with respect to the spread of the loss in density.

Montreal experienced losses in almost all inner-city census tracts, with losses scattered within four kilometres distance. While about half of the census tracts saw losses in Toronto, others experienced major gains within a distance of 2.5 km from the freeways. The rest of the cities do not individually display a close relationship between the two variables (for plots see Appendix 9 - Individual Cities - LPD vs. DCF).

4.4.1.1 Commercial core versus inner residential census tracts

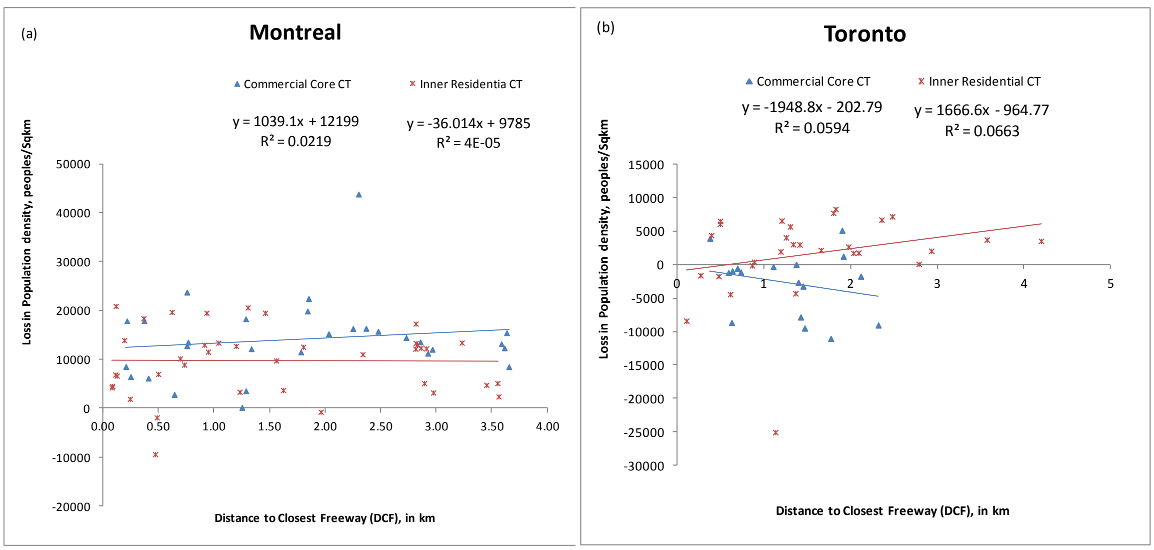

Figure 19. Relationship between loss in density and distance to freeway - Commercial core and inner residential census tracts separated for a) Montreal, and b) Toronto

The means of losses in density (section 4.1) for commercial core and inner residential census tracts were different for Montreal and Toronto, hence the relationship between loss in density and distance to freeway was plotted separately for these two cities. While the spread of loss in density across the distance to freeway is almost uniform in Montreal, the intercept and the coefficient of distance to freeway (slope) is slightly higher in commercial core than in inner residential census tracts (Figure 19). In Toronto, the commercial core census tracts almost all gained in density and those in inner residential area lost. Although R^2 isn't very different between the two groups of Toronto

(0.06 for CC and 0.07 for IR) the opposite direction of the slopes (negative for CC tracts, resulting from the overwhelming gains, and positive for IR tracts from predominant losses) is worth noting. In commercial core, more gains are observed as one moves away from freeways (up to approx. 2.5km), and inner residential census tracts exhibit losses at a distance further than those seen in commercial core (just over 4km).

4.4.1.2 Testing for outliers

Since both Montreal and Toronto exhibited outliers, the relationship between loss in density and distance to freeway was plotted without the outliers. The difference in R^2, however, was negligible (for plots see Appendix 10 - Testing for outliers at City Level).

4.4.2 Relationship between Loss in Density and Density in 1956

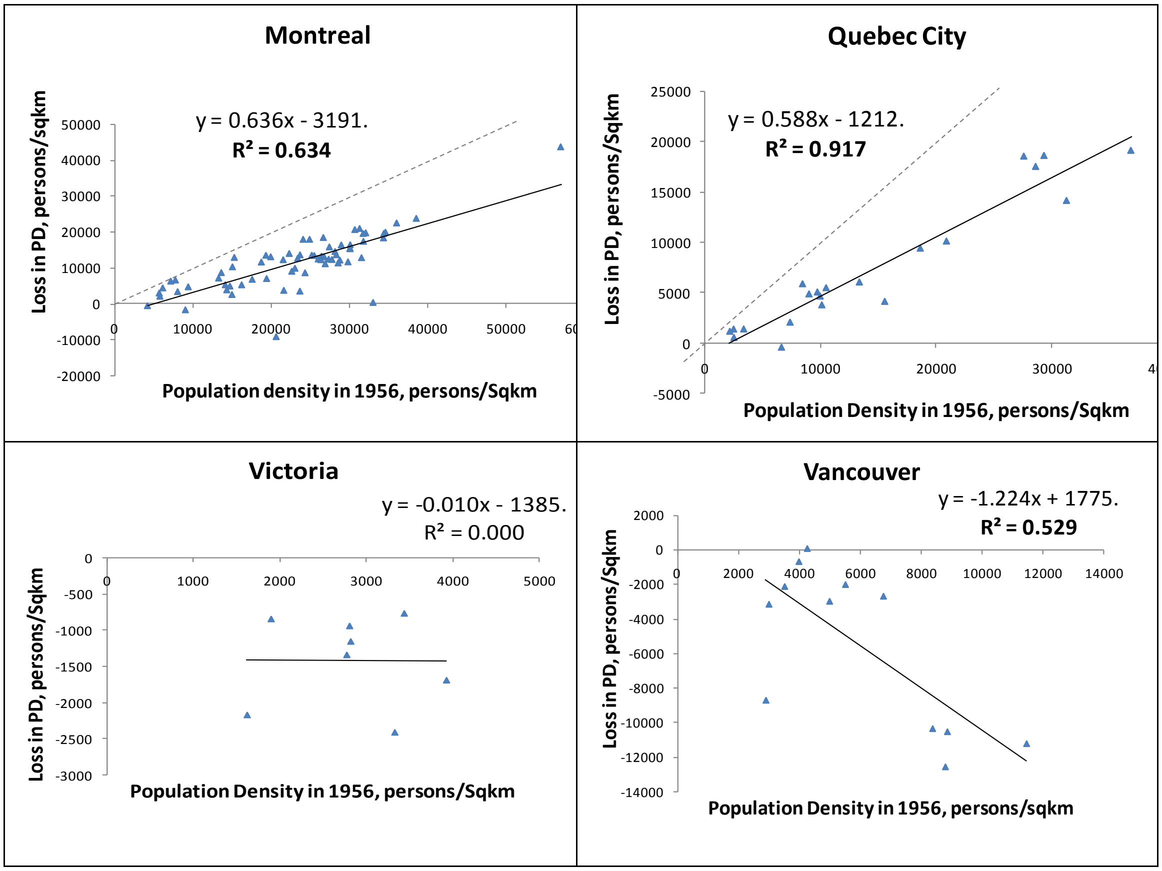

Figure 20. Relationship between loss in density and density in 1956 for individual cities

Figure 20 illustrates the relationship between loss in density and the density in 1956 for selected cities. The relationship is positive in all cities except for Vancouver and Victoria; census tracts with higher 1956 densities lost more population over the study period than those with lower initial densities. The R^2 of Montreal and Quebec City were particularly high, with .63 and .92 respectively. Victoria and Vancouver are exceptions, where in the former case, the gains in density do not seem to be related to the density in 1956. Vancouver saw gains where density in 1956 was already high, in the range of 8,000 to 11,000 persons/km^2. Again, all losses are below the dashed line (slope of 1). The relationship for the other cities was low to moderate (for plots see Appendix 11 - Individual cities - LPD vs. Density in 1956).

4.5 Relationship between loss in density and distance to freeway at different levels of Density in 1956

Four subsets of census tracts were created based on the value of density in 1956 - less than 10,000; between 10,000 and 20,000; between 20,000 and 30,000; and above 30,000. The relationship between loss in density and distance to freeway was plotted, however, no correlation was found between the two variables at different levels of density in 1956. For relevant plots see Appendix 12 - Plots for subsets of data.

4.6 Regression results with both variables

Previous sections covered simple linear regressions with one explanatory variable at a time: distance to freeway, and density in 1956. This section presents results of a multiple regression with both explanatory variables in the model. Overall, multiple regression does not provide much improvement over simple linear regressions with each variable (Figure 21). For all census tracts together, and for Montreal, Quebec City, and Vancouver, the R-squared with the multiple regression is practically the same as that with only density in 1956. Variance partitioning reveals the amount each variable contributes to the multiple R-squared.

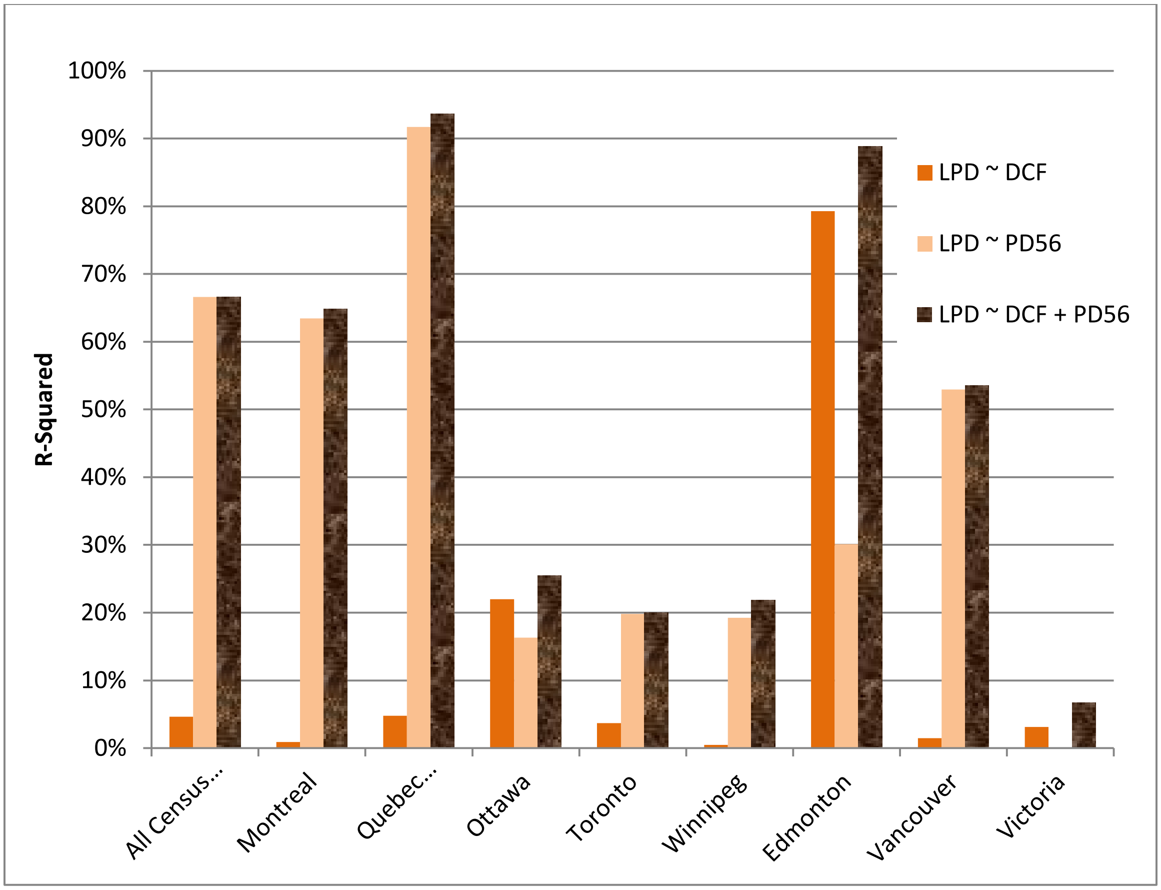

Figure 21. R-Squared values for various combinations of explanatory variables [distance to freeway (DCF), density in 1956 (PD56)] and response variable [loss in population density (LPD)]

Table 8. Regression results with explanatory variables density in 1956 and distance to freeway, and response variable loss in population density

	Cities, R-Squared and N	Variable	Coefficient	Std. Error	t-stat	p value	95% Confidence Interval	
							2.5%	97.5%
(1)	**All Cities** R^2 = 0.67; N = 205	Intercept	-3980 persons/km^2	709.00	-5.61	0.0000	-5378.40 persons/km^2	-2582.42 persons/km^2
		PD56	0.64	0.03	**19.37**	**< 2e-16**	0.58	0.71
		DCF	-18.85 persons/km^3	135.40	-0.14	0.8900	-285.89 persons/km^3	248.19 persons/km^3
(2)	**Quebec City** R^2 = 0.94; N = 21	Intercept	230.60 persons/km^2	889.70	0.26	0.7984	-1638.68 persons/km^2	2099.90 persons/km^2
		PD56	0.58	0.04	**15.92**	**0.0000**	0.50	0.66
		DCF	-1757 persons/km^3	741.20	-2.37	0.0292	-3313.90 persons/km^3	-199.55 persons/km^3
(3)	**Montreal** R^2 = 0.65; N = 68	Intercept	-2457.00 persons/km^2	1542.00	-1.59	0.1160	-5536.89 persons/km^2	622.57 persons/km^2
		PD56	0.66	0.06	**10.88**	**0.0000**	0.54	0.78
		DCF	-805.20 persons/km^3	501.70	-1.61	0.1130	-1807.16 persons/km^3	196.72 persons/km^3
(4)	**Ottawa** R^2 = 0.25; N = 14	Intercept	2894.12 persons/km^2	2871.73	1.01	0.3350	-3426.52 persons/km^2	9214.77 persons/km^2
		PD56	0.15	0.22	0.72	0.4890	-0.32	0.63
		DCF	-2145.18 persons/km^3	1846.57	-1.16	0.2700	-6209.46 persons/km^3	1919.09 persons/km^3
(5)	**Toronto** R^2 = 0.2;	Intercept	-5542.21 persons/km^2	2028.35	-2.73	0.0091	-9632.76 persons/km^2	-1451.65 persons/km^2

	Cities, R-Squared and N	Variable	Coefficient	Std. Error	t-stat	p value	95% Confidence Interval	
							2.5%	97.5%
	N = 46 (Toronto, continued)	**PD56**	0.50	0.17	**2.97**	**0.0049**	0.16	0.83
		DCF	334.05 persons/km^3	1029.98	0.32	0.7473	-1743.11 persons/km^3	2411.21 persons/km^3
(6)	**Winnipeg** R^2 = 0.22; N = 20	Intercept	3024.11 persons/km^2	3612.53	0.84	0.4141	-4597.67 persons/km^2	10645.90 persons/km^2
		PD56	0.34	0.16	**2.16**	0.0457	0.01	0.66
		DCF	-340.12 persons/km^3	454.32	-0.75	0.4643	-1298.65 persons/km^3	618.40 persons/km^3
(7)	**Edmonton** R^2 = 0.89; N = 16	Intercept	2692 persons/km^2	656.60	4.10	0.0013	1273.44 persons/km^2	4110.57 persons/km^2
		PD56	0.33	0.10	**3.34**	**0.0053**	0.12	0.54
		DCF	-1276 persons/km^3	154.30	**-8.27**	**0.0000**	-1609.05 persons/km^3	-942.49 persons/km^3
(8)	**Vancouver** R^2 = 0.54; N = 12	Intercept	2986.28 persons/km^2	4315.50	0.69	0.5064	-6776.05 persons/km^2	12748.61 persons/km^2
		PD56	-1.22	0.38	**-3.18**	0.0112	-2.08	-0.35
		DCF	-251.68 persons/km^3	728.92	-0.35	0.7378	-1900.62 persons/km^3	1397.26 persons/km^3
(9)	**Victoria** R^2 = 0.07; N = 8	Intercept	-1181.20 persons/km^2	1071.05	-1.10	0.3200	-3934.43 persons/km^2	1572.03 persons/km^2
		PD56	0.24	0.54	0.44	0.6790	-1.15	1.62
		DCF	-216.73 persons/km^3	360.75	-0.60	0.5740	-1144.06 persons/km^3	710.61 persons/km^3

PD56: Density in 1956; DCF: Distance to Freeway; N: Number of observations.

The regression results (Table 8, (1)) demonstrate that for all cities together, it is the explanatory variable density in 1956 (PD56) that is highly statistically significant ($p < 0.05$, and is <2e-16) with a coefficient of 0.64, whereas distance to freeway is statistically insignificant (p=0.89). In general, we can interpret the coefficient for the variable density in 1956 as all else being equal, one unit increase in the density in 1956 would correspond to 0.64 persons/km^2 increase in loss in density from 1956 to 2006.

In Quebec City, Montreal, Toronto and Edmonton (Table 8, (2), (3), (5) and (7)) variable density in 1956 (PD56) is highly significant (p very much less than 0.05); in cases of Vancouver (p = 0.0112) and Winnipeg (p = 0.0457) it is significant but not as much; in Ottawa and Victoria it is highly insignificant (Table 8, (4) and (9)). The coefficients, as above, are positive and is highest for Montreal (0.66) followed by Quebec City (0.58) and Toronto (0.50). Vancouver is an exception with a negative slope as discussed in section 4.4.2.

The explanatory variable distance to freeway (DCF) is highly significant statistically in the case of Edmonton (p = 0) and to a lesser extent in the case of Quebec City (p = 0.0292). Between the two, the latter has a higher (absolute) coefficient, -1757 persons/km^3 compared to -1276 persons/km^3 for Edmonton, and can be interpreted as all else being equal, with one unit (one kilometre) increase in distance to freeway we can expect an increase in density (or decrease in loss in density) by 1,757 persons/km^2 in Quebec City and by 1,276 persons/km^2 in Edmonton. Overall, it is for Edmonton and to a lesser extent for Quebec City that both the variables are statistically significant.

4.6.1 Variance Partitioning

Variance partitioning (or commonality analysis) attributes the contribution of each explanatory variable to the variability in the response variable. Figure 22 visually illustrates the unique (U_{DCF}, U_{PD56}) and shared or joint contributions ($S_{DCF\ and\ PD56}$) of each variable, for the eight cities together and for the individual cities.

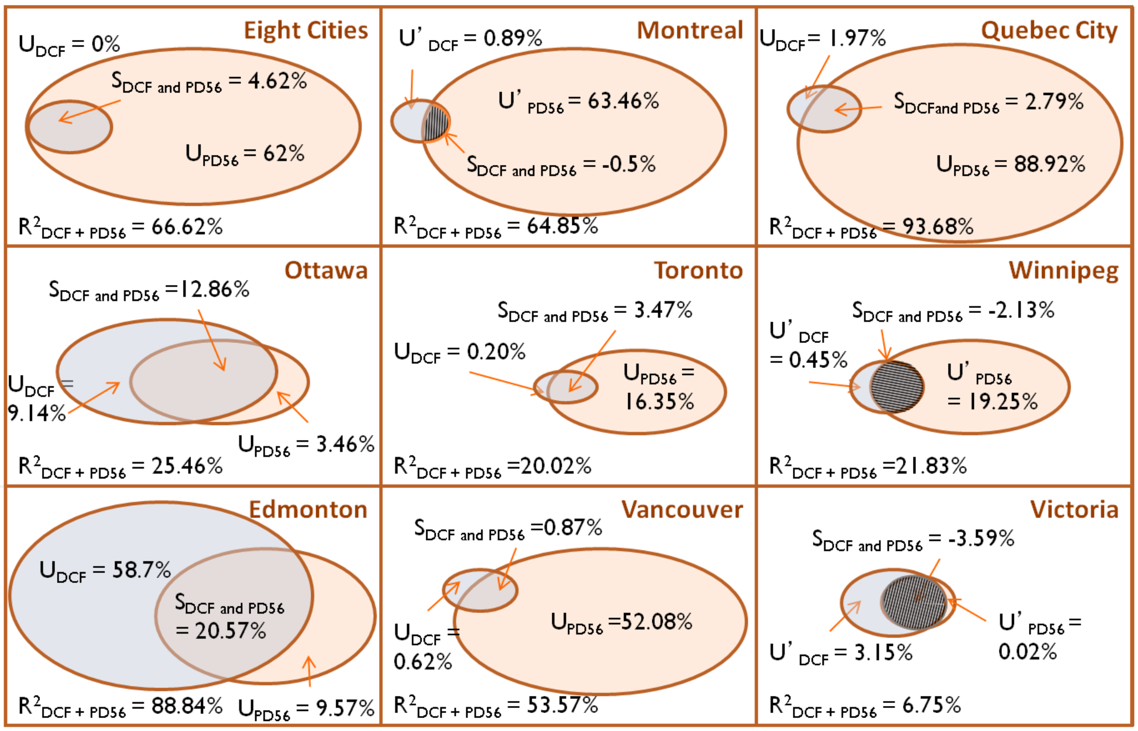

Figure 22. Variance partitioning, determining the unique and shared contributions of each variable to the variation in the response variable.

Note: U' is the R^2 from SLR and U = (U'-S).

Each rectangle in Figure 22 represents 100% of the variability in the response variable (loss in density) and the shaded regions altogether represent the proportion of the variability explained by the multiple regression, the R-squared for the two-variable model (distance to freeway and density in 1956: $R^2_{DCF + PD56}$). The individual ovals represent the proportion of the variability in the response variable explained by each explanatory variable separately.

The ovals are drawn approximately proportional to the amount a variable explains the variability in the response variable in the simple linear regression (SLR). For example, the R-squared for Edmonton in the SLR model with distance to freeway was 79% and that with density in 1956 was 30%; variance partitioning reveals that the unique contributions of the former (U_{DCF}) is 58.7% and that of the latter (U_{PD56}) is 9.57%, while the shared component between the two variables (intersecting area, $S_{DCF\ and\ PD56}$) is 20.57%. The effect of adding a variable to an existing model can also be observed, e.g., adding density in 1956 to the existing SLR model with distance to freeway ($R^2 = 79\%$) adds 9.57% (U_{PD56}) to the model. Thus unique contributions of each variable (U_{DCF}, U_{PD56}) and shared contributions ($S_{DCF\ and\ PD56}$) add up to the total contribution of both variables together, i.e., to a multiple R-squared ($R^2_{DCF + PD56}$) of 88.84% in the example of Edmonton.

In addition to illustrating the unique and shared contributions of each variable in a multiple regression, variance partitioning allows for a snapshot view of the contributions across different cities based on the representations by the ovals. For example, in the case of Quebec City, the contribution of DCF is very small while that of PD56 is large. Similarly, in Ottawa, the overall contribution of both variables is moderate.

In the cases of Montreal, Winnipeg and Victoria (where values of R^2, particularly that of DCF, are negligible) the shared contributions are negative. The negative joint effects indicate that the predictor variables suppress each other, instead of being additive which is the usual case (Chevan & Sutherland, 1991; Nally, 1996). The suppressing does not have considerable consequences when the negative joint component is low (Nally, 1996).

For all eight cities together, density in 1956 explains the variation in loss in population density with a high unique contribution, while distance to freeway offers almost no explanation. The stepped function, revealing the four kilometre threshold, discussed in section 4.2 cannot be captured by variance partitioning as R-squared here is for the linear regression of all distances. It could, however, be done separately for distance to freeway of 0-4km, and 4km and above.

5 DISCUSSION

5.1 Loss in population density

While an overwhelming majority (74%) of the census tracts included in the study lost density between 1956 and 2006, the magnitude of the loss differ between cities with Montreal experiencing highest overall losses (Figure 12). At the aggregate inner-city level, Montreal experienced the highest absolute change in density (a loss of over 7,300 persons/km^2) followed by Vancouver (a gain close to 4,000 persons/km^2), while the initial density in 1956 was almost 15,700 persons/km^2 in Montreal and nearly 4,800 persons/km^2 in Vancouver[14]. Relative loss in population density is again highest in Montreal (47%) closely followed by Quebec City (43%), then by Ottawa and Winnipeg (34% each); Vancouver experienced the highest relative increase in density (84%) while Victoria increased by nearly half that amount (48%).

At the aggregate level, losses in density in the inner-cities of Montreal and Quebec City confirm the hypothesis that already dense places in 1956 would lose greater density. Similarly, Vancouver and Victoria, two inner-cities with some of the lowest initial densities, gained density over the fifty-year period, confirming the hypothesis that those with lower initial densities would gain density. Conversely, Edmonton, which had the second lowest initial density at the inner-city level, contradicts this hypothesis, as density increased by only one percent over the study period.

[14] In 1956, the density of the inner-city of Montreal was the highest among the cities studied with 15,695 persons/km^2, which was significantly greater than the highest density found in the literature (core area of Vancouver, 11,198 persons/ km^2; see Table 3); Quebec City, with the second highest density in 1956, had 8,376 persons/ km^2.

Inner-city of Toronto where the aggregate initial density was moderate (6,800 persons/km^2) did not experience noteworthy increase over the study period (9% relative to the density in1956). The substantial increase in density in some census tracts was offset by decrease in others.

It is possible that the observed loss in density in some census tracts is the result of people/residents being replaced by jobs. Although data for employment was not available for 1956, it is important to mention that job density data would have helped assess if the reduced population density was compensated for by increased employment density, particularly in the commercial core (even if no clear difference was found in commercial core and inner residential census tracts, except for Toronto where density actually increased in the commercial core). It is feasible that the land in the central area could have become less desirable for living, and that businesses/offices were outbidding inhabitants. However, even if employment took the place of the people as population density reduced but if those people chose to move to the suburbs in low density housing which are considered unsustainable, then from an environmental perspective replacement of population (residents) by jobs would still be a concern.

5.2 Relationship between Loss in Density and Distance to Freeway

A non-linear relationship is found between loss in density and distance to freeway. Census tracts with centroids within four kilometres of the nearest freeway experienced major losses in density (Figure 15). This finding confirms the main hypothesis that higher losses in population density would be experienced in areas closer to the freeways. The findings can be understood in light of the direct impacts of the freeways on inner-cities, which include air and noise pollution from additional traffic volume to and from freeways, and the nuisance of its construction. Four kilometres appears to be the threshold within which the adverse effects of freeways can be felt. The presence of freeways in the vicinity reduces the quality of life and make a neighbourhood undesirable to live in (Burchell et al., 2005; also see Frumkin et al., 2004, and Gauthier, 2009). Additionally, expropriation and displacement of people brought about by the construction of freeways and other dismantling of built environment tremendously affects the inner-city fabric (Cervero et al., 2009; Henry, 2009; Burchell et al, 2005; Caro, 1974) and could contribute to lowering of population density (Altshuler, 1965). This might explain the observed four kilometre threshold below which major losses in density were observed in the present study.

Effects of freeways can be felt in two main ways. First, as discussed, the expropriation and destruction of neighbourhoods for the construction of freeway reduce the density and the very presence of freeways in the vicinity makes a neighbourhood undesirable to live in. Second, as per land use theory, freeways allow people to opt for housing in the suburbs as the freeways increase commuting speeds. Thus the reduced density may also be a result of the improved transportation option.

Apart from freeways, other factors also influence density patterns, as discussed in the literature review. Such factors include the topography of a city, built environment, land use and other policies and market and economic conditions. This thesis, however, does not address these or other factors that might be endogenous to the variables included in the present research. The thesis, therefore, does not make a causal claim related to freeways and the loss in density, but raises an alarm in showing that prominent and concentrated losses between 1956 and 2006 are found within four kilometres of freeways.

5.3 Relationship between Loss in Density and Density in 1956 (PD56)

The results in section 4.3 confirm the hypothesis that areas with higher density in 1956 would experience higher losses. Montreal and Quebec City show the highest correlations between loss in density and density in 1956 (section 4.4.2). The initial density was high in Montreal and Quebec City mostly due to prevailing types of housing forms - the attached housing types known as "duplex" and "multiplex" that are more typical of Quebec cities than elsewhere in Canada (see Filion et. al., 2010 and Schoenauer, 2000). Thus higher losses are observed where the initial density was high, confirming the hypothesis. Furthermore, a larger share of the population of these two cities grew when the dominant mode of transport was the electric streetcar or street railway. Improvements in transport facilities, namely freeways, allowed for faster travel and enabled people to live further apart from each other and from their employment, which could explain the decline in density (Giuliano, 2004).

The aggregate inner-city of Vancouver, which saw a tremendous increase in density over the study period, has the highest density levels in 2006, among the cities studied. As reverse hypothesis, the areas that were less dense in 1956 gained in density while those already dense lost it, homogenising the cities to some extent (also see Filion et al., 2010; Taylor and Burchfield, 2010); the aggregate inner-city of Edmonton is an exception where the population density is almost the same in both the years of study, 1956 and 2006.

5.4 Variance Partitioning

The relative usefulness of each explanatory variable in explaining the variability in loss in density is interpreted using variance partitioning (Figure 22). Except for Edmonton and to some extent Ottawa where a relationship between distance to freeway and the loss in population density existed, adding of density in 1956 (second variable) to distance to freeway does not explain much more the variability in the loss in population density. In cases of Edmonton and Ottawa, the multiple R-squared explains more of the variability in loss in density than either variable individually.

Quebec City, Montreal, and Vancouver exhibit similar phenomenon where the unique contribution of density in 1956 is significantly higher than that of distance to freeway. Thus for these cities, density in 1956 better explains the loss in population density from 1956 to 2006 than distance to freeway. Same is the case with Toronto and Winnipeg but with a lesser magnitude. In the multiple regression, the unique contribution of distance to freeway is highest in Edmonton followed by Ottawa, which points to the fact that it is this variable that has more effect on loss in density than the density in 1956.

Using variance partitioning it is clear that relative importance of the two variables vary quite a bit between cities and that in general density in 1956 is more important in explaining the variation in loss in density than the distance to freeway. In light of the results of multiple regression, interpreted by variance partitioning, the Stepped function (presented in section 4.2), although not included in variance partitioning, becomes more important as it suggests that within the variable, distance to freeway, higher effect on loss in density is found at a distance lower than four kilometres.

5.5 Discussion at City-level

The individual cities included in the study were fairly different from one another particularly with regards to the magnitude of loss or gain in density between 1956 and 2006 and related to the distance to freeway at which the loss or gain occurred. This might explain the lack of significance of variable distance to freeway when all cities' census tracts were modelled together. This section, therefore, addresses particularities at city level, although we should remind ourselves that the present study attempted to find correlation between loss in density and the two independent variables, distance to freeway and density 1956 and that the study is far from ascertaining causation.

5.5.1 Montreal

Montreal was the largest city in 1956, had the largest inner-city and consequently contained the highest number of census tracts included in the study. All the tracts, except for three, lost density over the study period and the magnitude of the loss was highest compared to other cities in the study. Two highways go through the inner city and all the census tracts were within four kilometres of freeways. While no correlation is found between distance to freeway and loss in density, the fact that losses were so concentrated near the freeways is worth reporting.

A strong positive relationship between the loss in density and the density in 1956 provides a related and complementary explanation to the losses found in Montreal. Areas that were high in density in 1956 decreased considerably over the study period. The variable, density in 1956 was found to be a statistically significant variable in explaining the loss over the study period, while distance to freeway was insignificant.

5.5.2 Quebec City

Except for one gain all census tracts in Quebec City experienced loss in density where all the tracts were within two kilometres of the freeways. Census tracts in Quebec City were closest to freeways with one centroid of a tract falling within a few metres of the freeway as two of the freeways in the area penetrate the inner city. Similar to Montreal, one would suspect that some phenomenon related to freeway, among other factors, would influence population density. At least one other variable that might explain the loss in density is density in 1956. In Quebec (with R-squared of 92%) it can be clearly seen that where initial density was higher high losses were experienced and tracts where the initial density was lower saw lower losses flattening the density to some extent. Density in 1956 was also found to be a statistically significant variable that could explain the loss in density while the other variable, distance to freeway, was not as significant.

5.5.3 Ottawa

Ottawa is the only city in the study that lost density in all the census tracts in its inner-city. Ottawa's census tracts were some of the closest ones to freeways. Both the freeways included in the study penetrate the inner-city while one of them goes across it. Although the present study did not look at causation of the loss in density, the extreme closeness of the census tracts (within approximately 1.5 km) to the freeways point to a close relationship between distance to freeway and the loss in density. The density in 1956 in the case of Ottawa was not very high (highest in a census tract was around 15,000 persons/km^2) compared to Montreal (highest: 57,000 persons/km^2) and Quebec City (highest: almost 37,000 persons/km^2) and the losses from 1956 to 2006 did not correlate much with the density in 1956. Neither of the explanatory variables was found to be significant in explaining the loss in density.

5.5.4 Toronto

Toronto was a unique city in that some of its census tracts gained density while they were as close as a kilometre to freeway, and overall most of the gains were observed in the commercial core. None of the other cities showed this demarcation between commercial core and inner-residential census tracts. The latter predominantly experienced losses. The highest gain is density among all the census tracts included in the study was found in Toronto with an increase of 25,000 persons per sq. km.

The gains in density could be correlated to some extent with the density in 1956 (an R-squared of 20%) where tracts with lower initial density gained and those with higher density in 1956 lost although the losses at census tract level were not very high (below 10,000 persons/km^2). A Toronto census tract experienced the highest relative gain of all the census tracts in the study; this relative gain could be explained by the fact that this tract was very sparsely populated in 1956. At an aggregate level, the losses seem to have cancelled out the gains as overall gains in density for the inner-city were only 9% (or just over 600 persons/km^2). The variable density in 1956 was found to be significant in explaining the loss in density while the distance to freeway was not.

5.5.5 Winnipeg

Winnipeg was exceptional in the sense that not only did no freeway go through the inner-city, but also the closest freeway, Perimeter Highway, passes almost all around the inner-city at a distance ranging from about six to ten kilometres from the inner-city census tracts. Almost all losses are registered in these census tracts between 1956 and

2006 (Figure 15c). No correlation is found between distance to freeway and loss in density; the losses in Winnipeg are unlike other losses found in the study as the others were approximately within the distance of four kilometres from the freeway. The results of regression indicate that neither distance to freeway nor density in 1956 was a significant variable that could explain the loss in density.

5.5.6 Edmonton

Edmonton lost density closer to freeway, within three kilometres, and gained further from it, making it the only city that shows very high correlation between loss in density and proximity to freeway. The gains seem to even out the losses since at aggregate inner-city level the density in 2006 remains pretty much the same as it was in 1956. Overall, the freeways were within five kilometres from the inner-city census tract centroids although the freeways remain outside of the inner city. Census tracts where the density was high in 1956 (around 7,000 persons/km^2) lost more over the study period (as hypothesized) although some with medium density in 1956 gained more than those that had lower initial density. Overall, both distance to freeway and density in 1956 were found to be statistically significant variables that could explain the loss in density.

5.5.7 Vancouver

Freeways in Vancouver did not penetrate the inner city and remained at a distance of about three to eight kilometres. It is interesting to note that high gains were found at a distance between four to six kilometres from freeway though no clear relationship is seen between distance to freeway and the loss in density. At aggregate level, Vancouver experienced high gains in density in its inner-city over the study period: 84% or close to 4,000 persons/km^2. These gains were experienced in a manner contrary to the hypothesis, that is, higher gains were found in areas that had high initial density. Although initial density in Vancouver was much lower compared to cities such as Montreal, Quebec City or Toronto. Density in 1956 was found to be statistically significant in explaining the loss in density in case of Vancouver, and distance to freeway was not significant.

5.5.8 Victoria

All of the census tracts from Victoria gained density although not many of them (only eight) were included in the study since the defined inner-city was very small. Freeways do not enter the inner-city of Victoria and remain at a distance of about 2.5 to 6 kilometres. Gains are found no matter what the distance is from the freeway. As such, variable distance to freeway was not found to be significant in explaining the loss (or gain) in density. The same was the case for density in 1956, where the initial level did not seem to have any effect on the loss (gains) in density. Whether the initial density was low (around 1,500 persons/km^2) or high (4,000 persons/km^2) moderate gains were observed, ranging from about 500 persons/km^2 to 2,500 persons/km^2.

6 Conclusion

Three quarters of census tracts in eight Canadian inner-cities lost population density over the second half of the twentieth century. While inner-city population loss cannot be attributed solely to proximity to freeways, inner-city population density appears to be strongly affected by freeway until as far as four kilometres straight line distance from the closest freeway. Census tracts in five cities experienced losses in density within this distance. Thus, a non-linear relationship is found between distance to freeway and loss in population density.

The results of the present study imply that the undesirable effects of freeways (such as air and noise pollution and emissions from motor vehicles from increased traffic volume) are reflected by decreases in population density within a four kilometre distance from freeways. The displacement of people for the building of freeways and voluntary dislocation due to the construction nuisance can be important reasons for the decrease in density. This finding suggests that freeways should not be built closer than 4 km in areas where higher densities are desired.

Beyond the threshold of four kilometres distance, a pattern is observed where census tracts at a moderate distance from freeways gained density (mostly Vancouver and Victoria) and those further away (Winnipeg) lost, with an R^2 of .33.

At city-level, Edmonton shows a high correlation between loss in density and distance to freeway with losses observed closer to freeways and gains further away (Figure 18). While the others cities did not show any trend, losses in Montreal were spread out within a 4km distance to freeway. Toronto was distinct in that a marked difference was found between commercial core and inner residential census tracts. Almost all of the former gained in density with gains increasing as we go further from freeways (negative slope) and the latter saw almost all losses (Figure 19).

The relationship between loss in density and density in 1956 was strong for Quebec City and Montreal (R^2 of .91 and .63) suggesting that places with initial high densities lost higher (Clark, 1951). Victoria saw all gains at all levels of density in 1956; Vancouver, with a negative slope, was opposite to Montreal and Quebec City such that it gained higher amounts where the initial density was already high (Figure 20).

The aggregate inner-city population density soared in both Vancouver and Victoria and to a much lesser extent in Toronto and Edmonton (which increased barely) over the study period; the aggregate densities declined in rest of the cities included in the study. This study also demonstrates that the areas with higher density in 1956 saw higher losses over the study period. Despite the fact that the density of Montreal and Vancouver moved in the opposite directions between 1956 and 2006, Montreal's inner-city takes the position of second most dense (with density of 8,368 persons/km^2) barely behind the inner-city of Vancouver (8,749 persons/km^2), which has become the most dense inner-city in 2006 among the cities included in the study. It should be noted that Vancouver as well as Victoria did not have freeways inside the inner city and they both gained density over the study period. However, the same cannot be said about Edmonton and Winnipeg where freeways also did not penetrate the inner city.

A non-linear relationship is found between loss in density and distance to freeway where loss in density is high and considerable up until four kilometres of freeways and the losses are spread throughout this distance. Also, higher losses were found where the initial density of 1956 was very high confirming the hypothesis that denser cities would lose density over the study period. Nearly all cities exhibited different effects with respect to the two explanatory variables, loss in density and density in 1956. The main take away from the study is the identification of the four kilometre threshold within which overwhelming losses are seen in at least three cities (and overall in five cities) no matter the distance to freeway. Beyond the threshold a trend is seen where gains are found at a moderate distance to freeway and losses further away.

The results and the four kilometre threshold, in particular, indicate that freeways should not be built within this distance in areas where high density is desired. The population density would reduce due to displacement of people for the construction of the freeway; people residing around the freeways may also move out due to the nuisance of construction. Once the freeways are built the noise and air pollution may discourage people from residing in proximity to freeways. Furthermore, building freeways encourages sprawl, which leads to unsustainable land consumption and transport energy use (Newman & Kenworthy, 1999).

Since the cities included in the present research do not constitute a random sample nor a representative one, caution should be exercised when applying these results to other cities in Canada, unless they exhibit similar characteristics as the cities included in the present thesis.

6.1 Limitations

The limitations of the thesis, which arise in part because of the limited scope of the present master's project, need to be mentioned even though the thesis was carefully researched and prepared. The number of census tracts included for some inner-cities, in particular for Victoria, was very small due to the way inner-city was defined (based on land-use in 1956). The small size may not have helped in finding statistically significant relationships. Additionally, a limited number of variables was included for the most part due to lack of availability of relevant data for 1956 such as job or income data; other factors that influence population density also need to be considered to get a well rounded perspective while testing and controlling for endogeneity. It was very much outside the scope of the present project, however. Lastly the cities included in the study were for the most part considerably different from one another. As a result, a general conclusion was difficult to draw, aside from the threshold of four kilometres, which was based on the cities where the losses were observed below this threshold.

6.2 Future Research

Recognising that distance to freeway is one of many factors that might influence people's residential choice and that the air and noise pollution as well as the nuisance of the construction of the freeway may be felt as far as four kilometres, we suggest further research to investigate various other factors that may also play a role in the observed reduction of density within a four kilometre distance from freeway. Whether the loss was due to indirect effects (e.g., attractiveness of the suburbs) or direct effects (e.g., degree of desirability of a neighbourhood) of freeway is not identified in the present research. A study with comparable areas with and without (serving as control group) freeways at a distance of four kilometres using variables such as race, income, prosperity, crime rate, city vitality, suburban growth rate and other socioeconomic variables could help disentangle these effects. Winnipeg experienced lower losses but away from freeways (between about six to ten kilometres); an in-depth case study comparing the losses in Montreal and Quebec City versus those in Winnipeg would be useful and interesting.

Other ways to quantify the impact of freeways would be to measure changes in land use using parameters such as changes in employment/job density, commercial building, residential units, new housing stock and property value. Other ideas for future research include changing the time frame: a study between 1950's (similar to the present study) and 1980s, before the wave of gentrification in inner-city that brought back some of the suburbanites to the city (see Smith, 1996). Although average household size declined in all the cities included in the present thesis over the study period, change in household size can be one of the variables considered in a future research that further investigates decline in densities. Whether the four-kilometre threshold identified by the present study applies to other Canadian and US cities or not is also left to future research.

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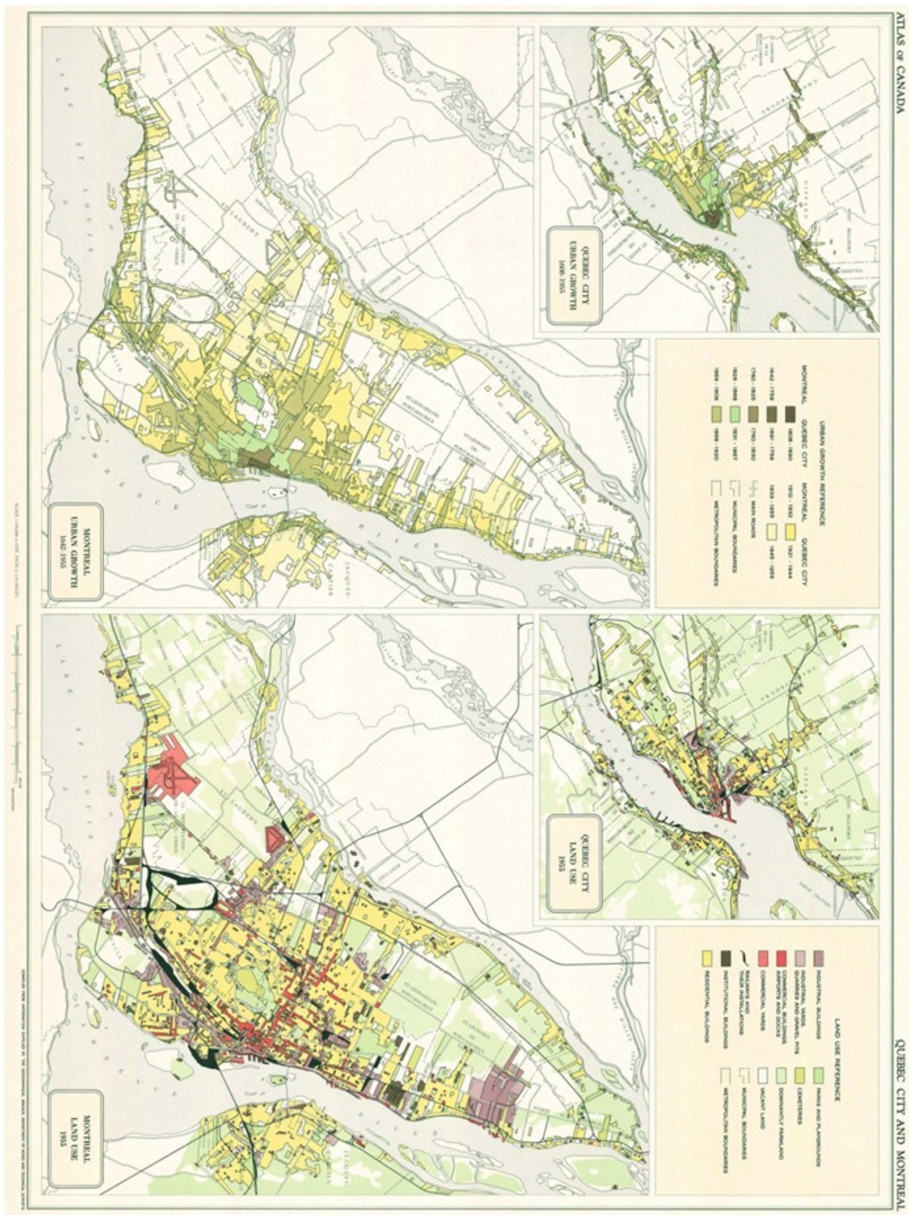
APPENDICES

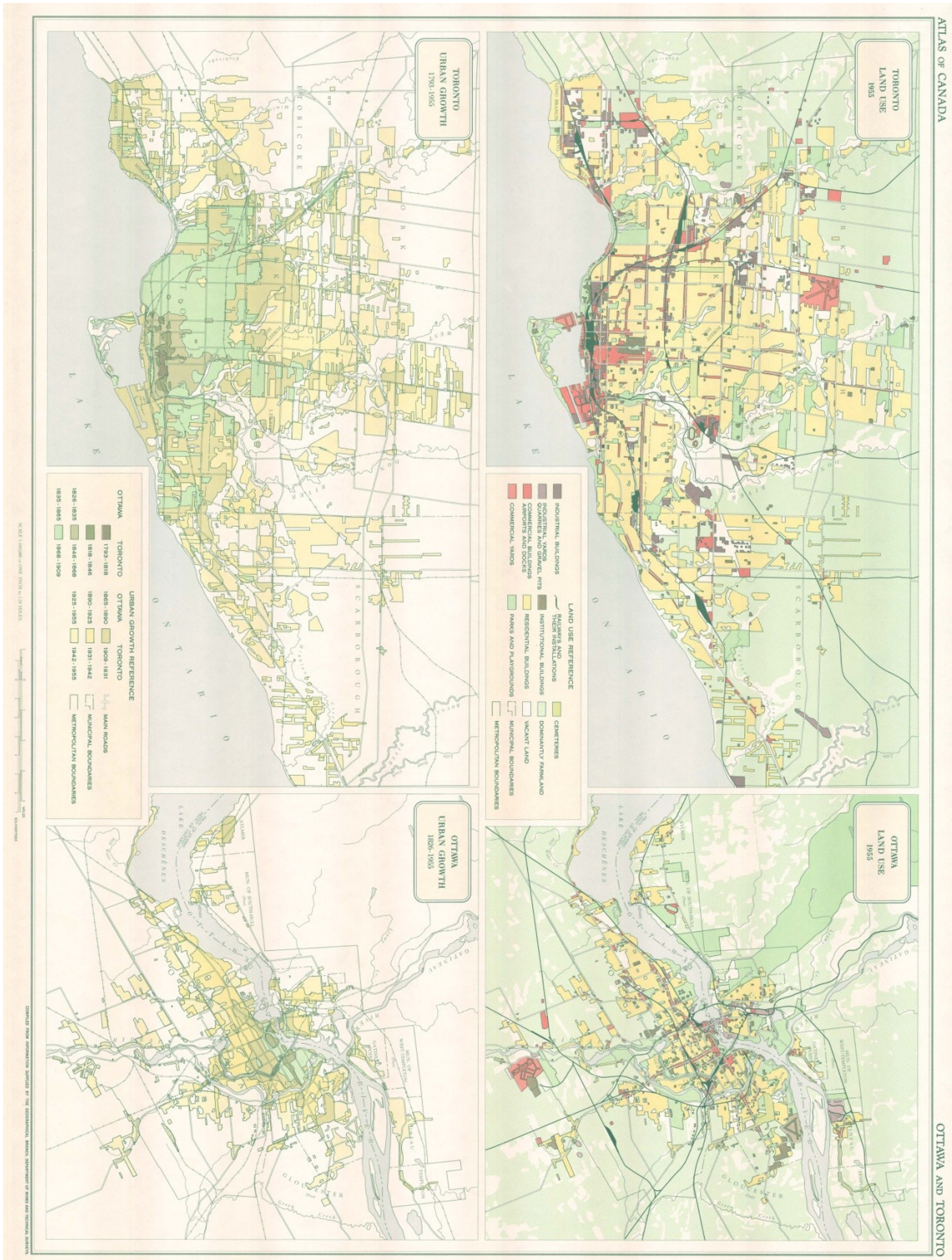
Appendix 1 - Land-use maps used to define inner-city

Appendix 1a - Montreal and Quebec City (1955)



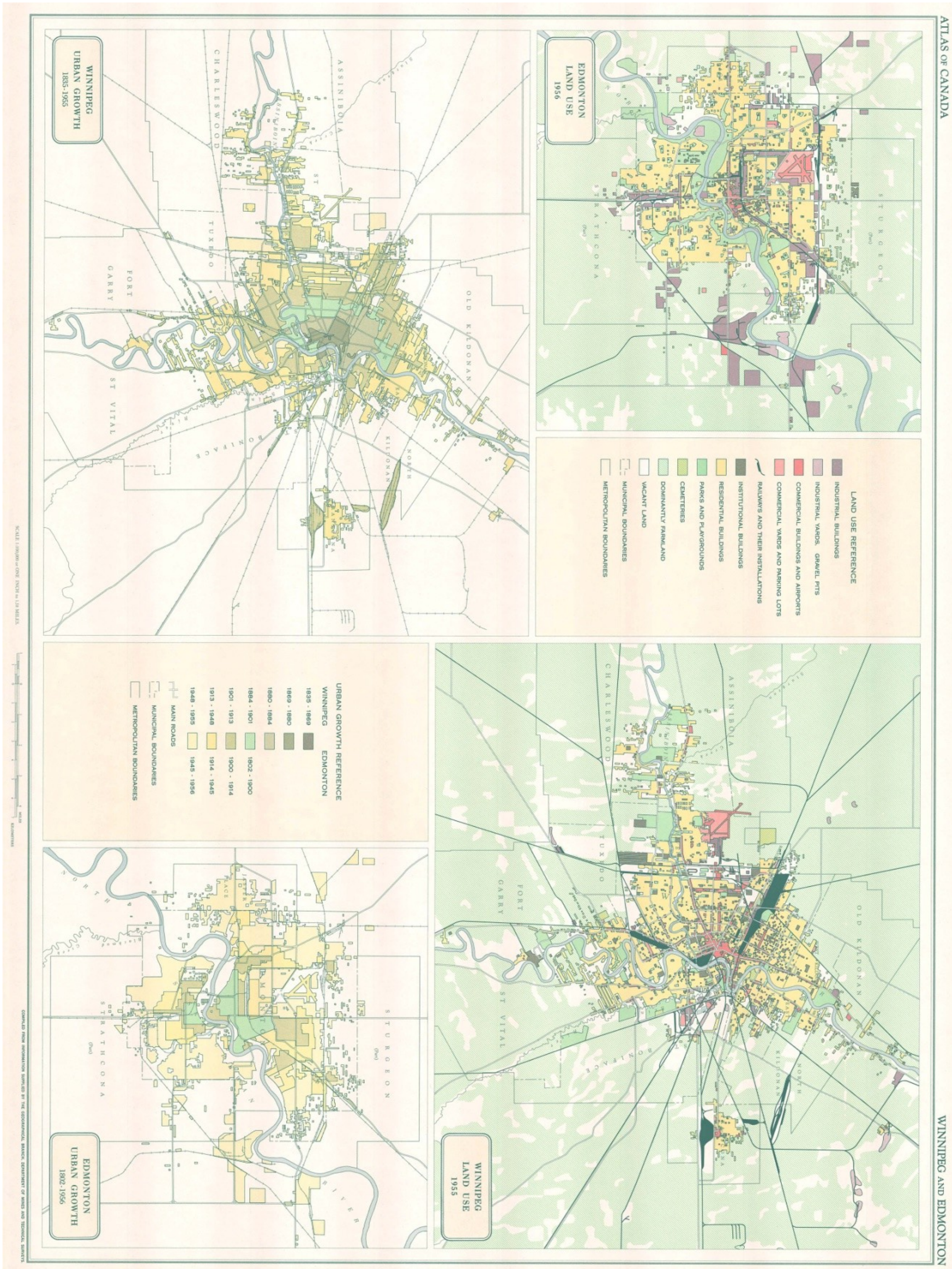
Source: Government of Canada (1957)

Appendix 1b - Toronto and Ottawa (1955)



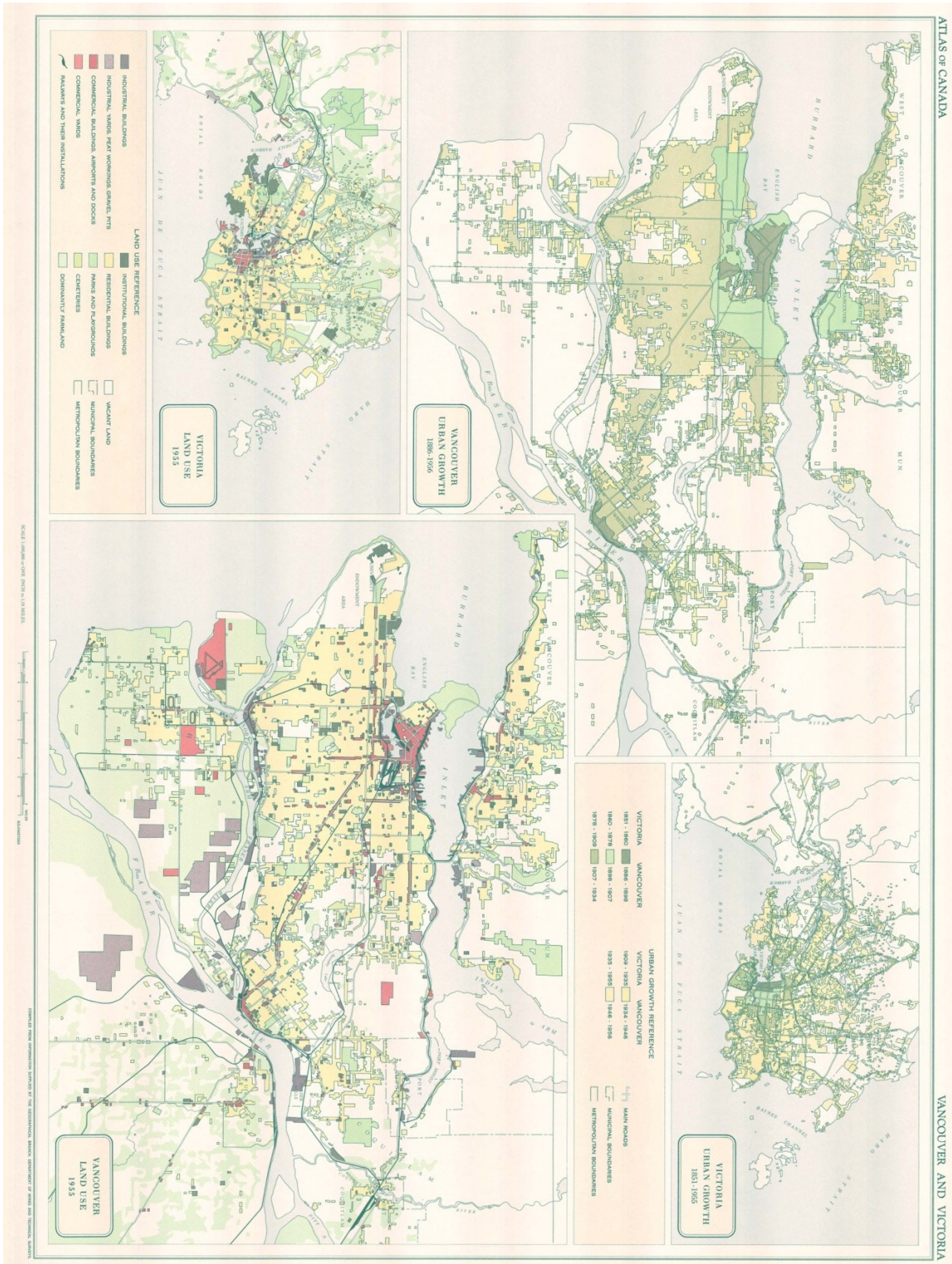
Source: Government of Canada (1957)

Appendix 1c - Edmonton (1956) and Winnipeg (1955)



Source: Government of Canada (1957)

Appendix 1d - Vancouver and Victoria (1955)



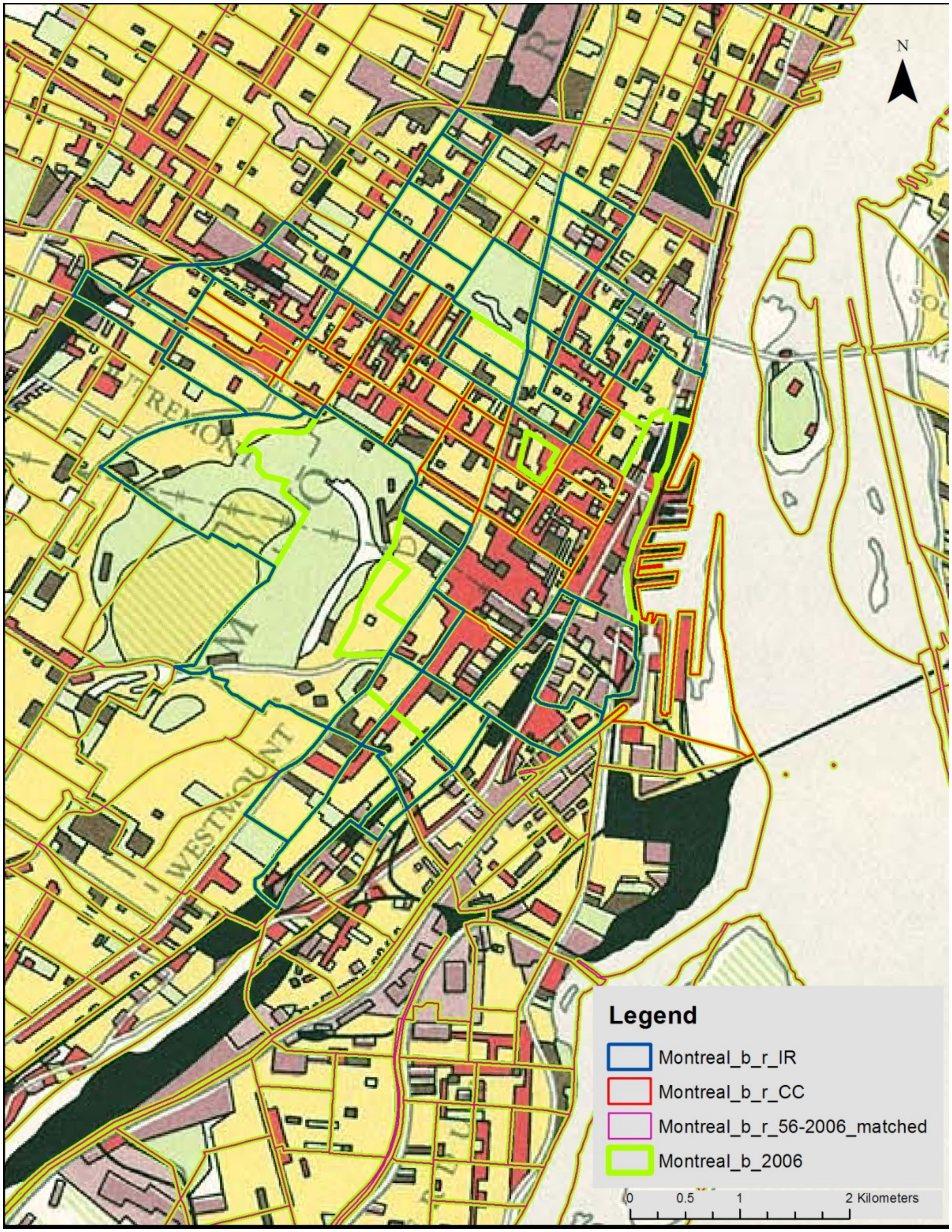
Source: Government of Canada (1957)

Appendix 2 - Maps of inner-city boundaries and freeways

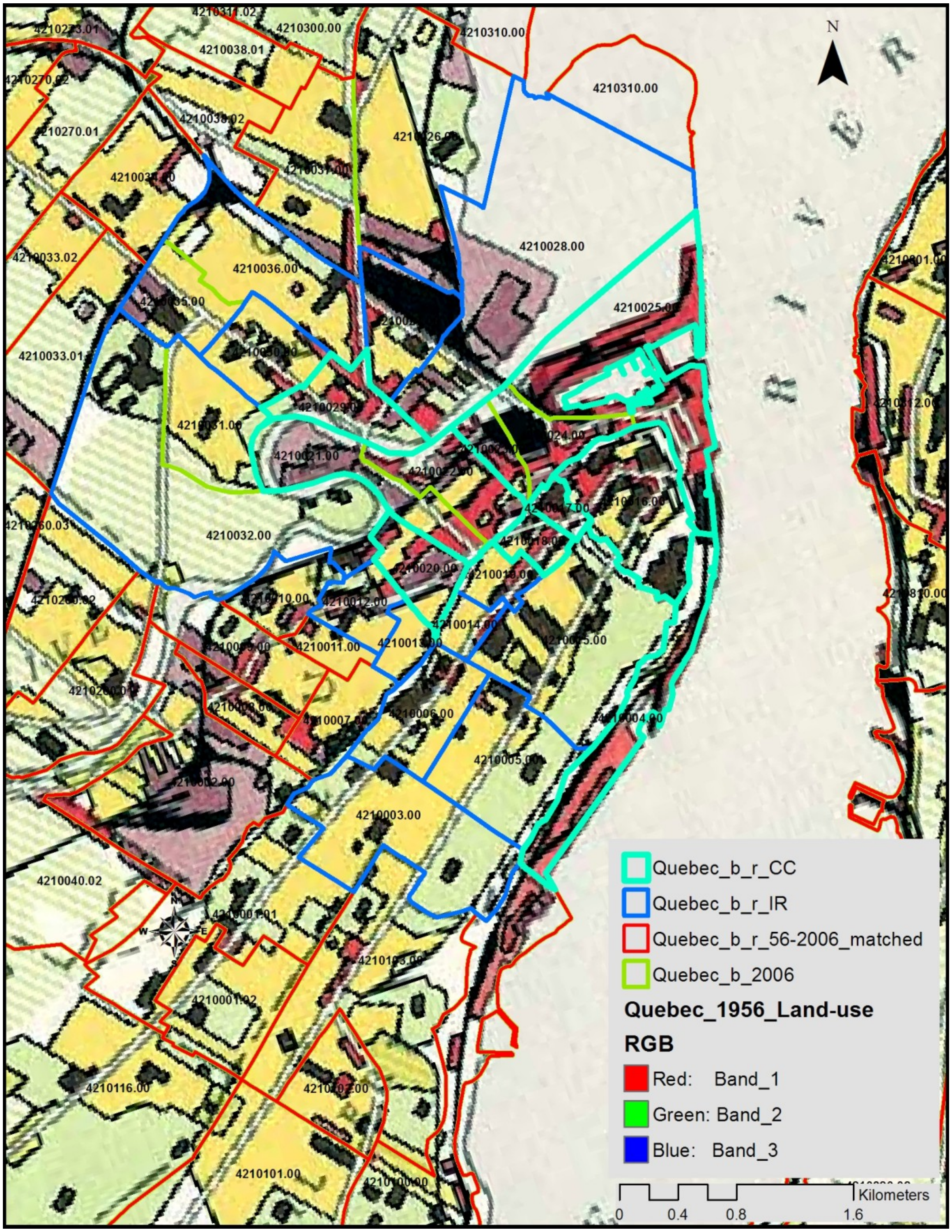
Appendix 2a to 2g - Inner-city definition showing Commercial Core (CC) and Inner Residential (IR) census tracts for all cities

Note: In the following maps, the notation "..b_r.." (as in Montreal_b_r_CC) indicates that the census tract boundary shape file used for the maps are cartographic boundary files (denoted by b) (boundaries are aligned with the land) and that 2006 boundaries are matched to those from 1956 (denoted by r). This is the case throughout the study.

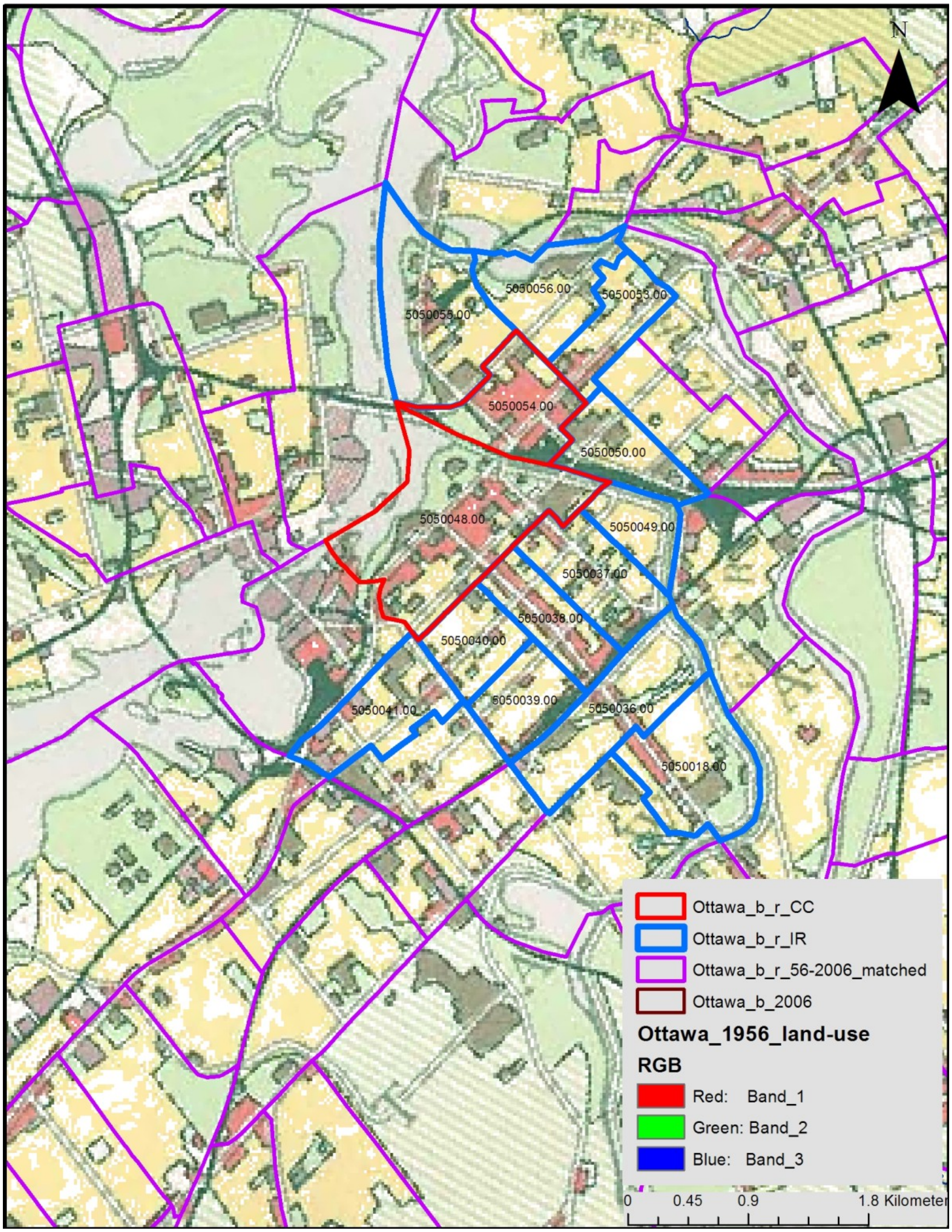
Appendix 2a - Montreal: Inner-city definition showing Commercial Core and Inner Residential census tracts



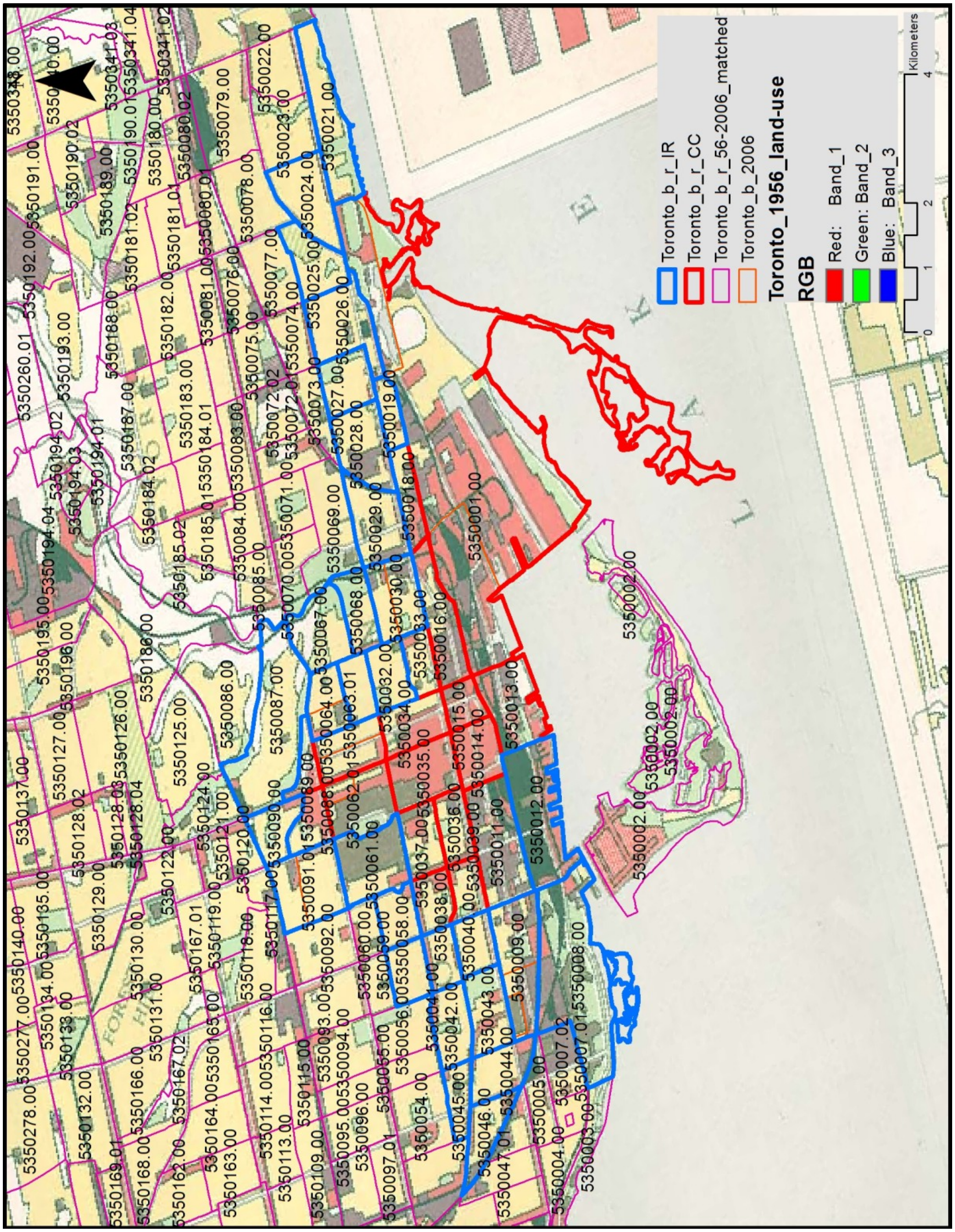
Appendix 2b - Quebec City: Inner-city definition showing Commercial Core and Inner Residential census tracts



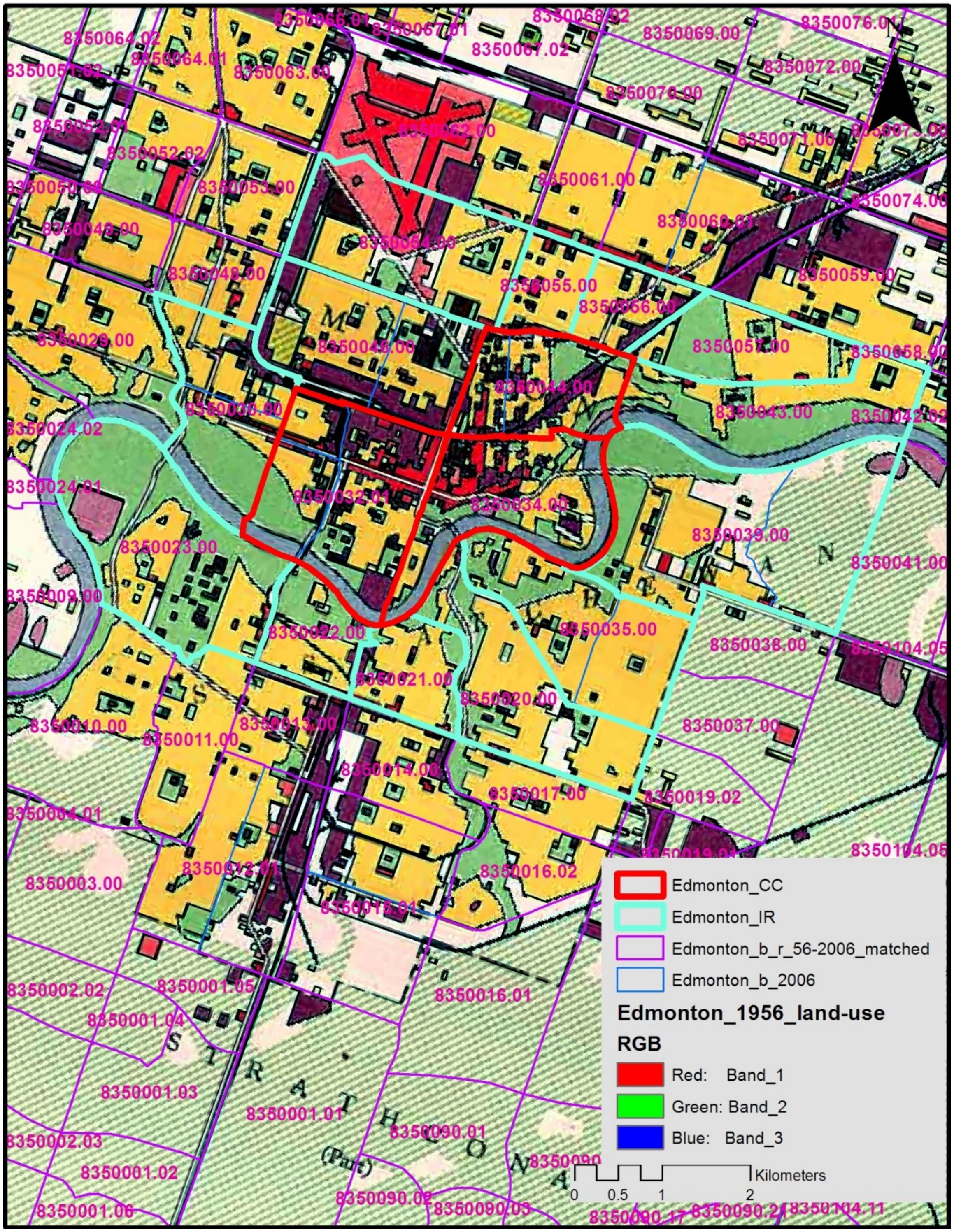
Appendix 2c - Ottawa: Inner-city definition showing Commercial Core and Inner Residential census tracts



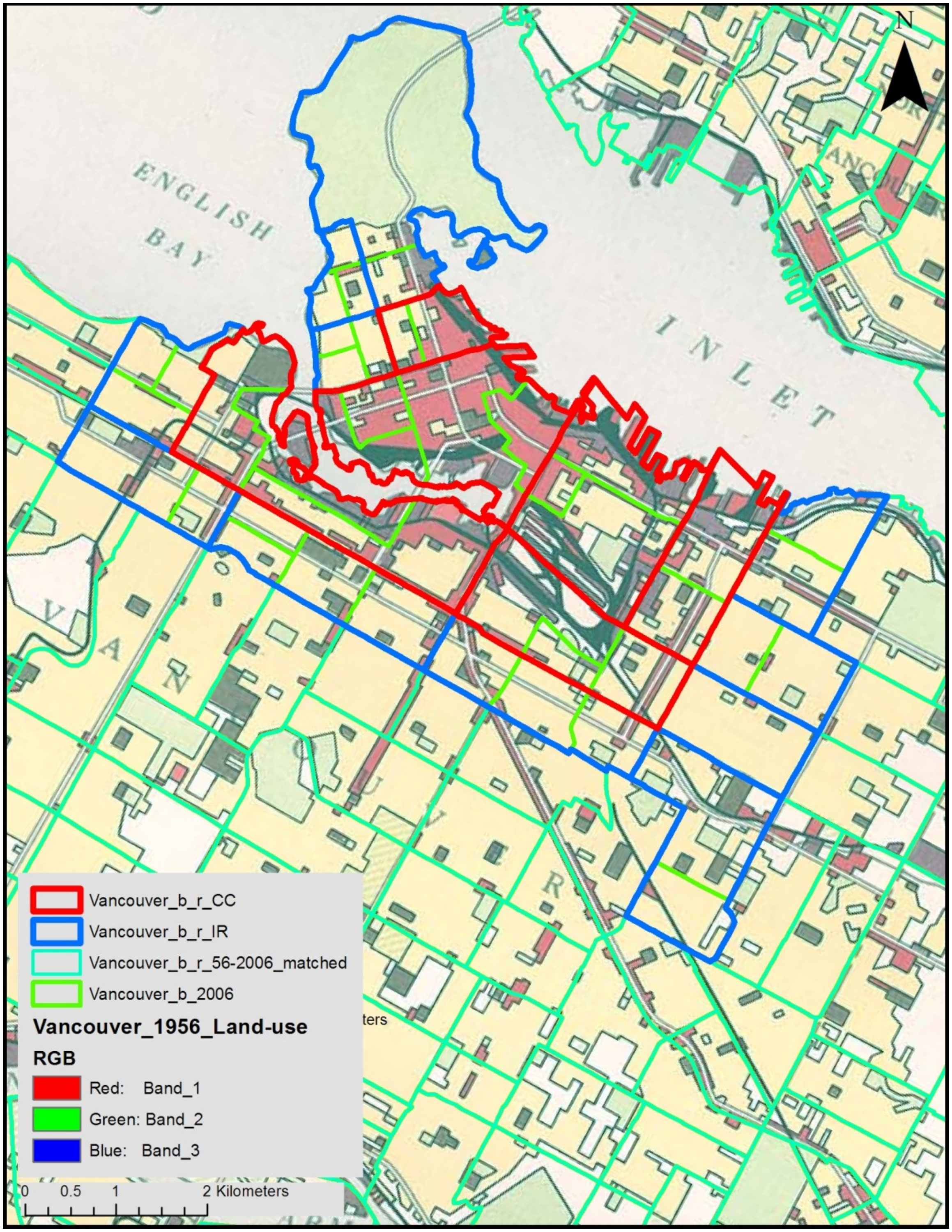
Appendix 2d - Toronto: Inner-city definition showing Commercial Core and Inner Residential census tracts



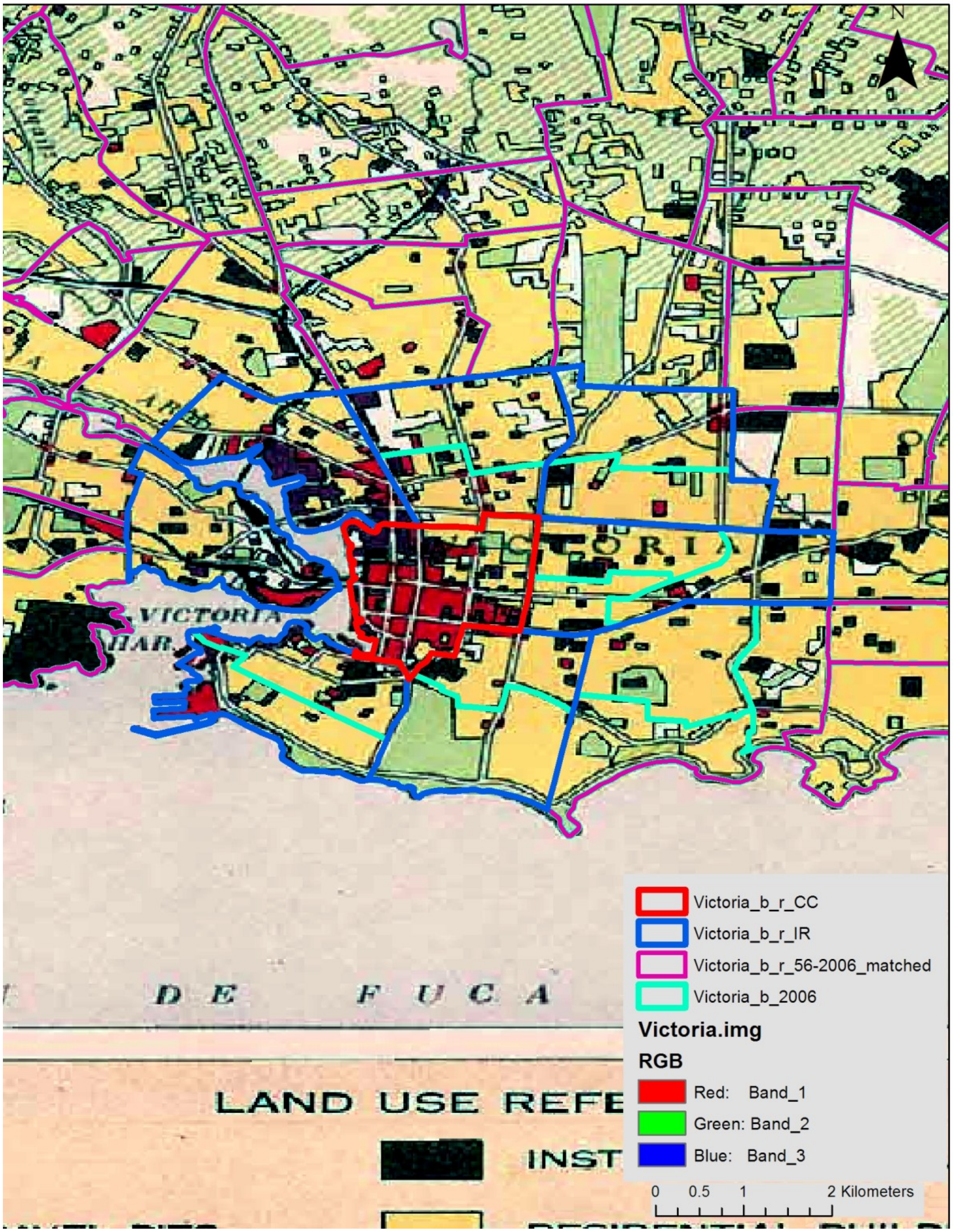
Appendix 2e - Edmonton: Inner-city definition showing Commercial Core and Inner Residential census tracts



Appendix 2f - Vancouver: Inner-city definition showing Commercial Core and Inner Residential census tracts

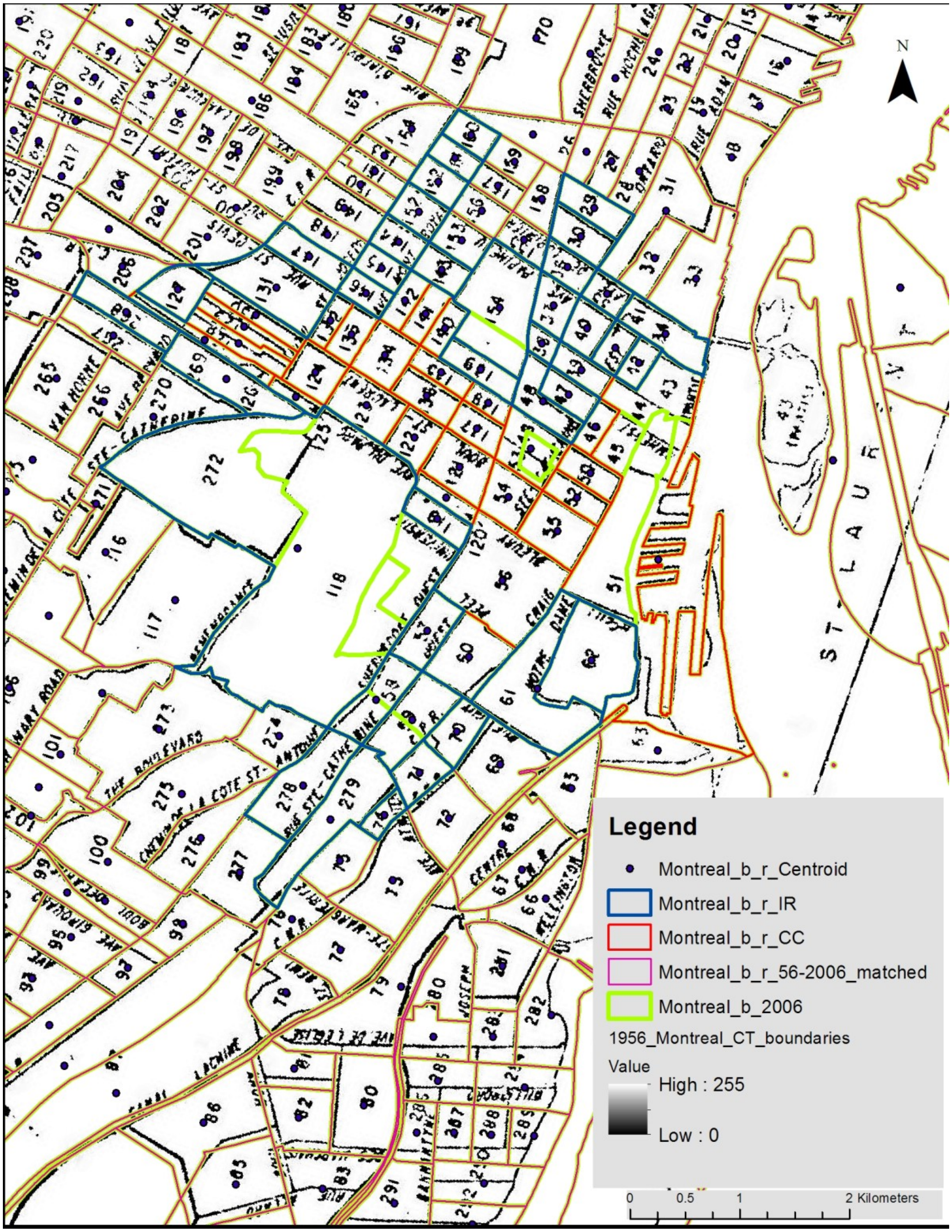


Appendix 2g - Victoria: Inner-city definition showing Commercial Core and Inner Residential census tracts

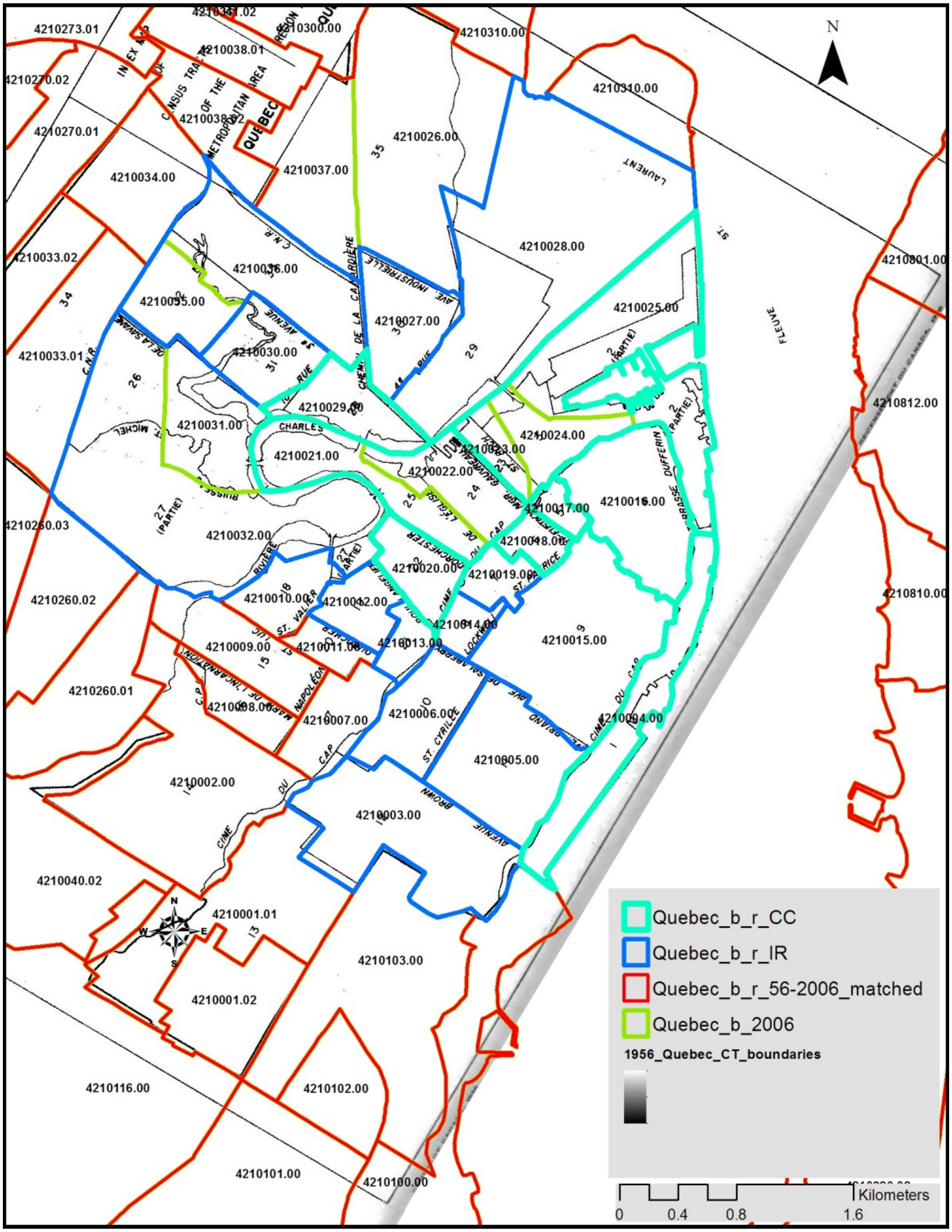


Appendix 2h to 2o - 1956-2006 Census Tracts matched for all cities

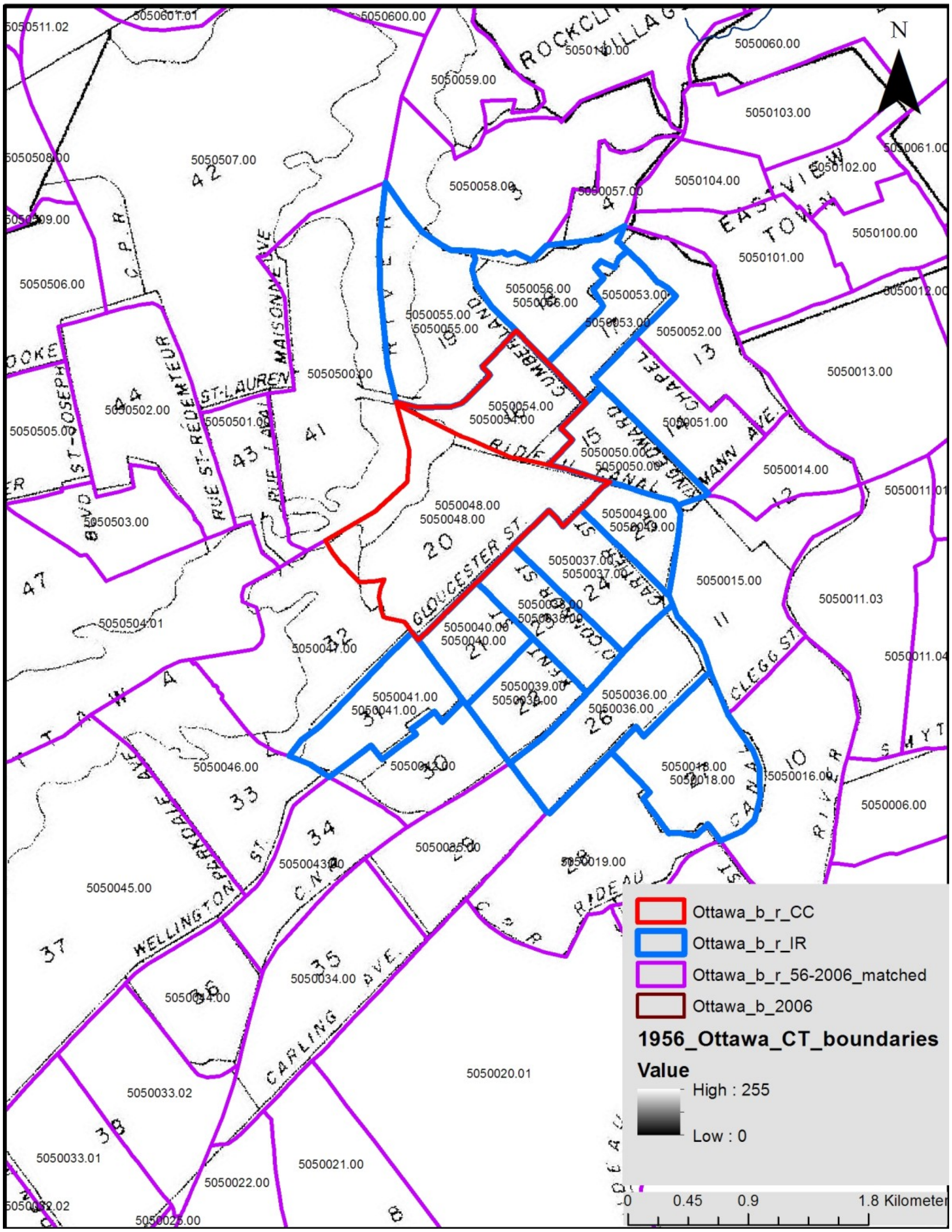
Appendix 2h - Montreal: 1956-2006 Census Tracts matched

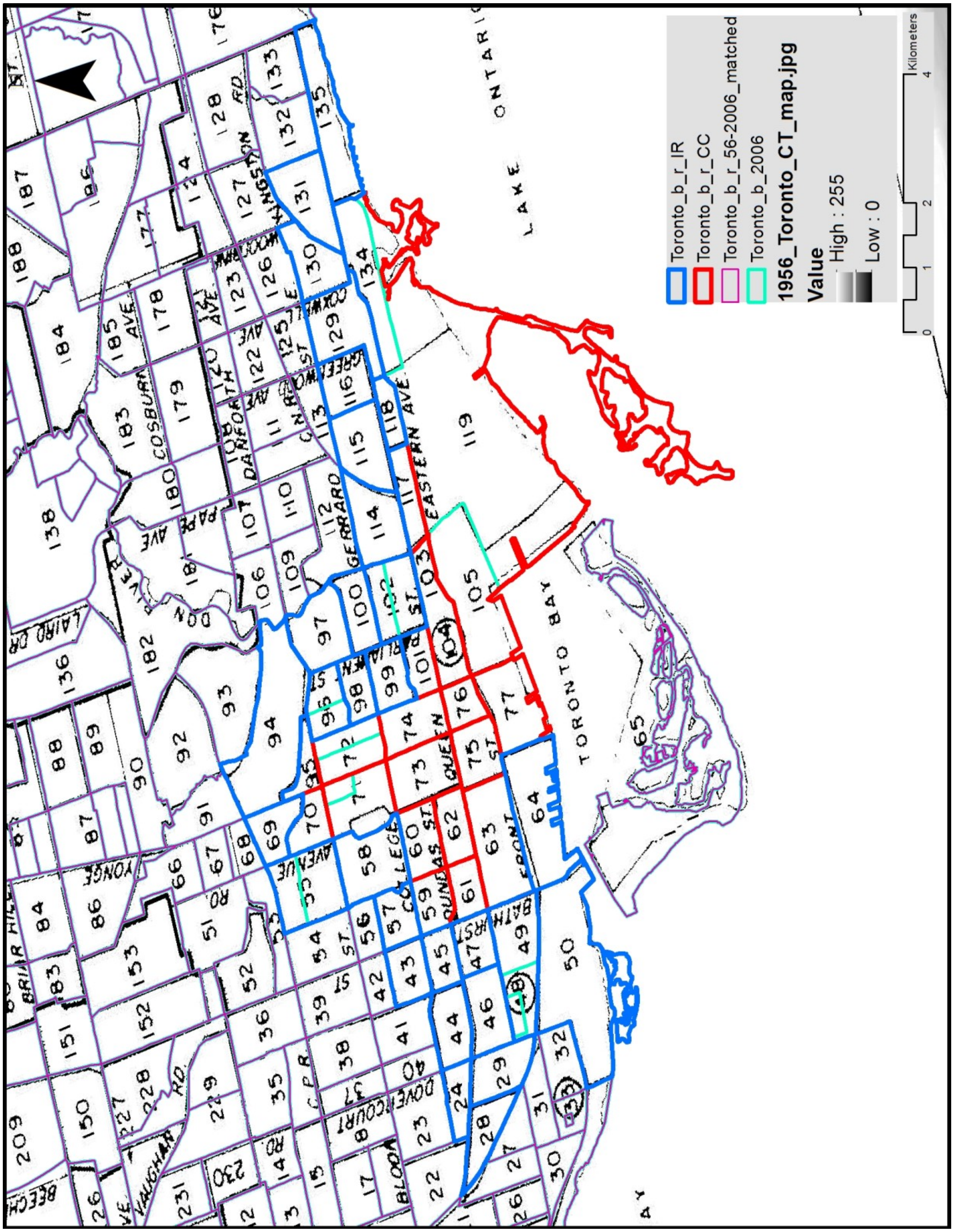


Appendix 2i - Quebec City: 1956-2006 Census Tracts matched



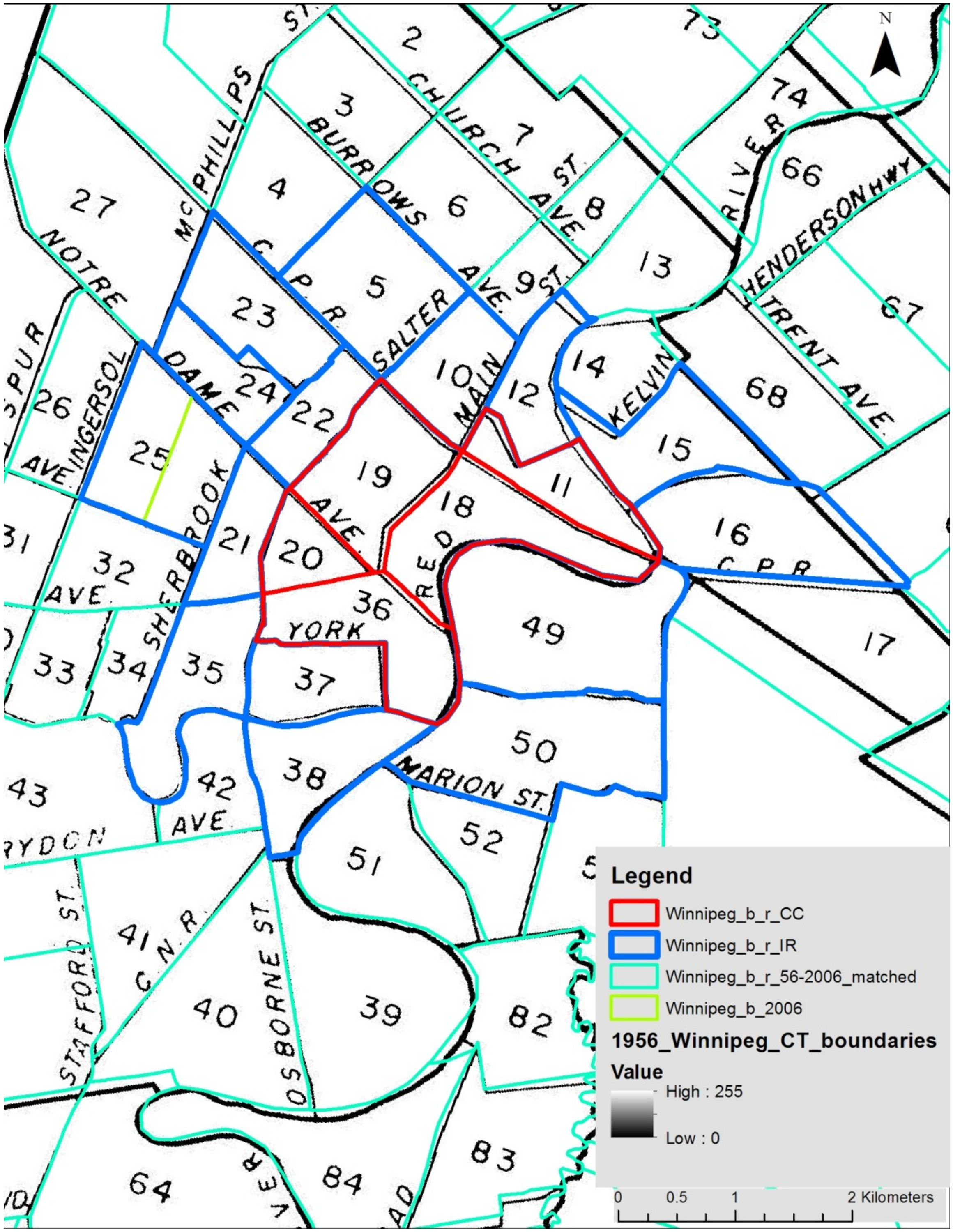
Appendix 2j - Ottawa: 1956-2006 Census Tracts matched



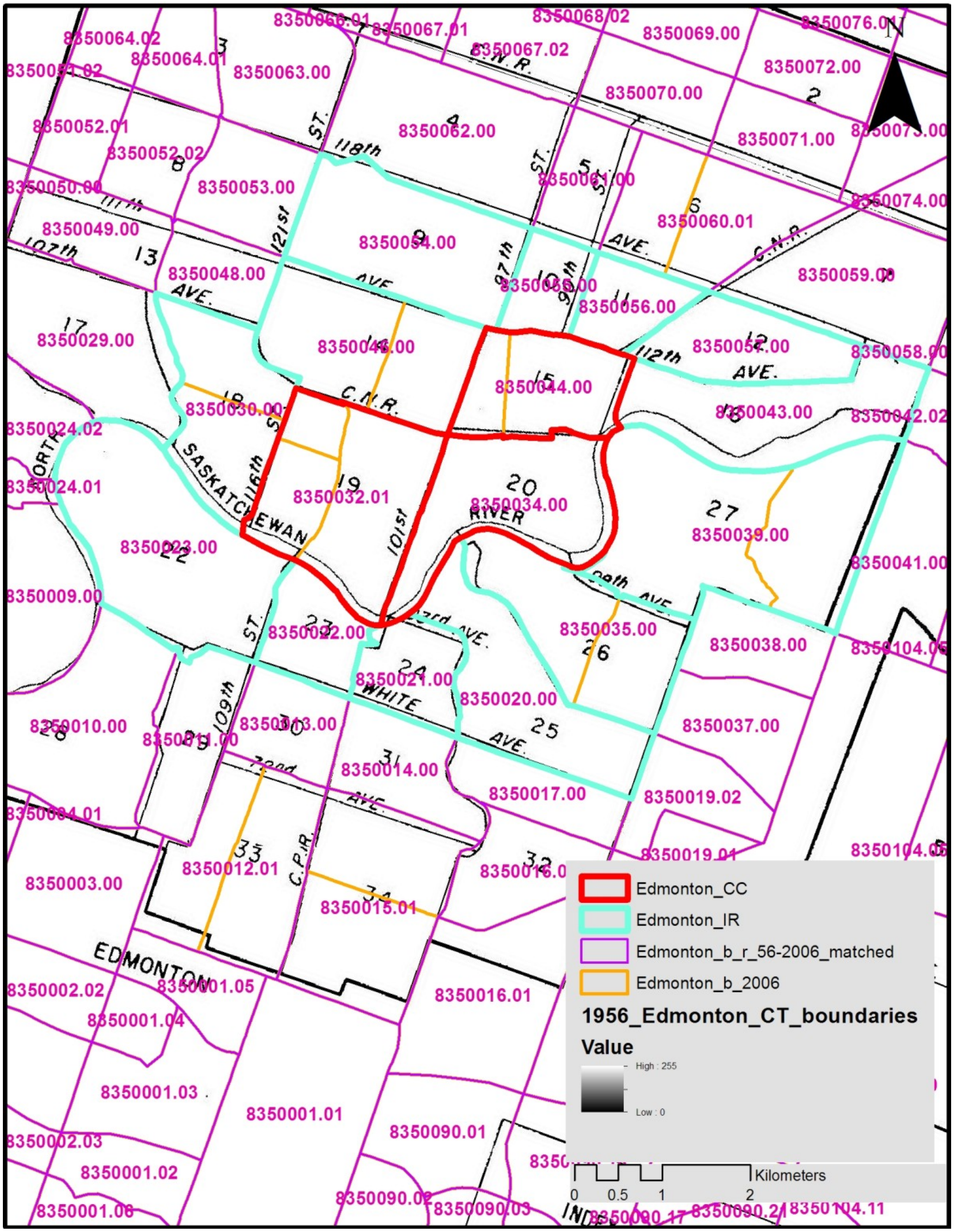


Appendix 2k - Toronto: 1956-2006 Census Tracts matched

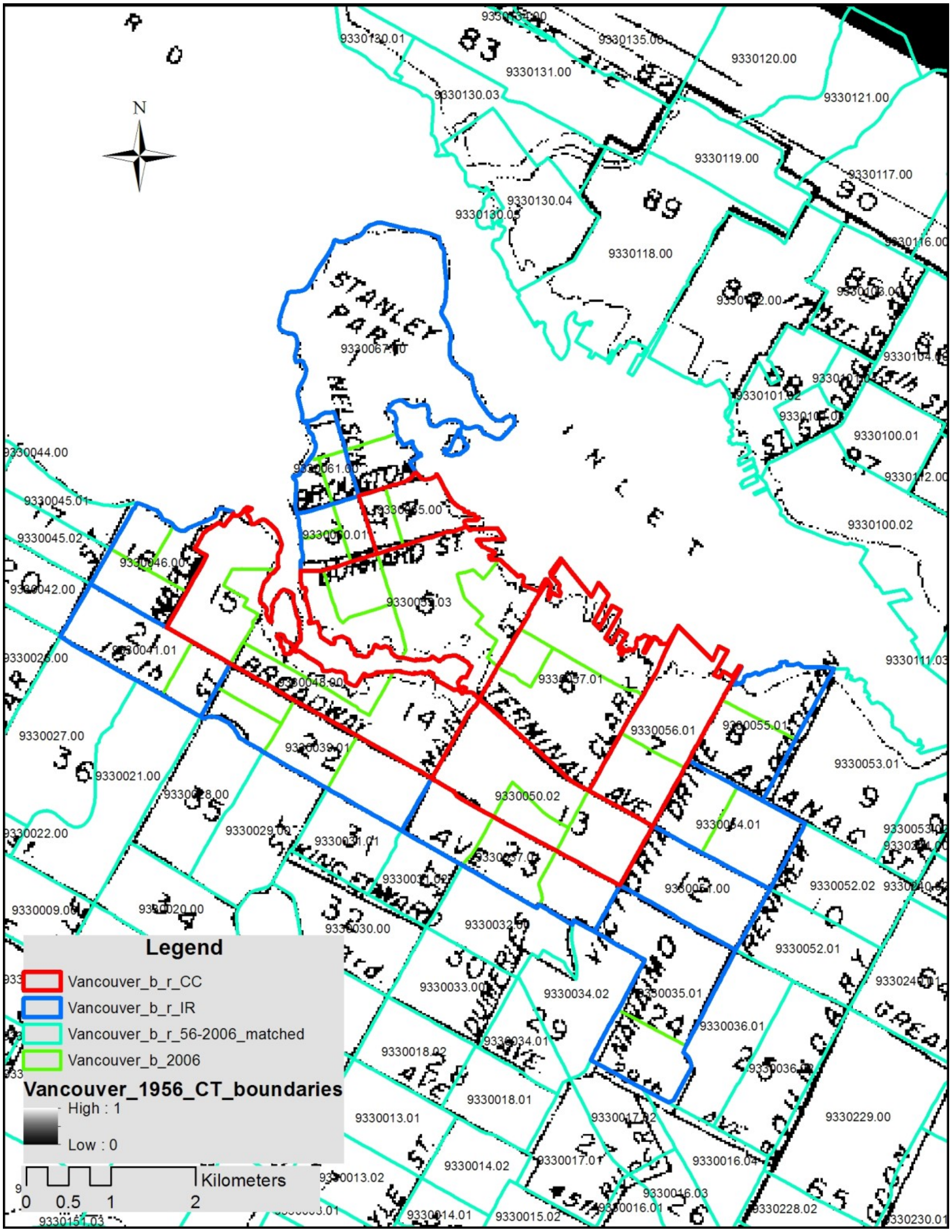
Appendix 2l - Winnipeg: 1956-2006 Census Tracts matched



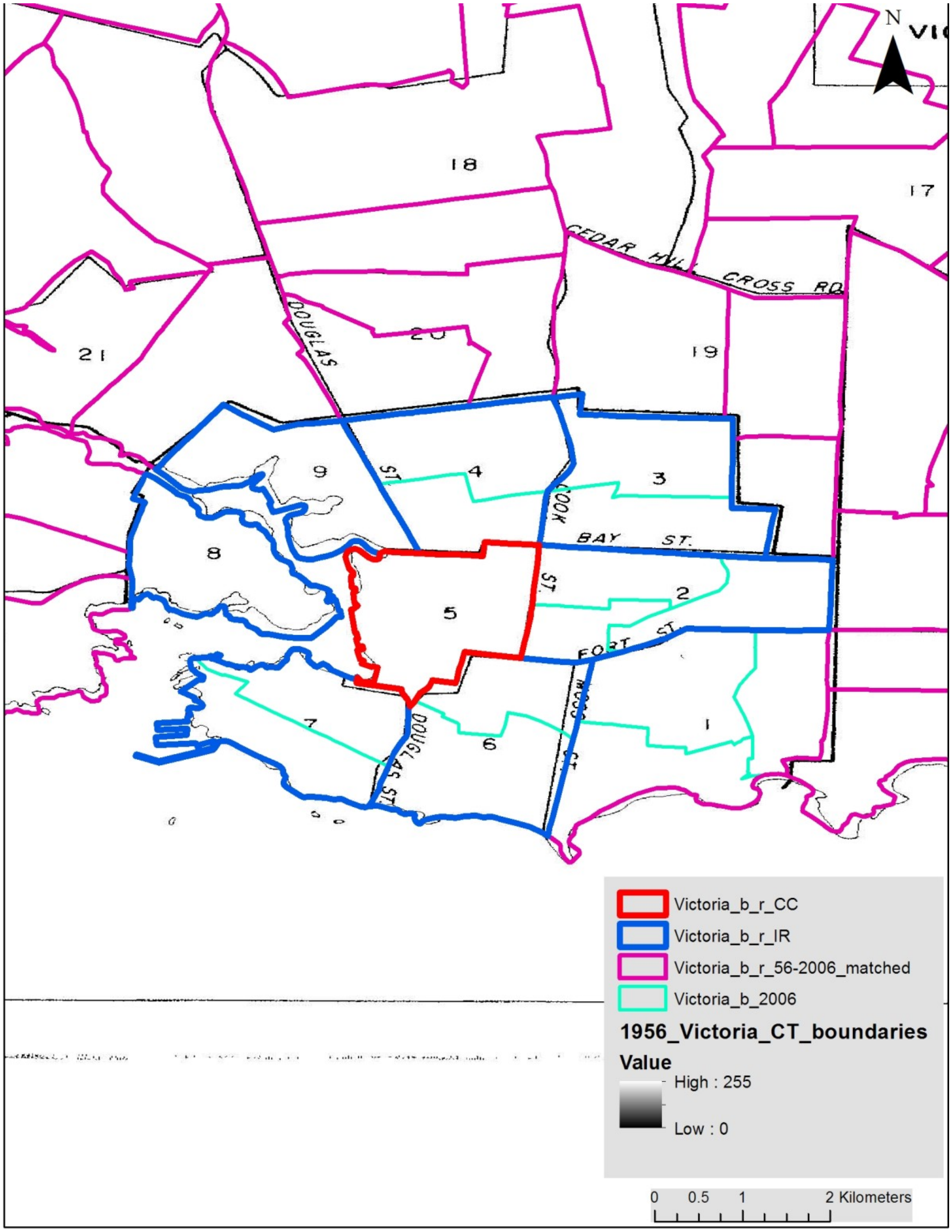
Appendix 2m - Edmonton: 1956-2006 Census Tracts matched



Appendix 2n - Vancouver: 1956-2006 Census Tracts matched

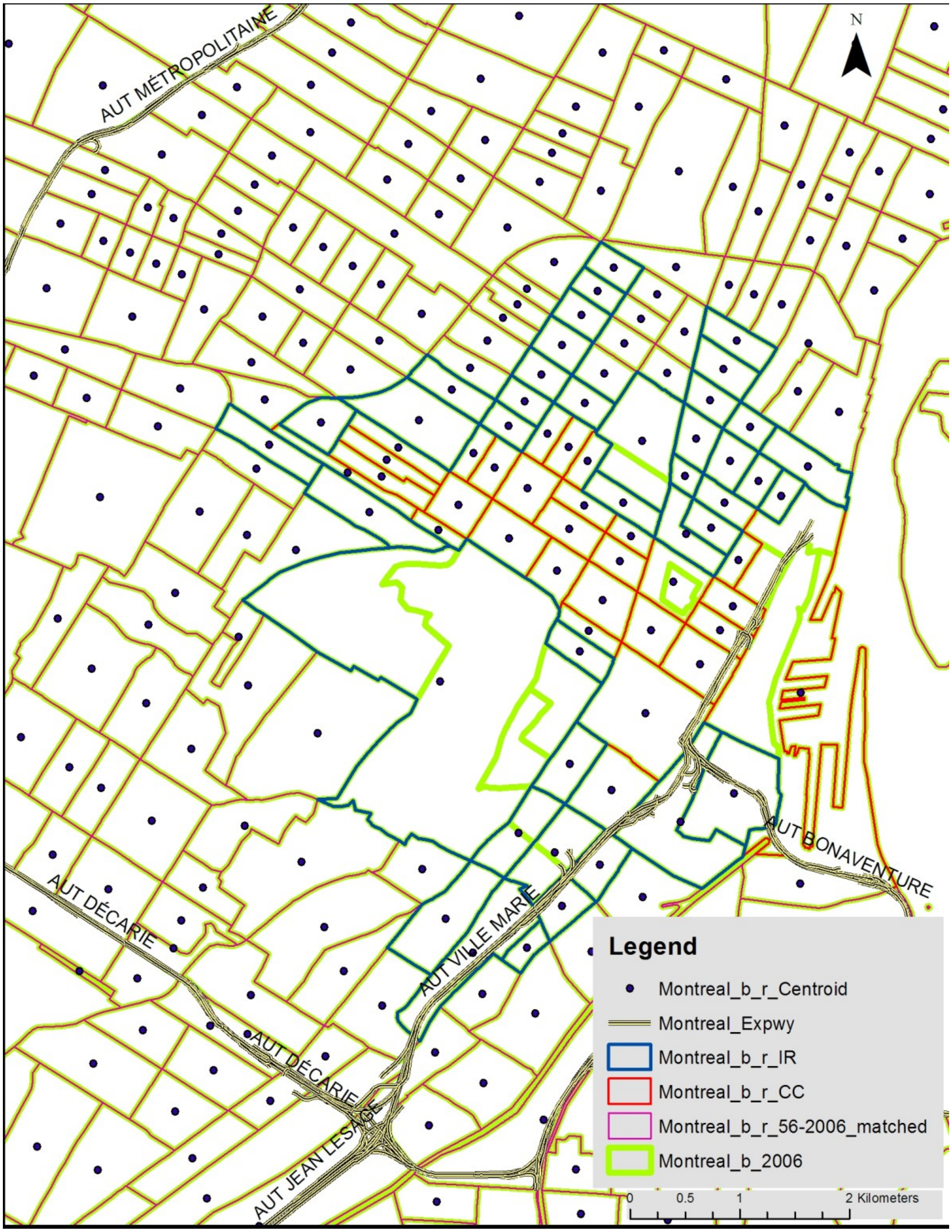


Appendix 2o - Victoria: 1956-2006 Census Tracts matched

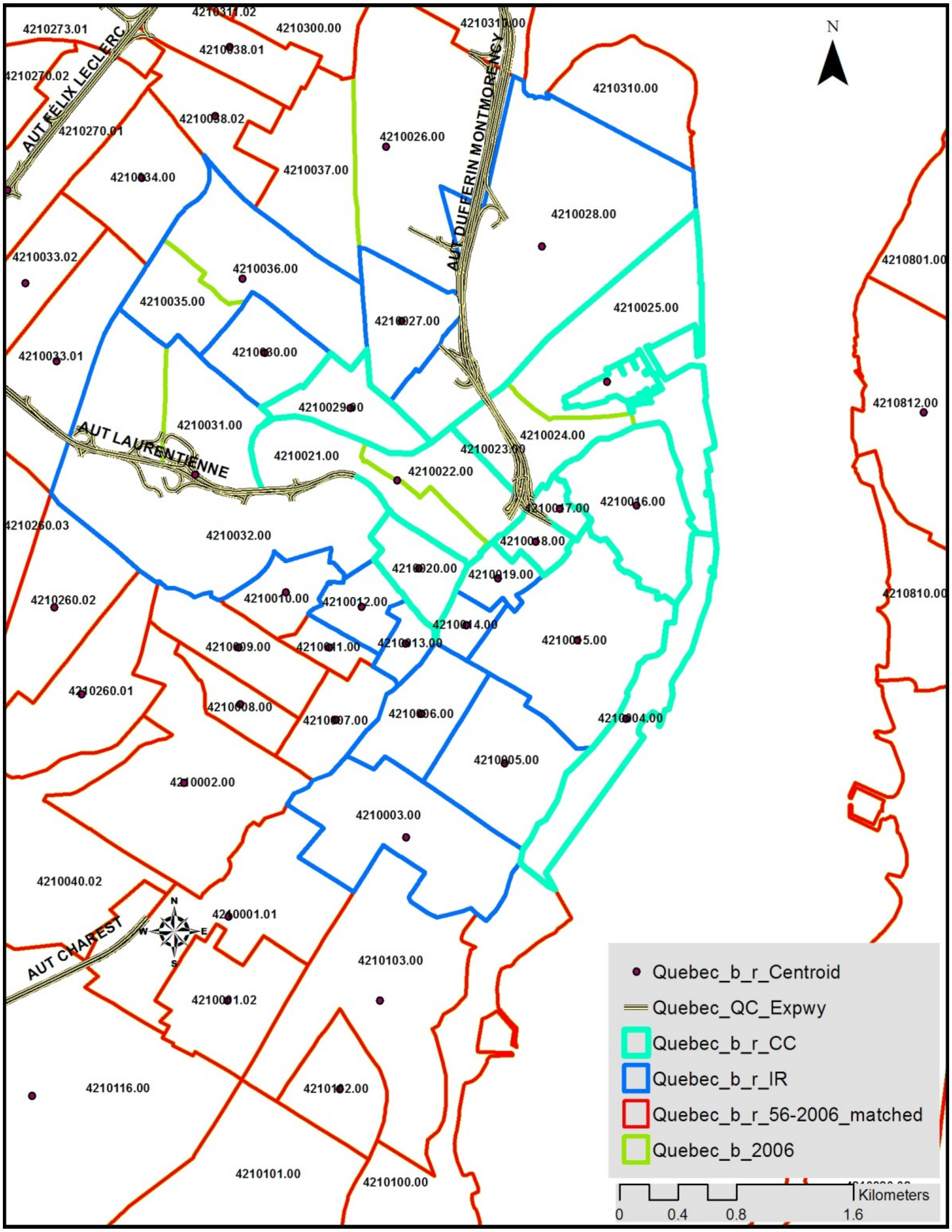


Appendix 2p to 2w - Inner-city showing freeway

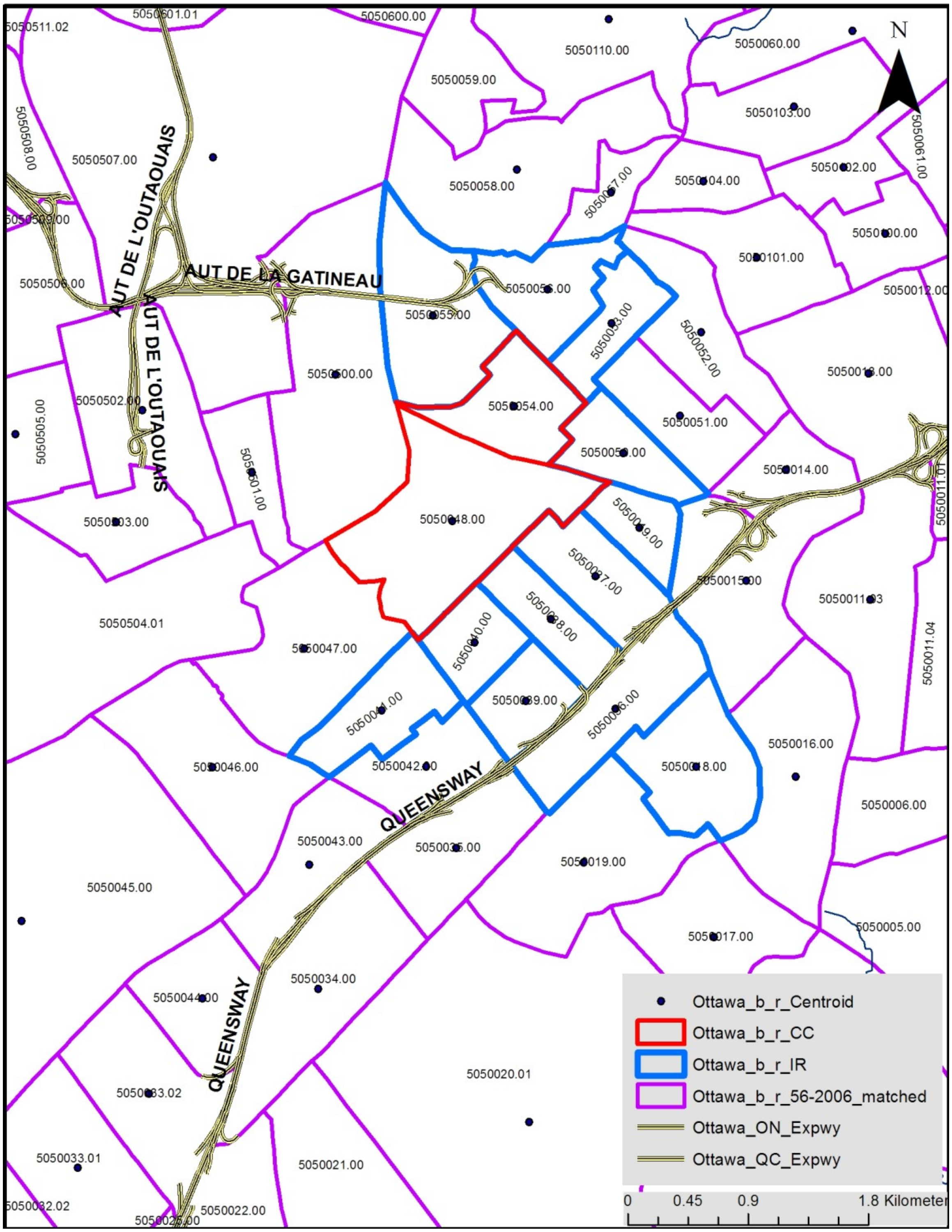
Appendix 2p - Montreal: inner-city showing Freeway



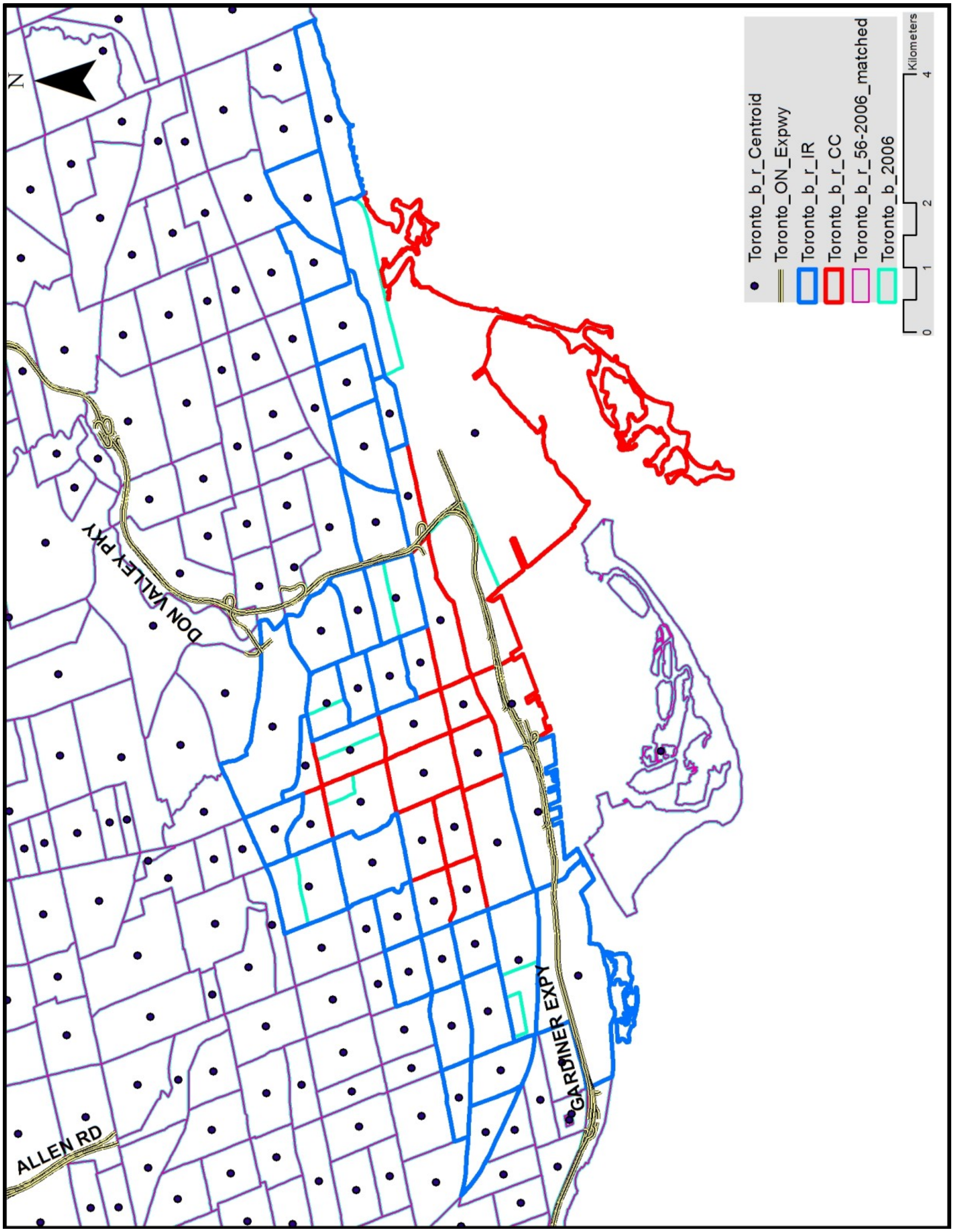
Appendix 2q - Quebec City: inner-city showing Freeway



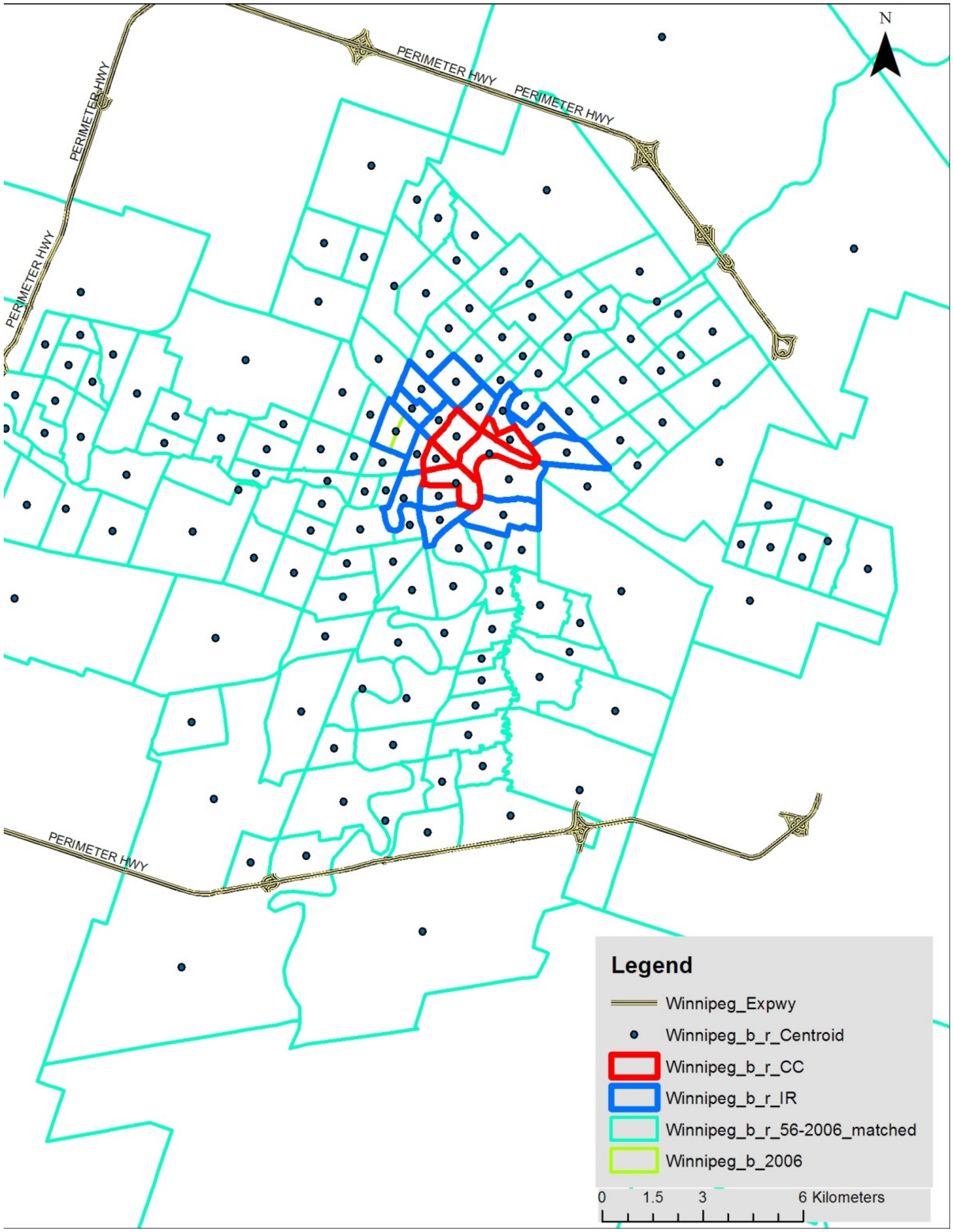
Appendix 2r - Ottawa: inner-city showing Freeway



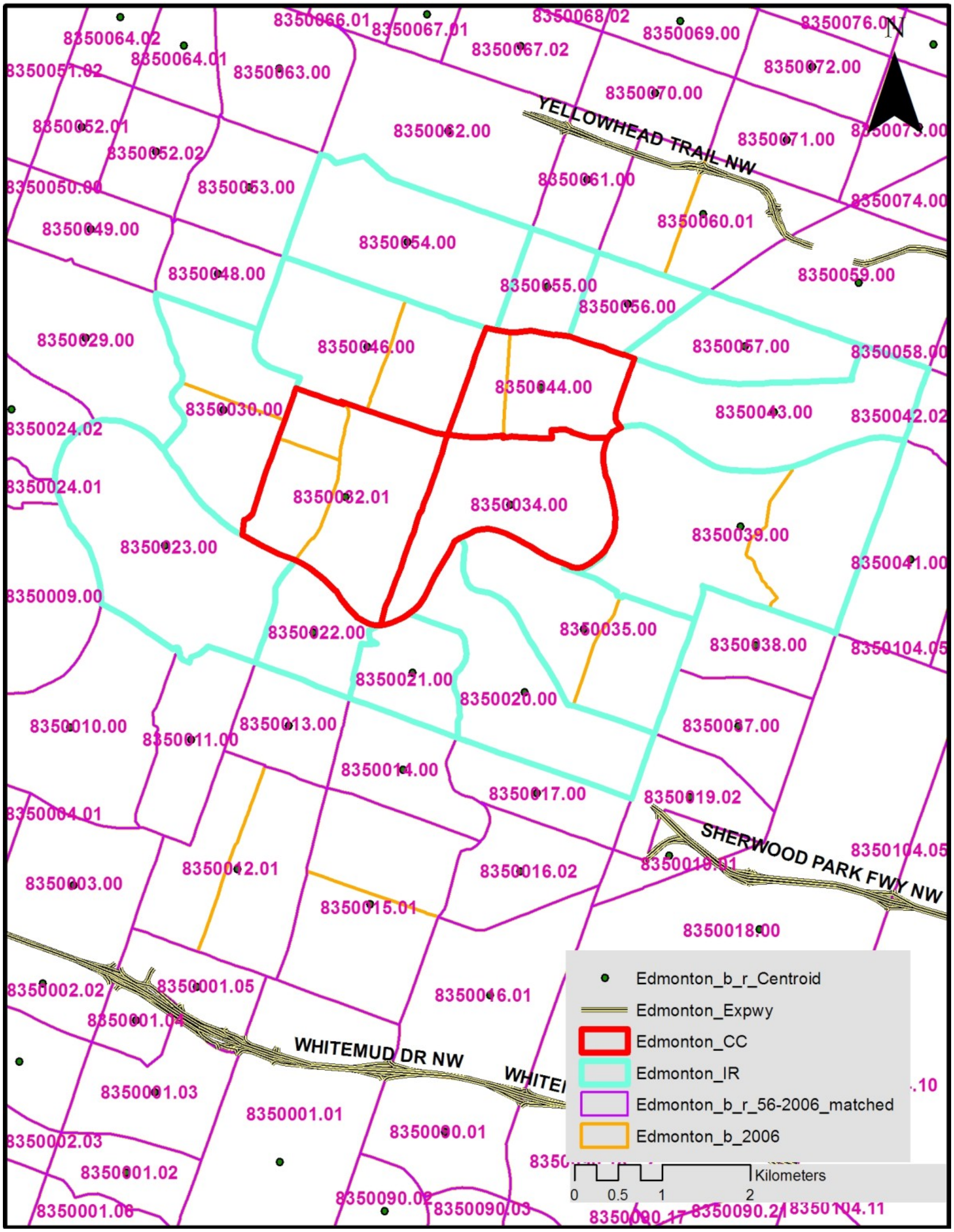
Appendix 2s - Toronto: inner-city showing Freeway



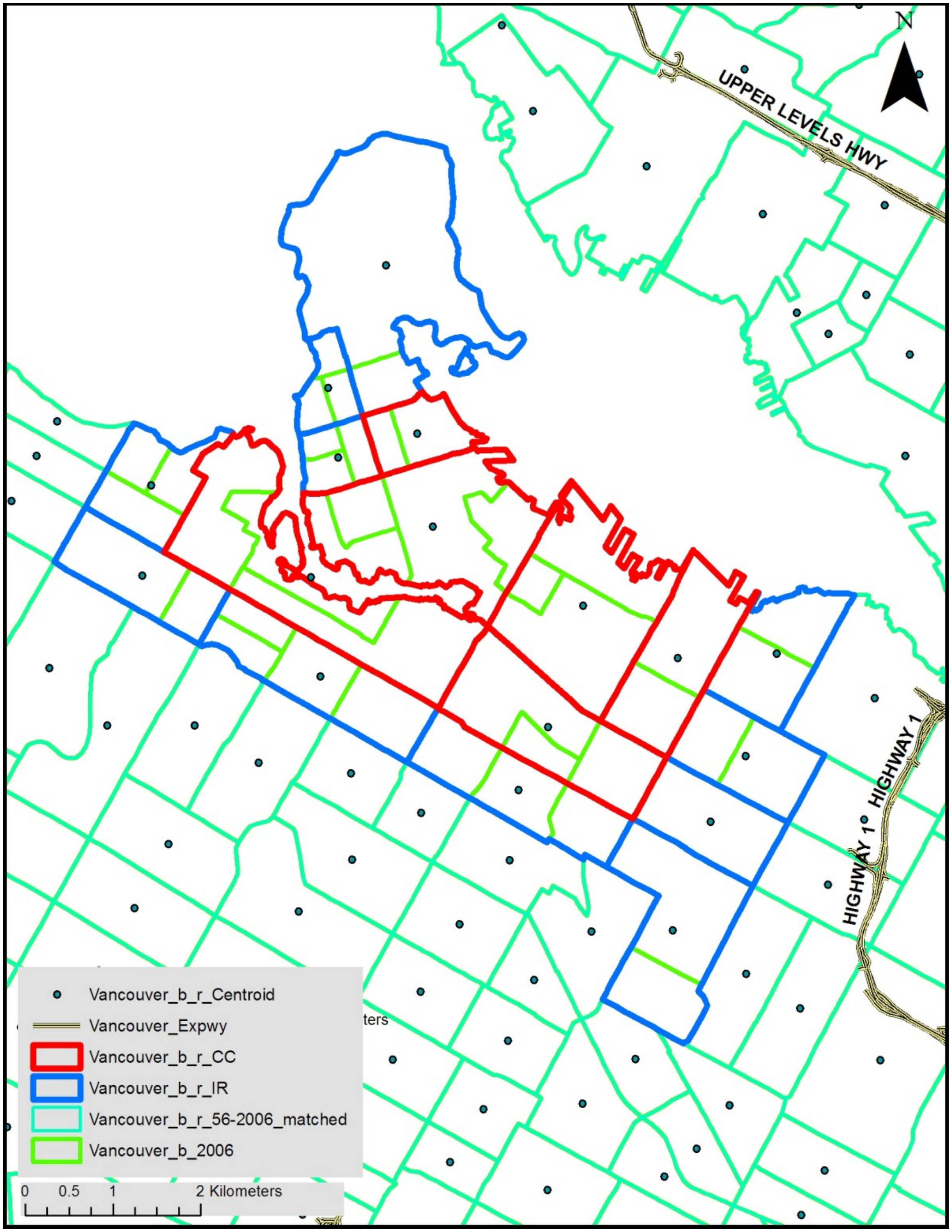
Appendix 2t - Winnipeg: inner-city showing Freeway



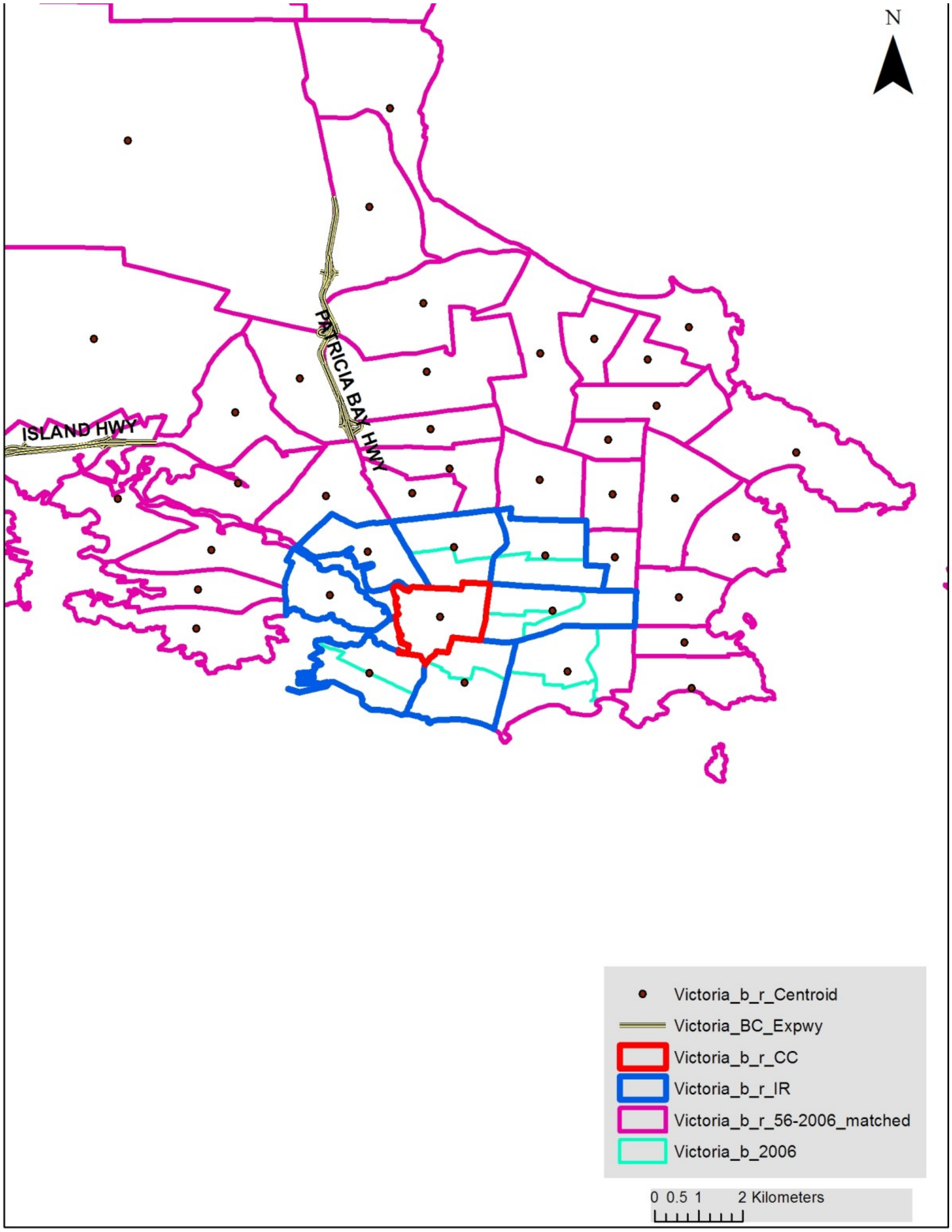
Appendix 2u - Edmonton: inner-city showing Freeway



Appendix 2v - Vancouver: inner-city showing Freeway

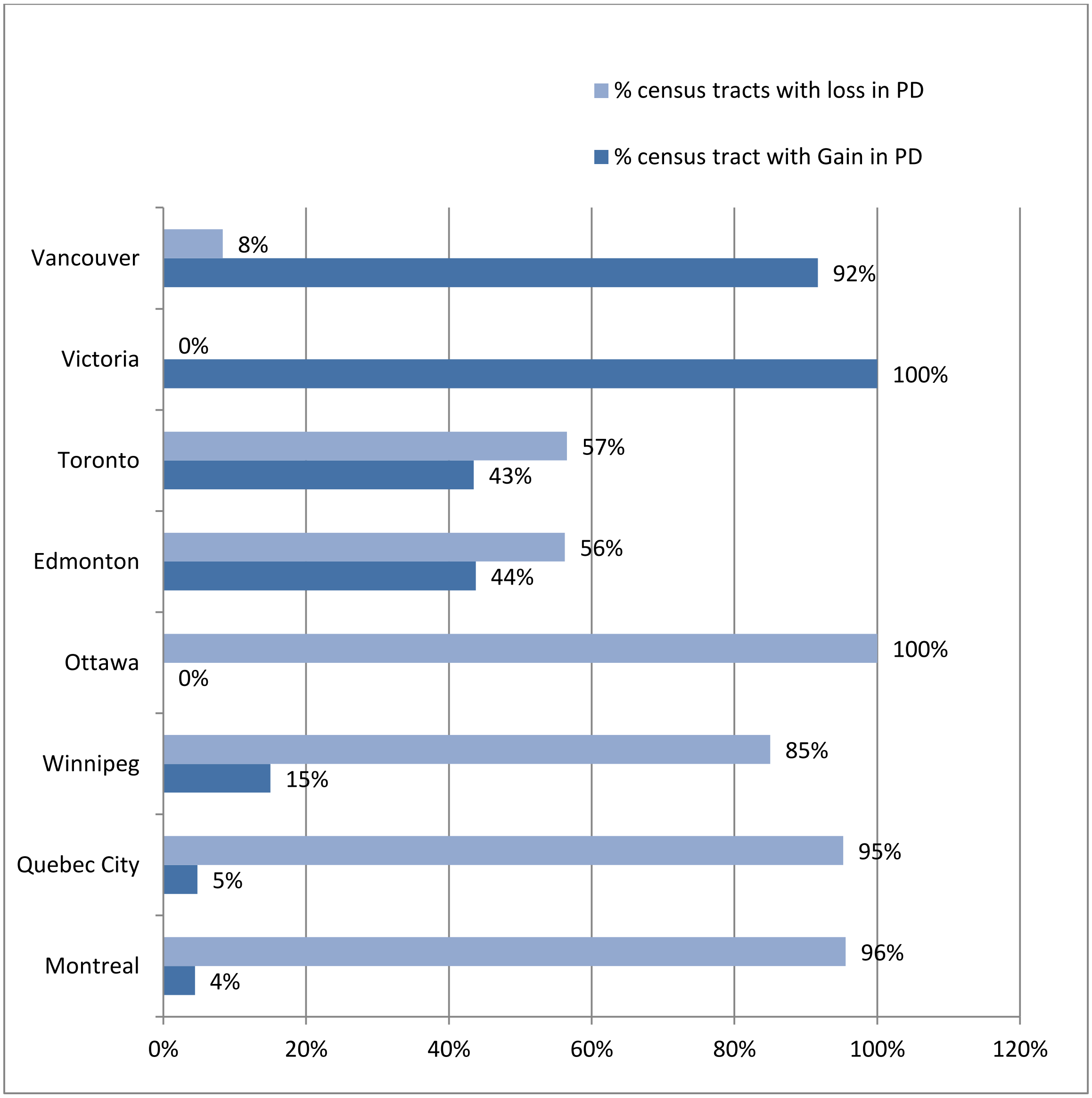


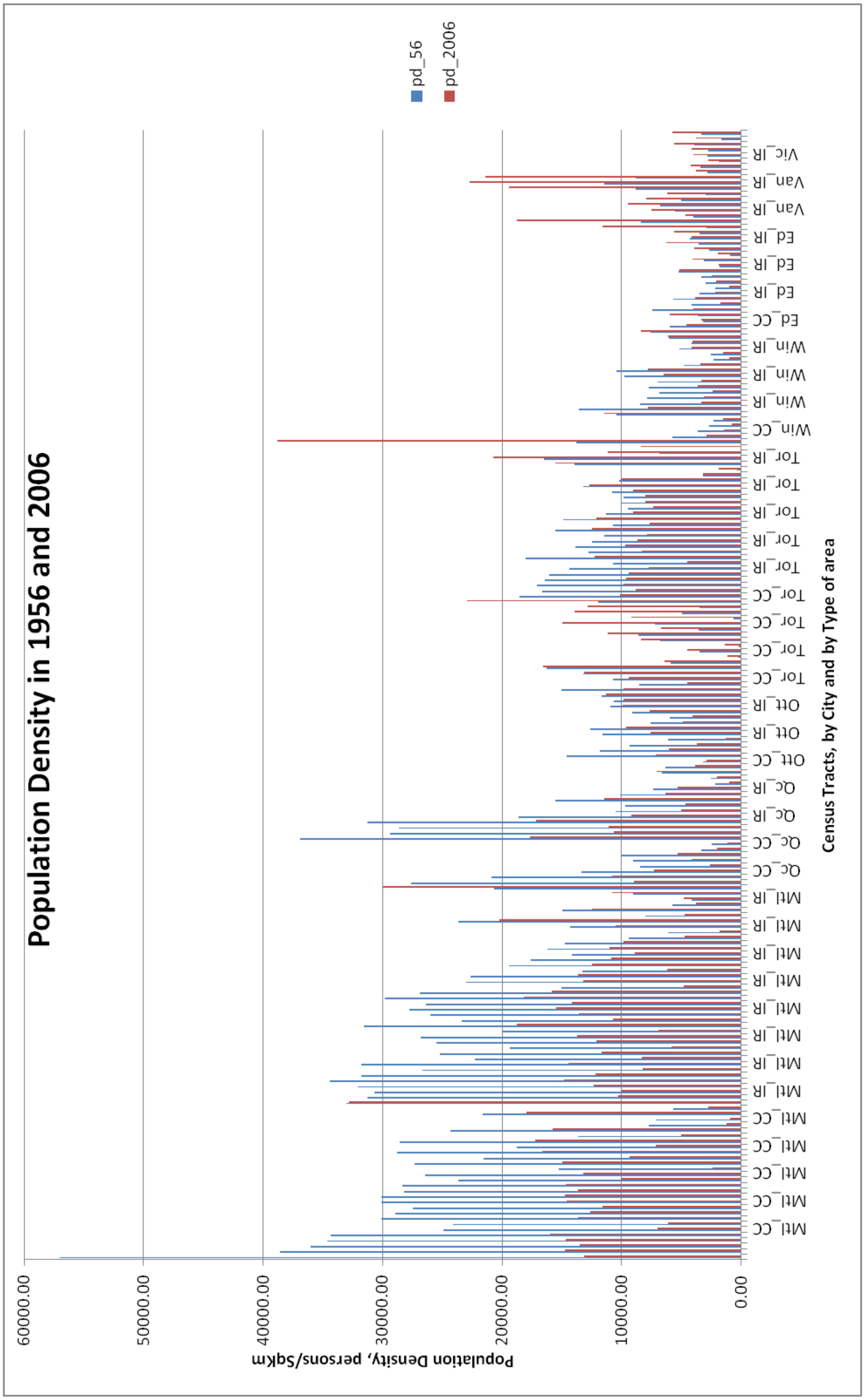
Appendix 2w - Victoria: inner-city showing Freeway



Appendix 3 - Snapshot of all cities

Appendix 3a - Percentage of census tracts with loss / gain in population density from 1956 to 2006

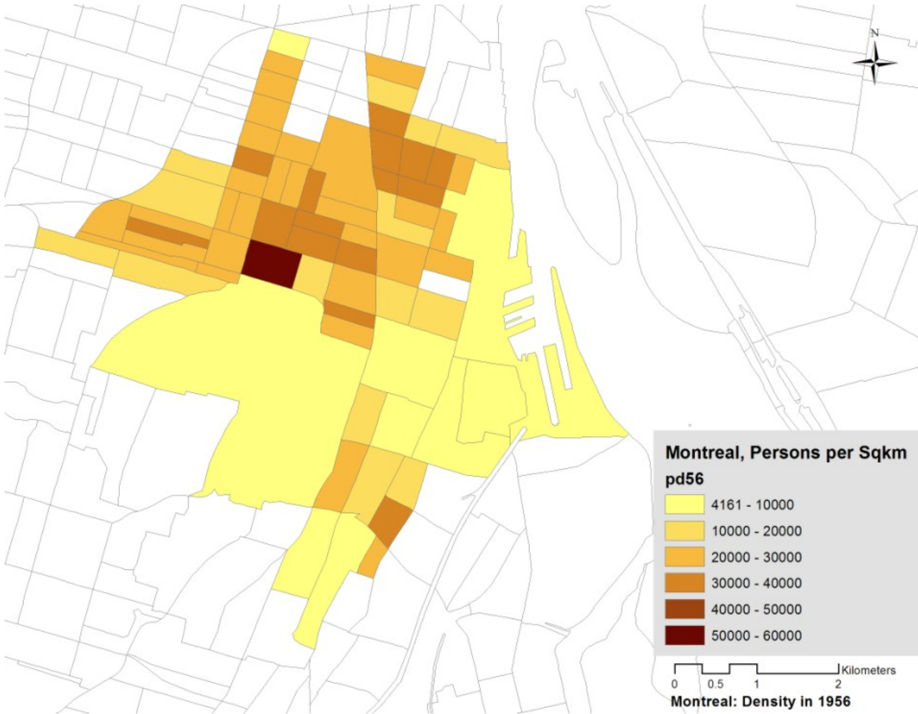


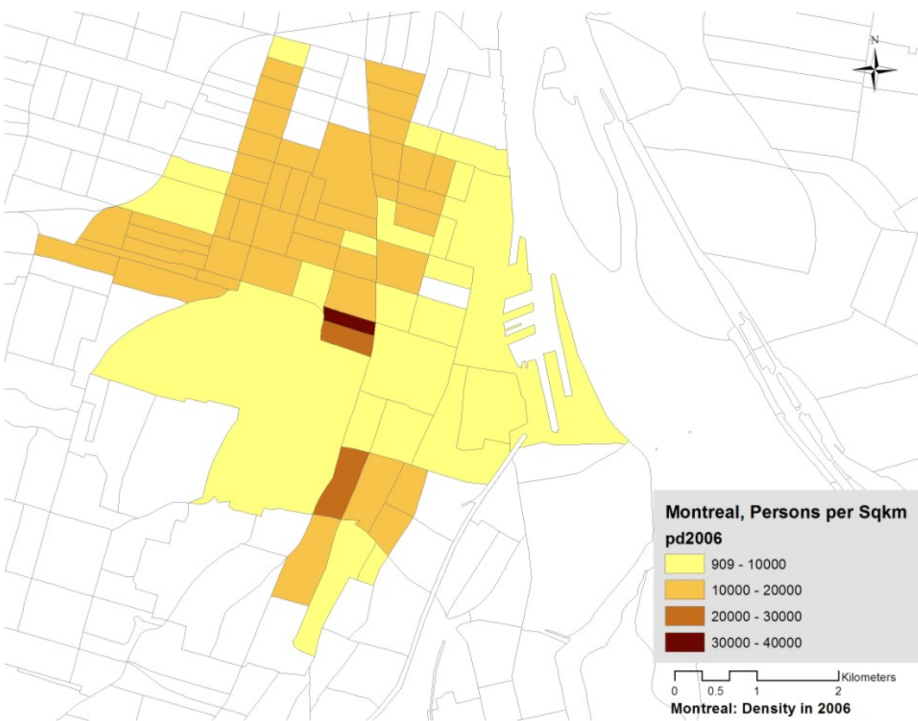


Appendix 3b - Population density in 1956 & 2006 in all census tracts

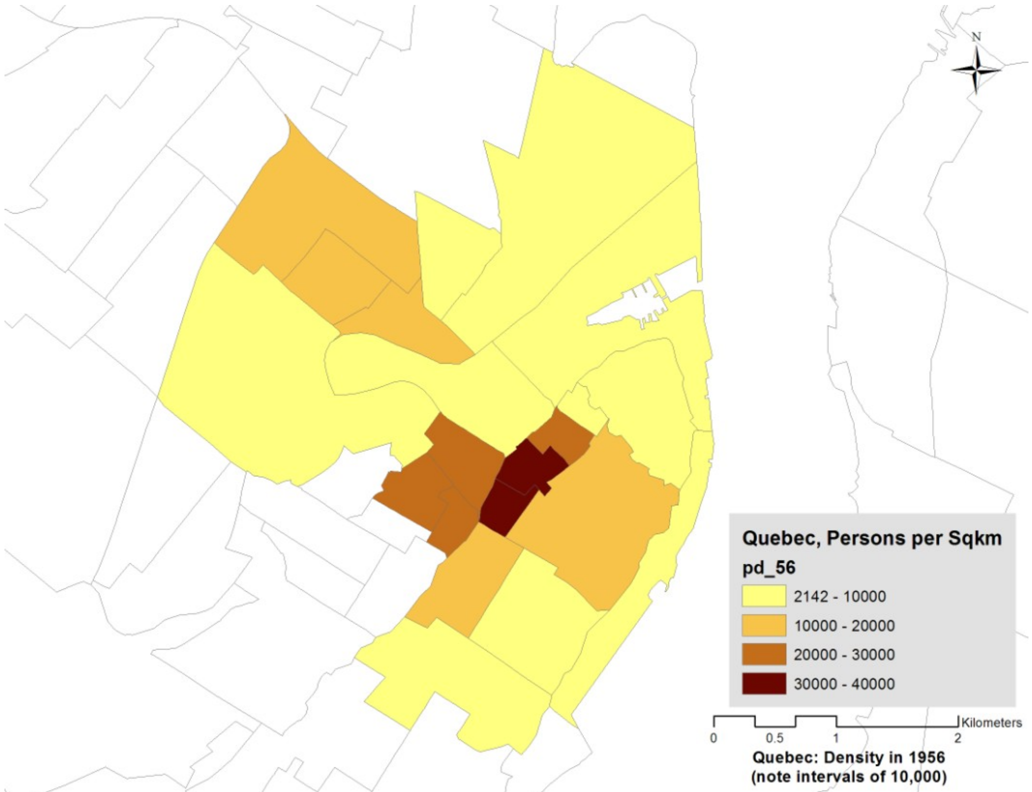
Appendix 4 - Density Diagrams for 1956 & 2006 for all cities

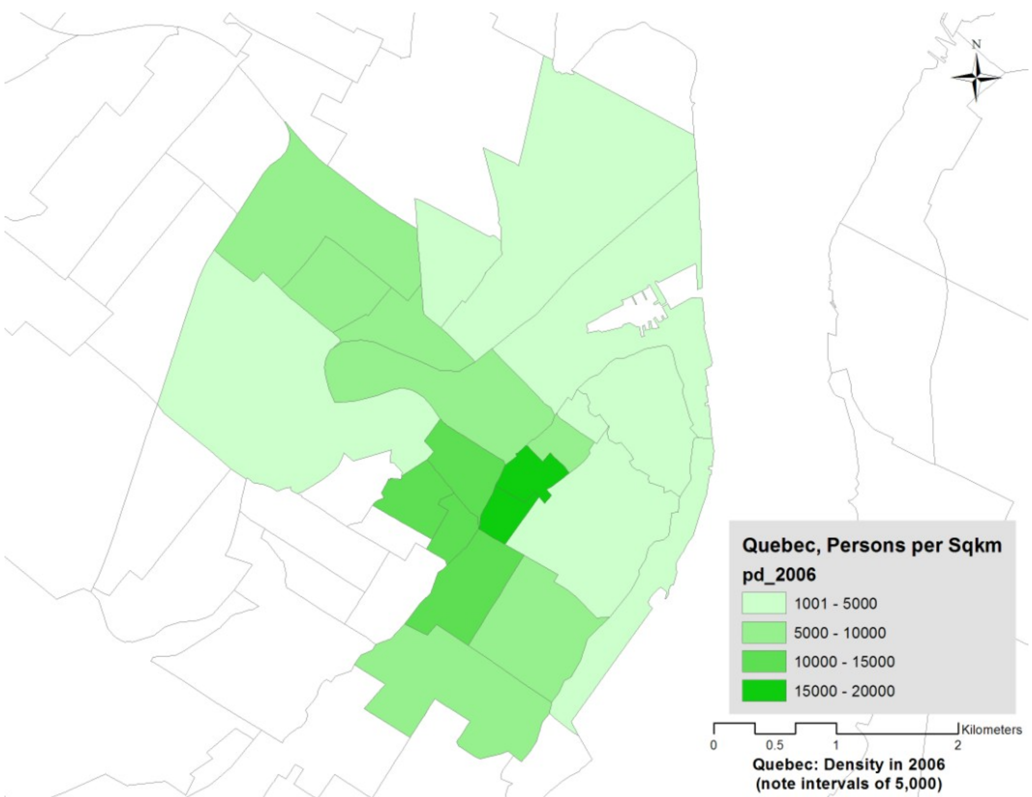
Appendix 4 - 1: Montreal



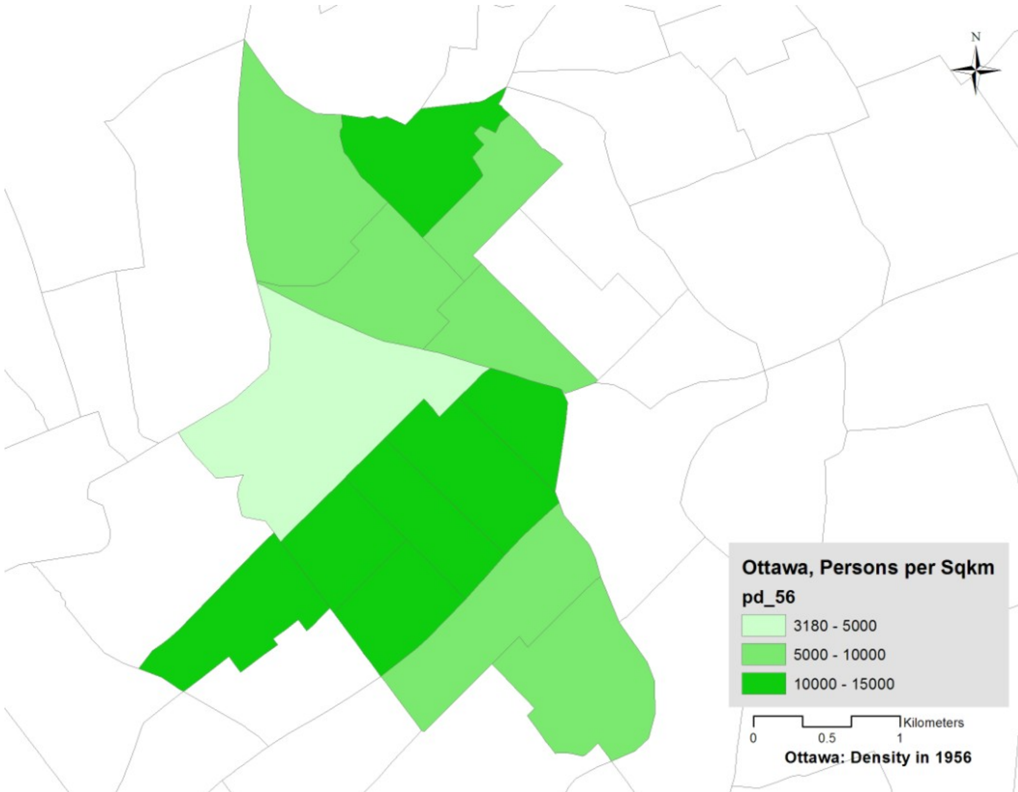


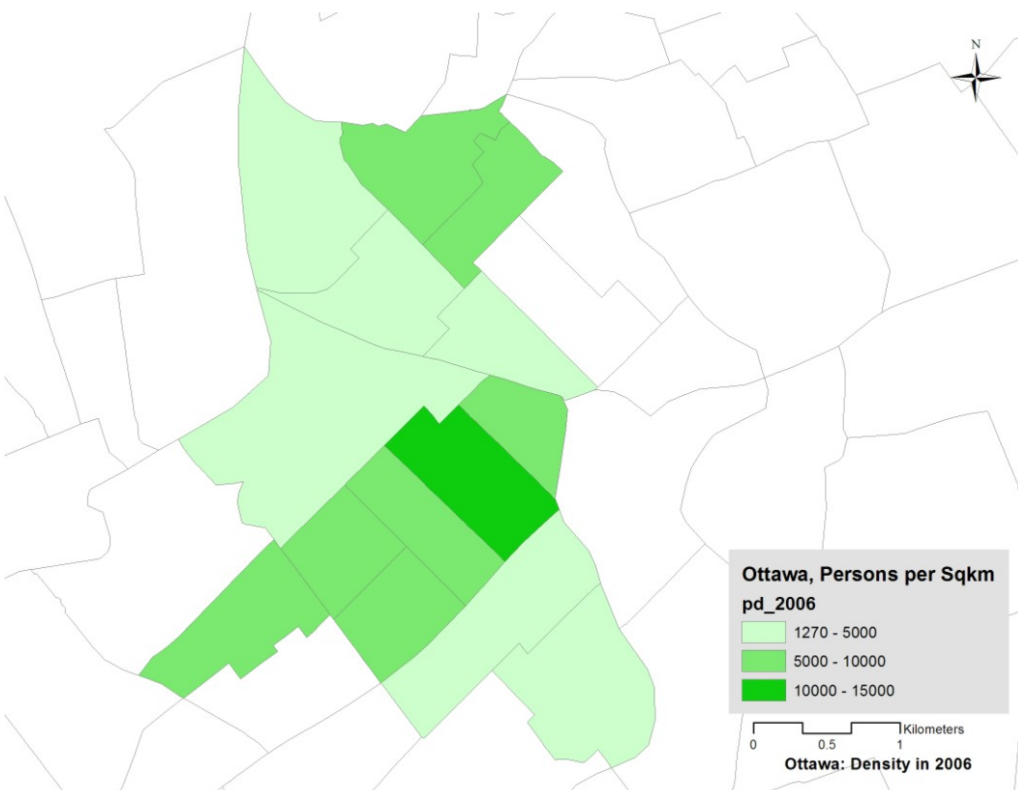
Appendix 4 - 2: Quebec



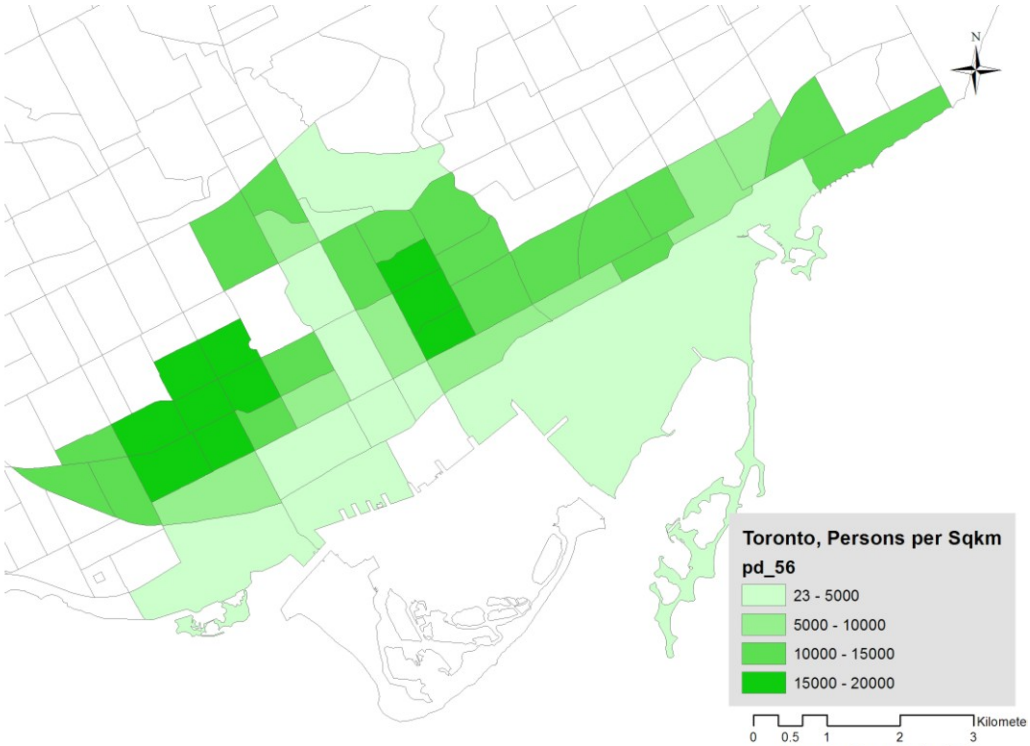


Appendix 4 - 3: Ottawa

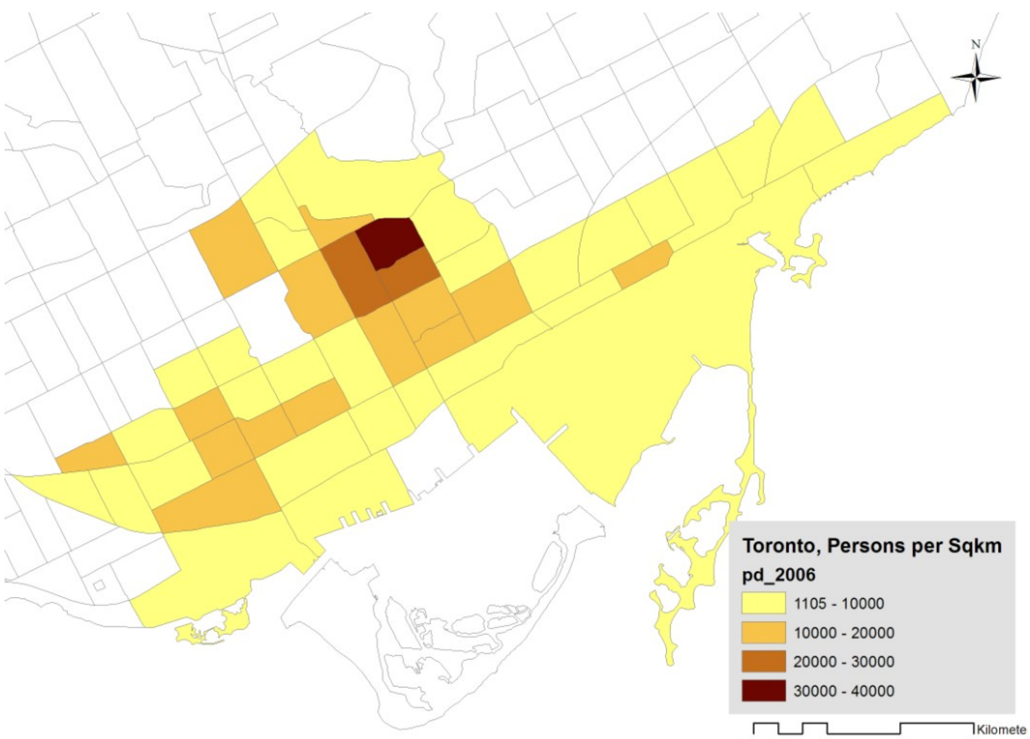




Appendix 4 - 4: Toronto

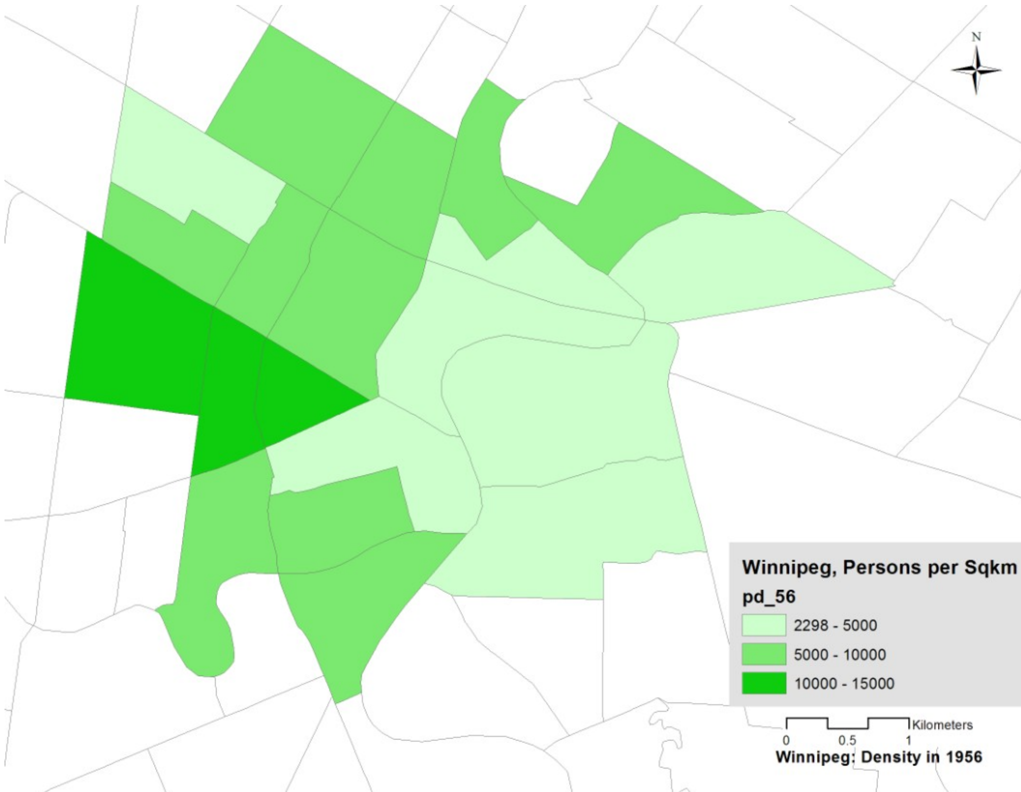


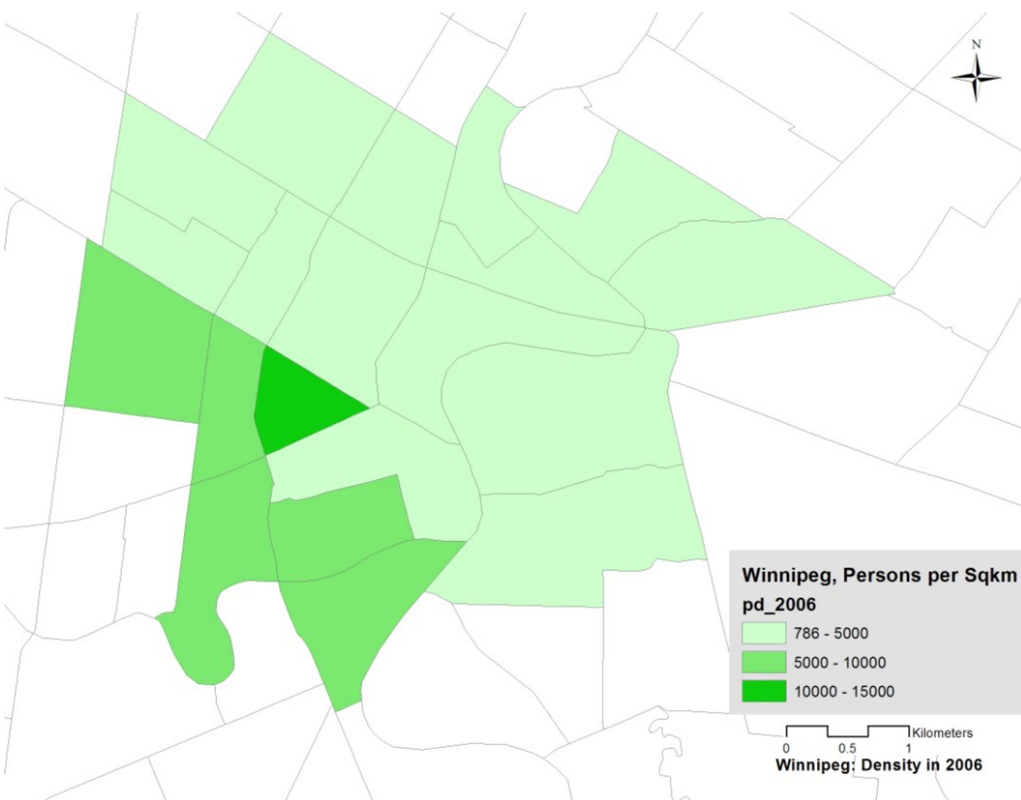
Toronto: Density in 1956
(note intervals of 5,000)



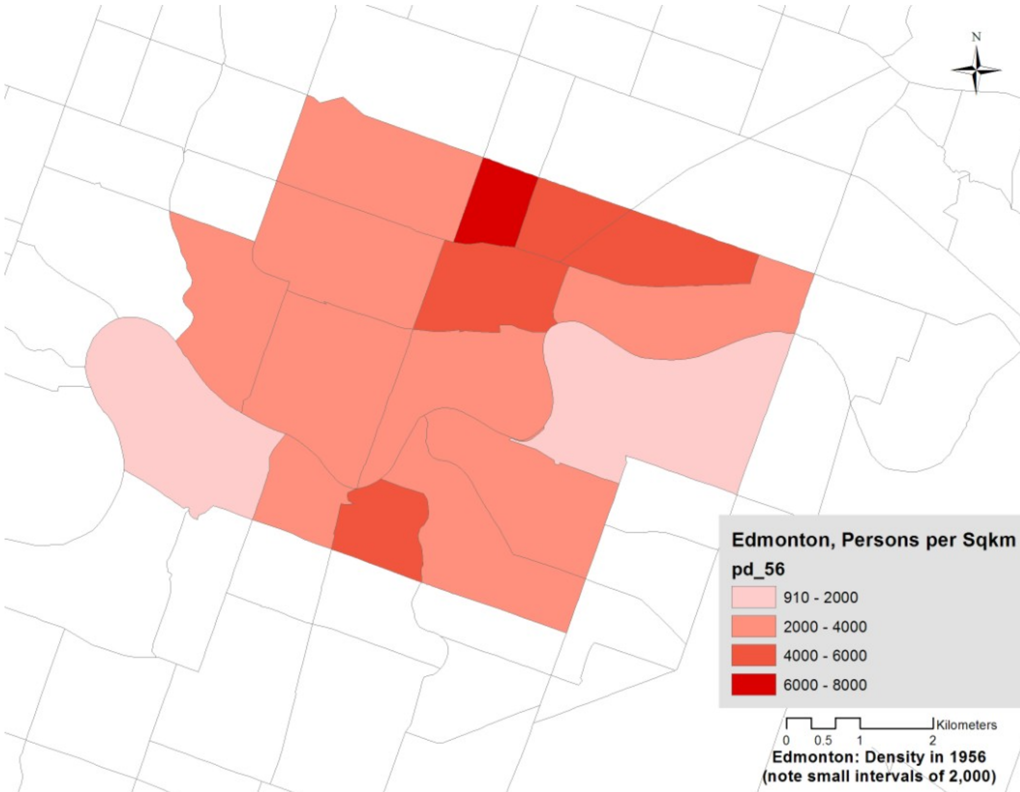
Toronto: Density in 2006
(note intervals of 10,000)

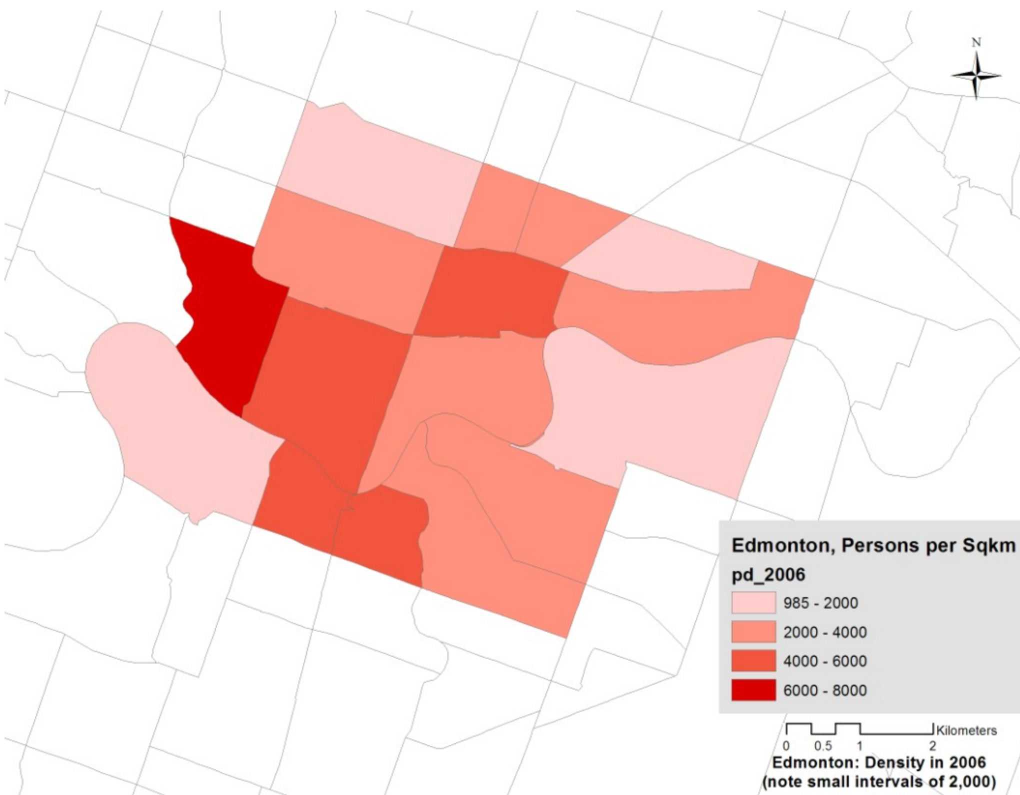
Appendix 4 - 5: Winnipeg



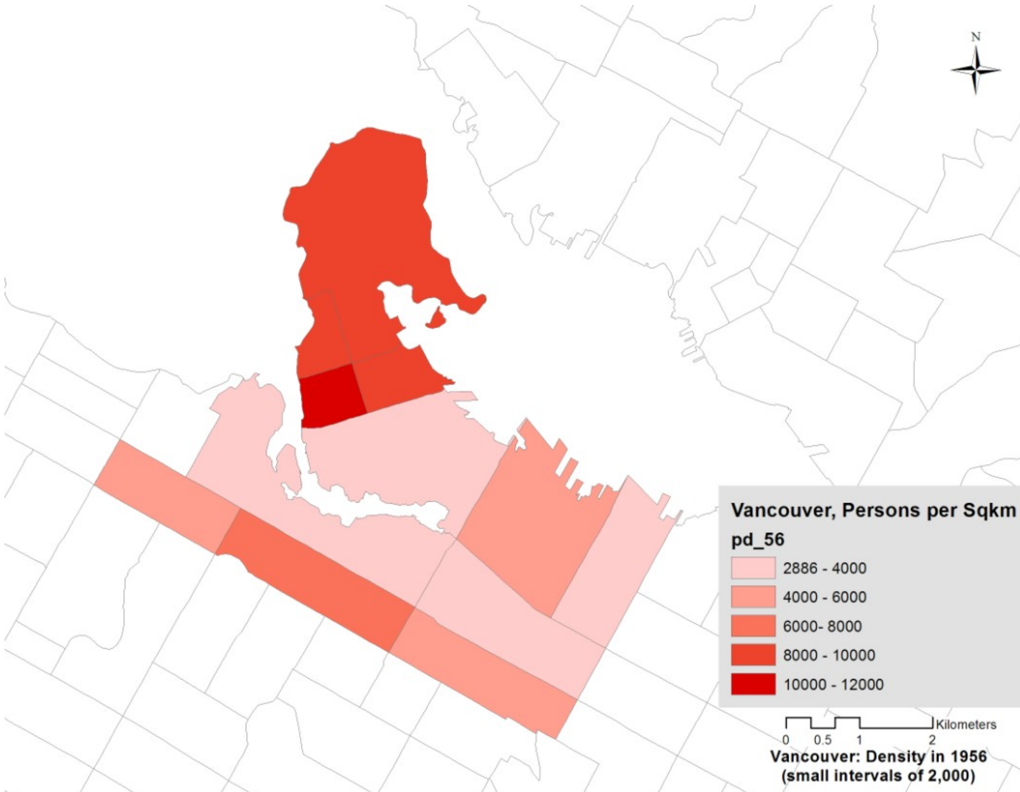


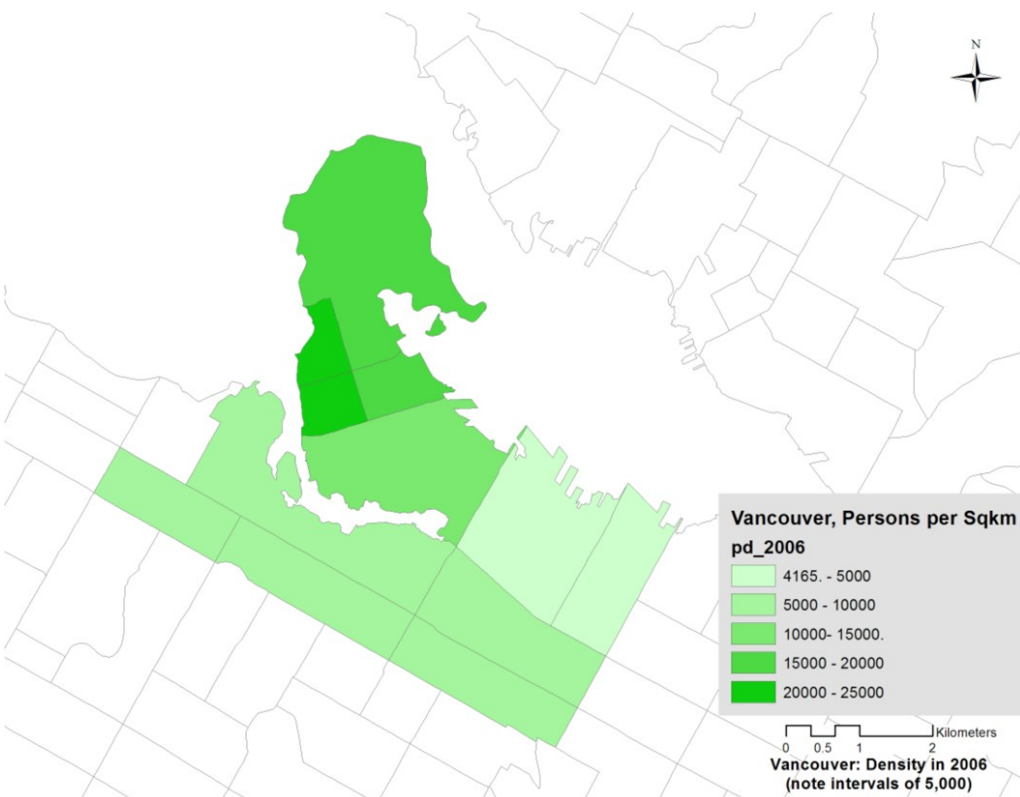
Appendix 4- 6: Edmonton



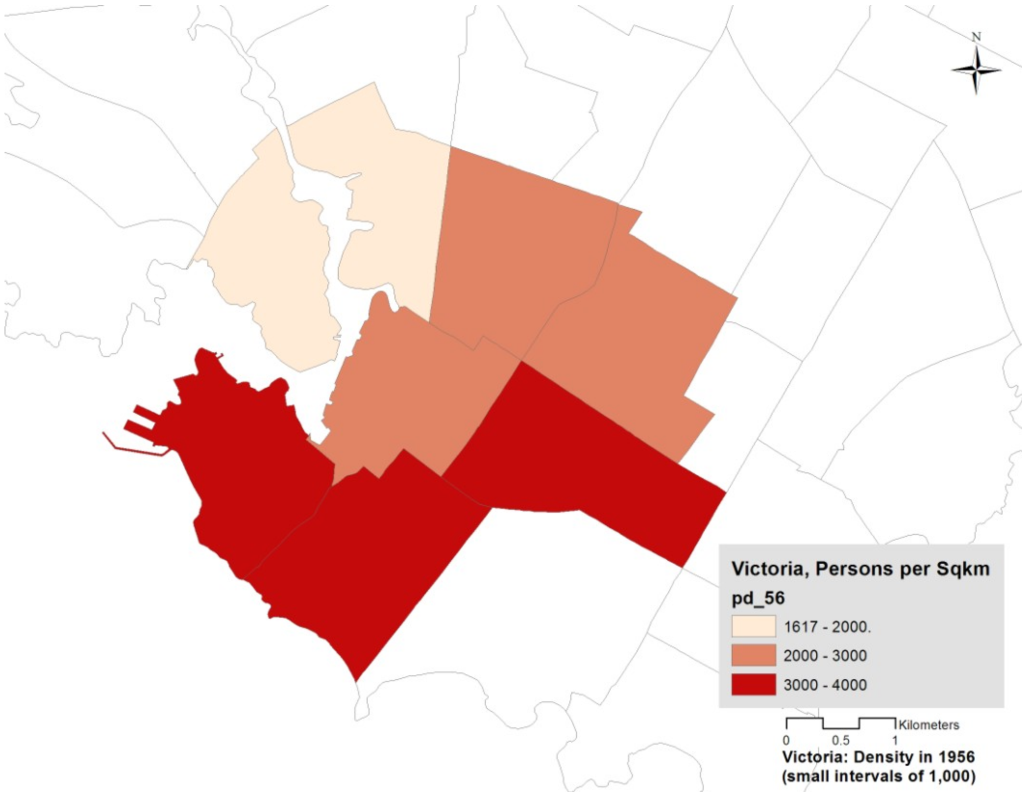


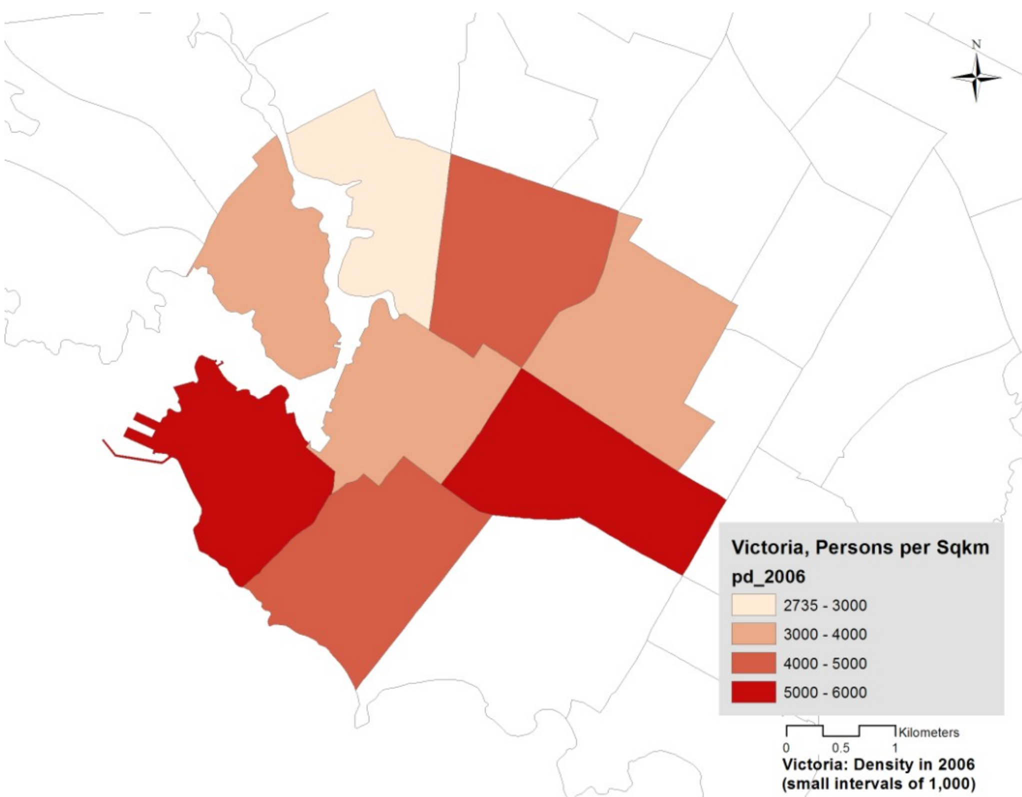
Appendix 4 - 7: Vancouver





Appendix 4- 8: Victoria





Appendix 5 - Aggregate summaries

Appendix 5a - Total population in 1956 and 2006

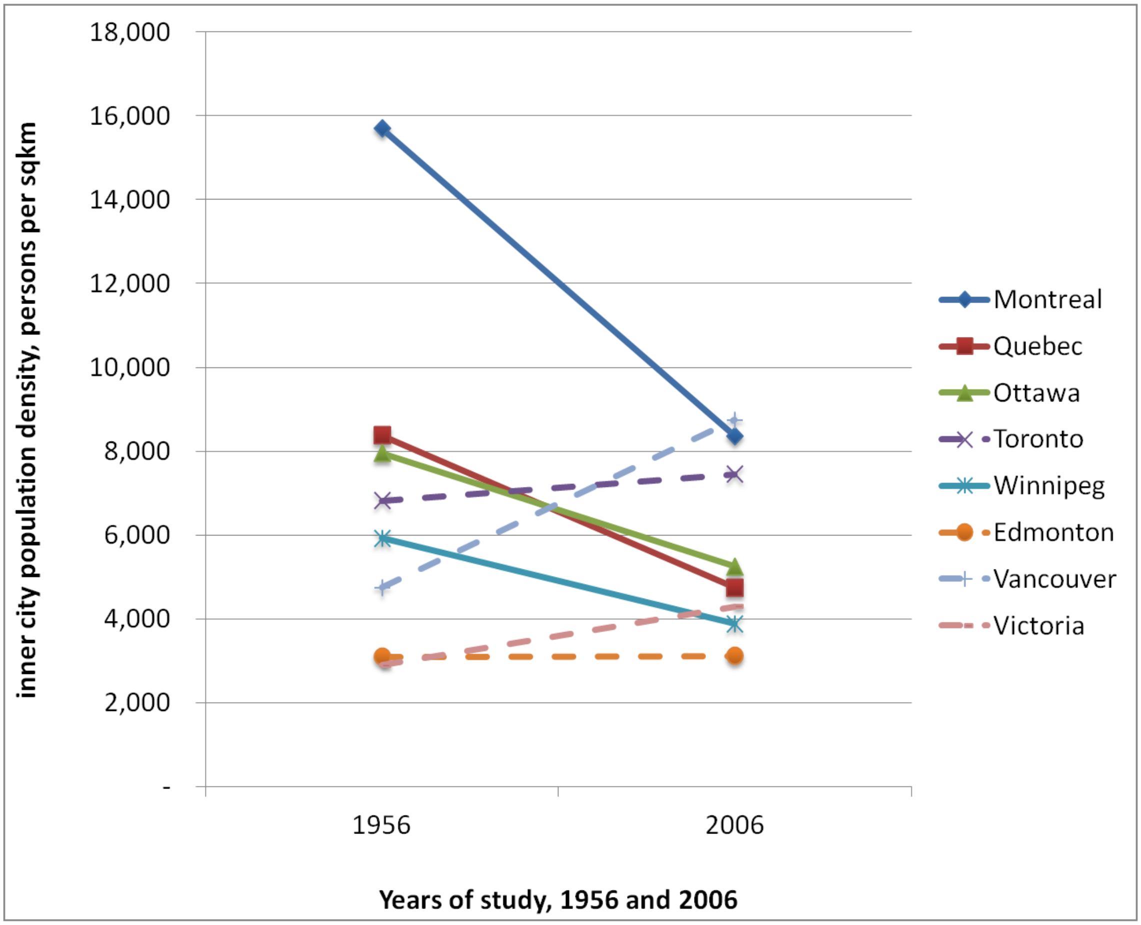
Aggregate (Inner city level) totals	Total 1956 inner city population	Total 2006 inner city population	Total aggregate loss in population from 1956 to 2006	Relative loss in population in the inner city (loss/1956Pop)
Montreal	307,615	164,005	143,610	0.47
Quebec	111,992	63,539	48,453	0.43
Ottawa	72,097	47,591	24,506	0.34
Toronto	234,100	255,647	(21,547)	-0.09
Winnipeg	109,731	71,967	37,764	0.34
Edmonton	109,565	110,559	(994)	-0.01
Vancouver	99,221	182,673	(83,452)	-0.84
Victoria	46,357	68,650	(22,293)	-0.48

Appendix 5b-1 - Population density in 1956 and 2006

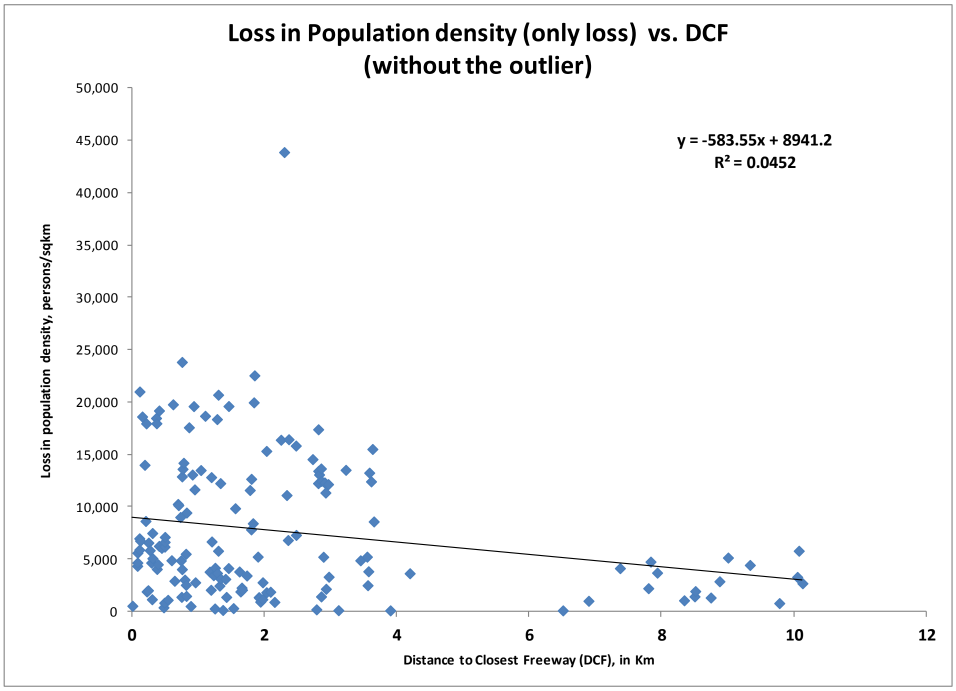
Aggregate (Inner city level) totals	Area for the inner city, sqkm	1956 inner city population density, people per sqkm	2006 inner city population density, people per sqkm	Loss in PD (1956 - 2006), as a whole for the inner city	Relative loss in PD (loss/1956PD)
Montreal	19.60	15,694.64	8,367.60	7,327.04	0.47
Quebec	13.37	8,376.36	4,752.36	3,624.01	0.43
Ottawa	9.06	7,957.73	5,252.87	2,704.86	0.34
Toronto	34.31	6,823.08	7,451.09	(628.01)	-0.09
Winnipeg	18.52	5,925.00	3,885.91	2,039.09	0.34
Edmonton	35.42	3,093.31	3,121.37	(28.06)	-0.01
Vancouver	20.88	4,751.96	8,748.71	(3,996.74)	-0.84
Victoria	15.98	2,900.94	4,295.99	(1,395.06)	-0.48

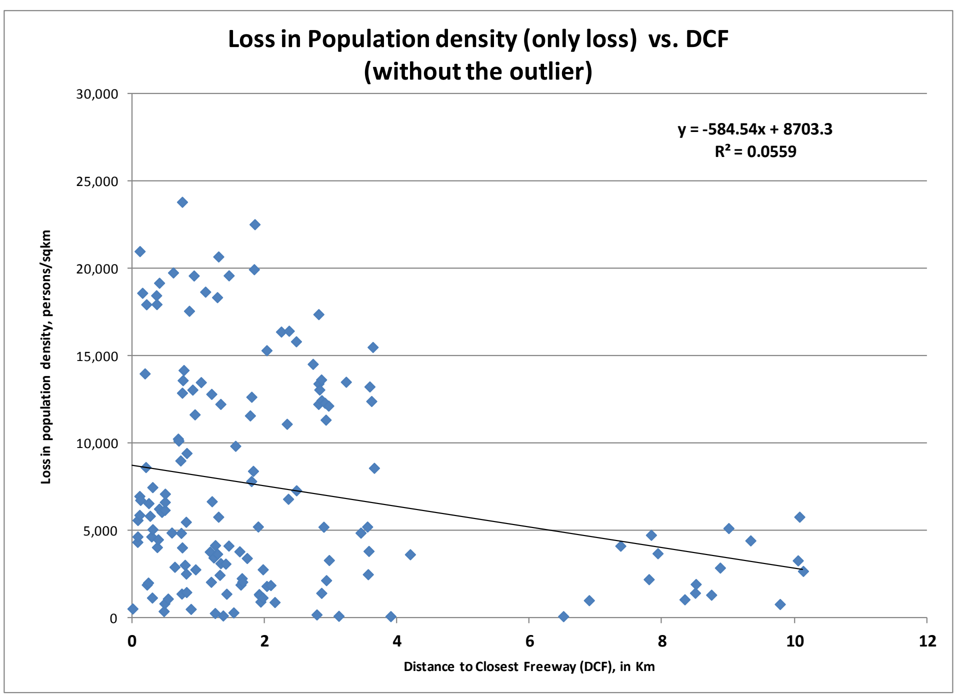
Note: the relative loss in population and population density (a) and (b) is the same due to the same area used for both 1956 and 2006.

Appendix 5b-2 - Aggregate population density in 1956 and 2006



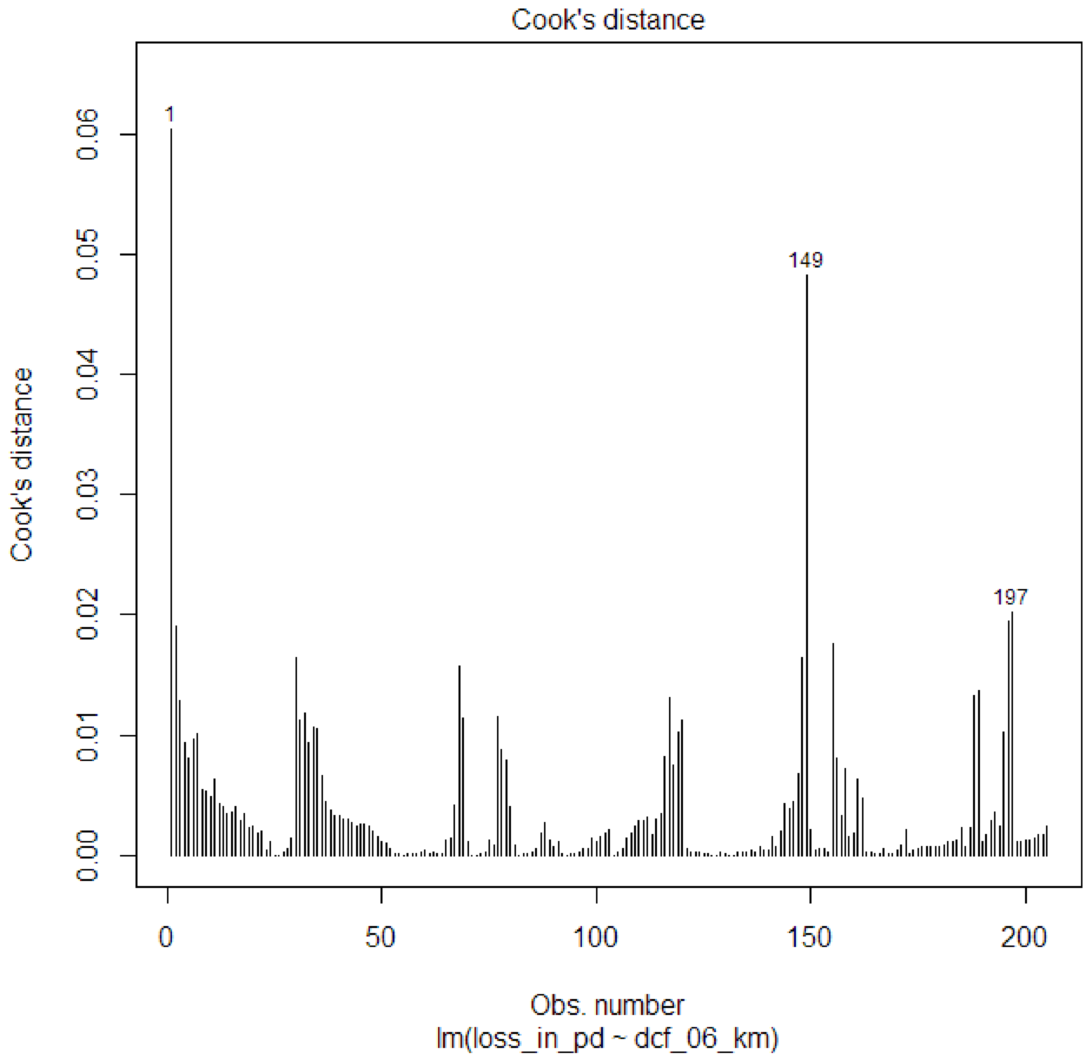
Appendix 6 - Relationship between loss in density and distance to freeway - only for census tracts that experienced a loss.





Appendix 7 - Testing for Outliers

Appendix 7a - Cook's D plot for LPD vs DCF

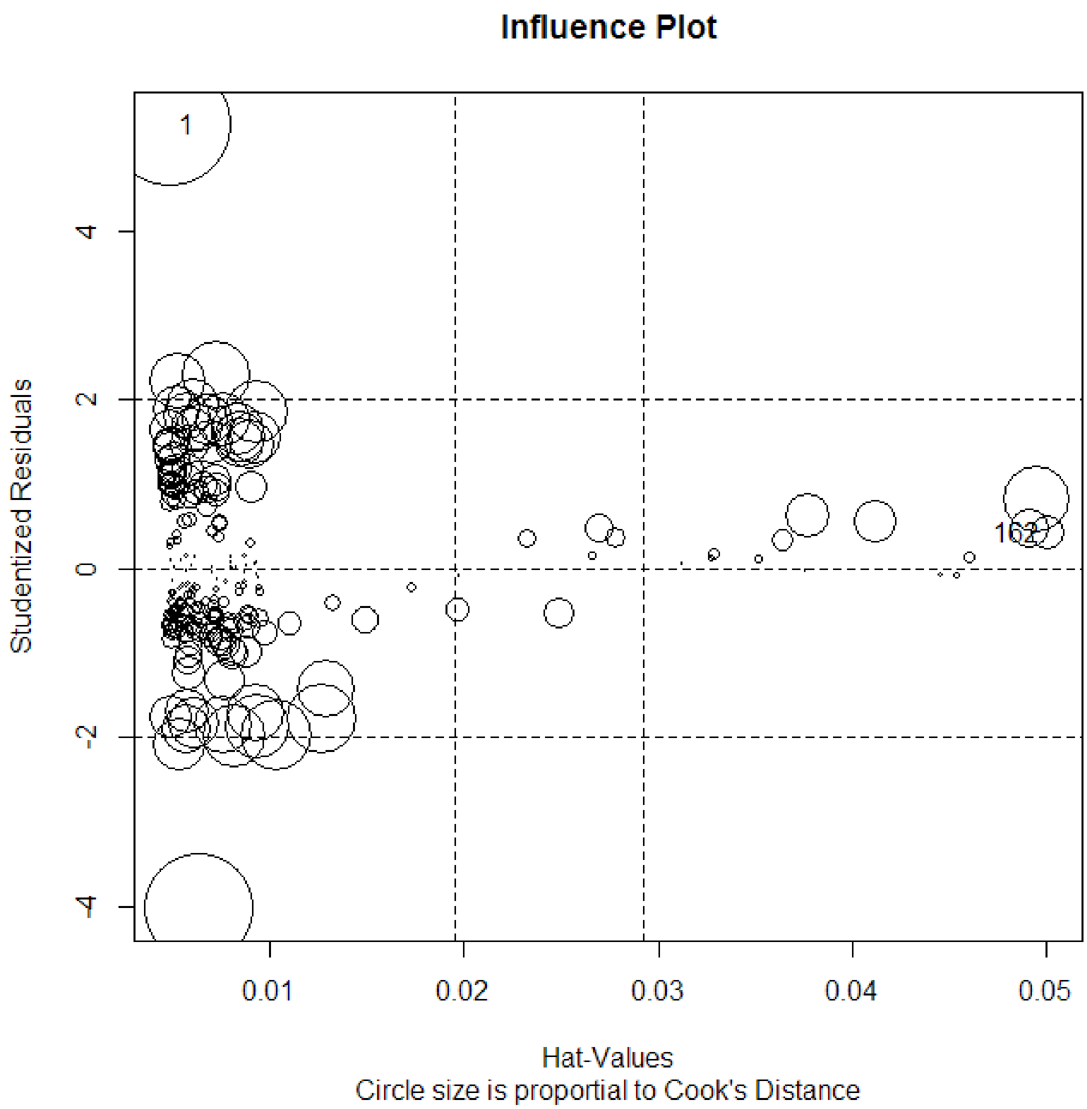


Observation 1: Montreal census tract with loss in density of over 43,000 (population in 1956: 8,837, in 2006: 2,039; area: 0.15 km^2; census tract (2006): 4620138; Location: Ave du Parc, Ave Mont-Royal, St- Laurent st. and Duluth (map below).

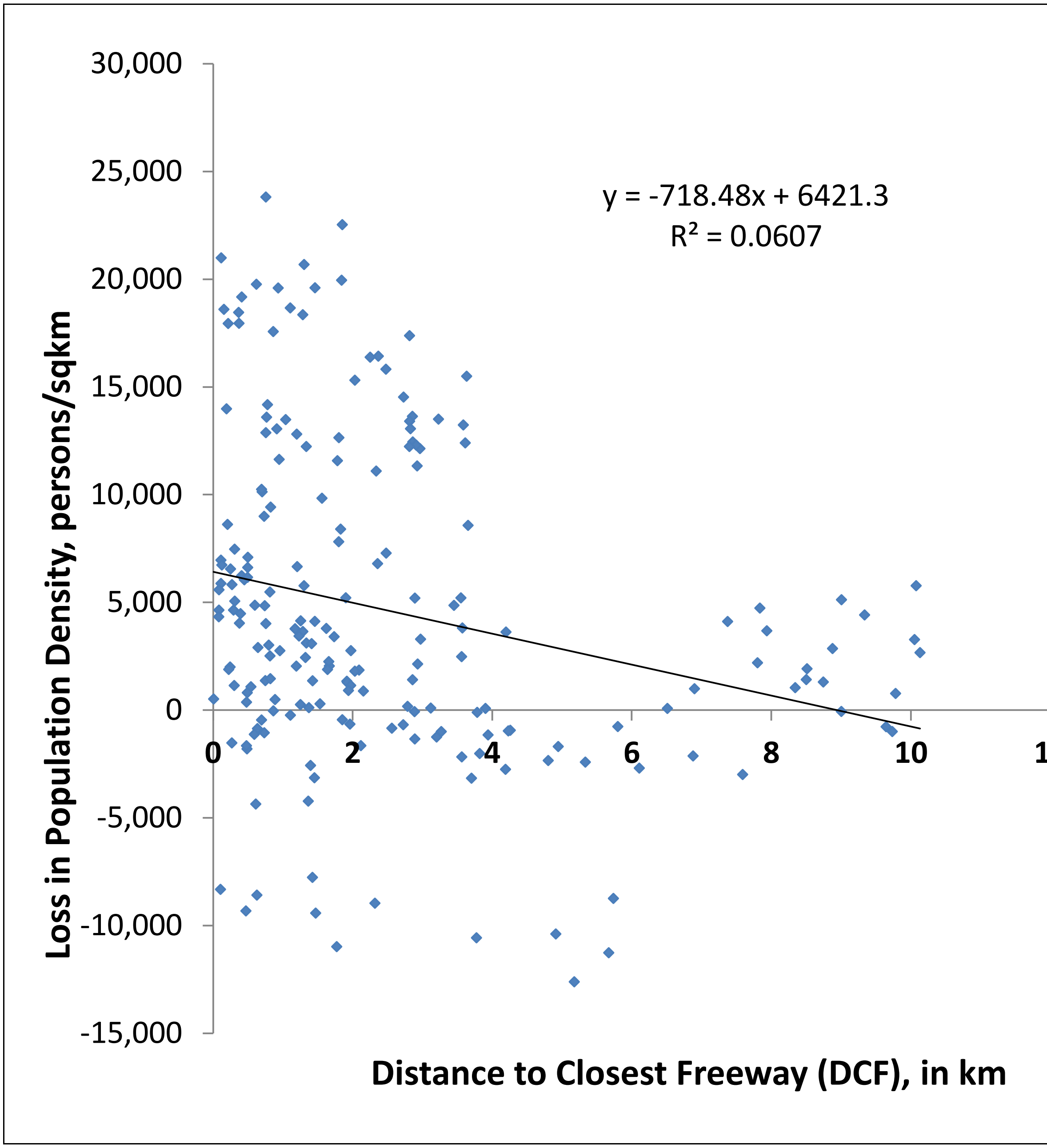
Observation 149: Toronto census tract with gain in density of over 25,000 (population in 1956: 6,086, in 2006: 17,114; area: 0.44 km^2; census tract (2006): 5350064; Location: Quadrilateral bound by Jarvis st., Bloor st. E., Parliament and Wellesley (map below).

Observation 197: It is at the borderline of 0.02 (the calculated cutoff); I also ran the model without this data point and the R^2 was not much different (after removing two outliers: 0.06 and after removing the third borderline outlier, it is 0.057).

Appendix 7b - Influence plot for LPD vs DCF

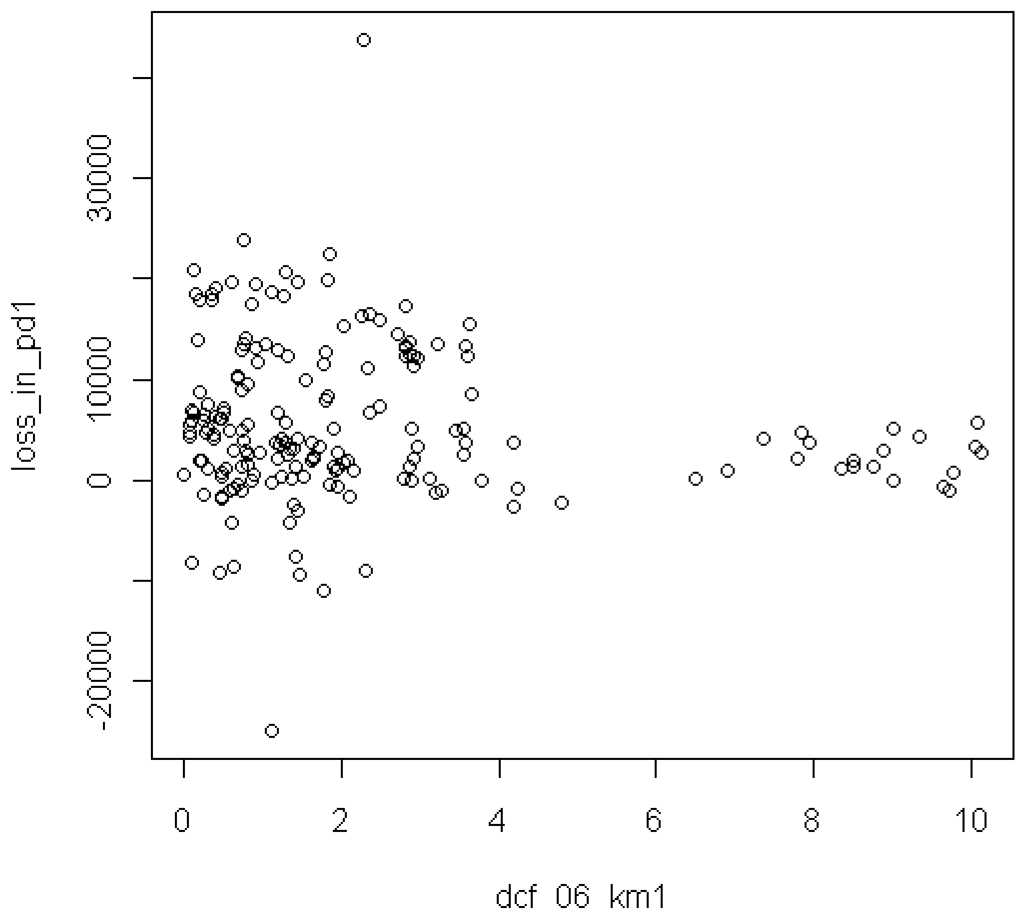


Appendix 7c - Plots for relationship between Loss in Density and Distance to Freeway without the two outliers (from the Cook's Distance plot)



Appendix 7d - plot without Vancouver and Victoria (185 data points)

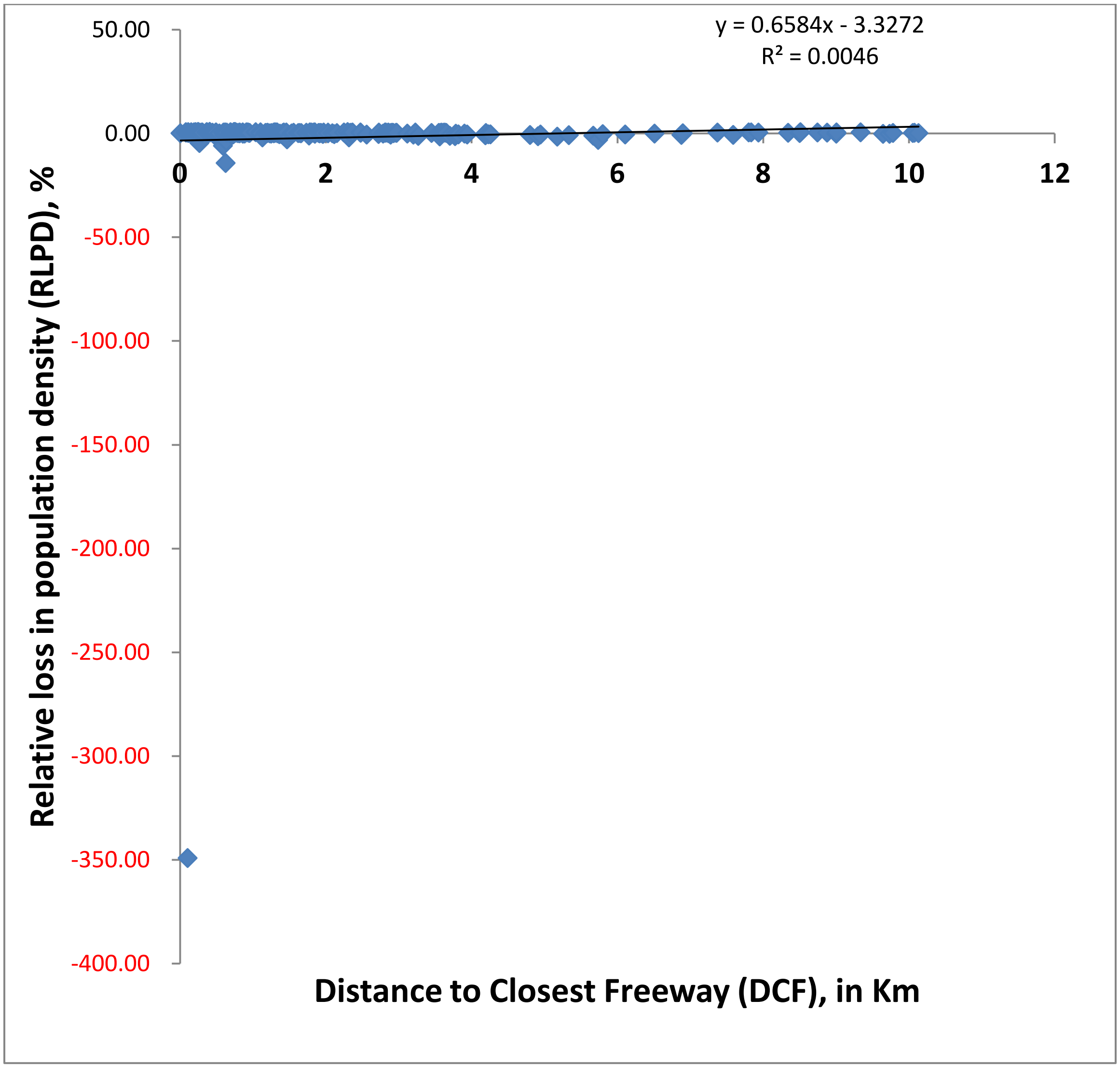
(that had almost all gains)



Multiple R-squared: 0.01577

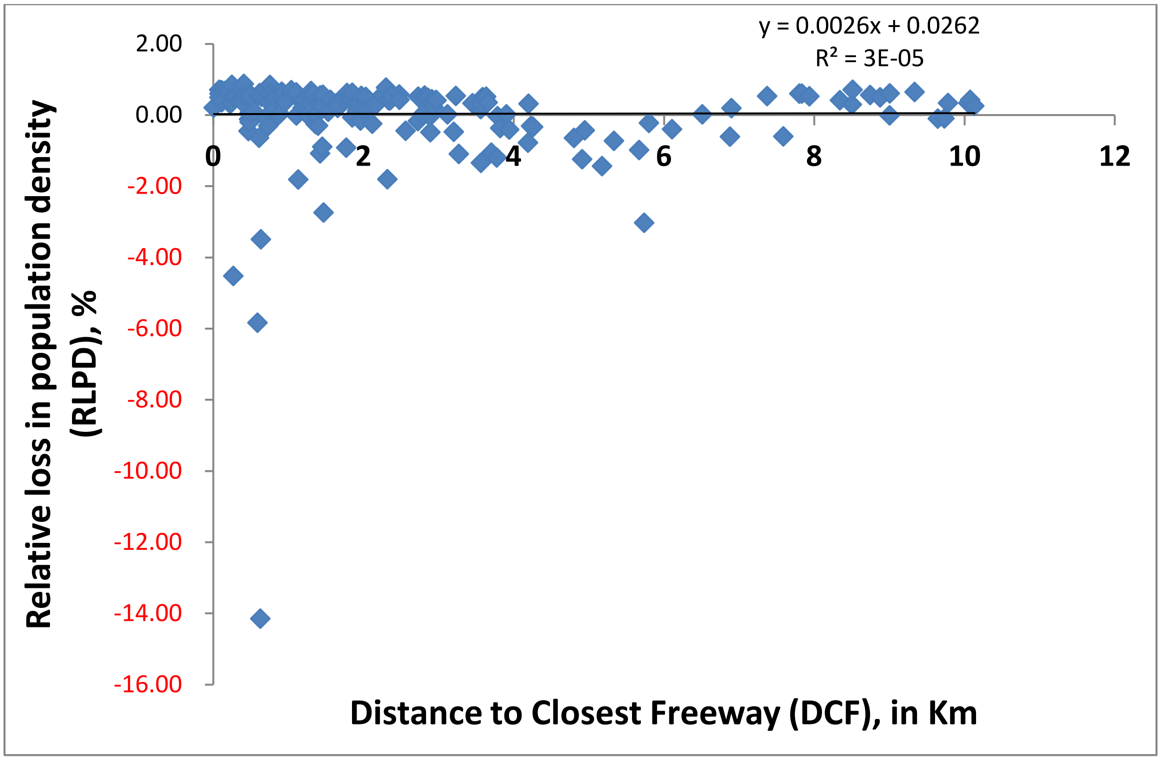
Appendix 8 - Relative loss in population density and distance to freeway

Appendix 8a - with all data points

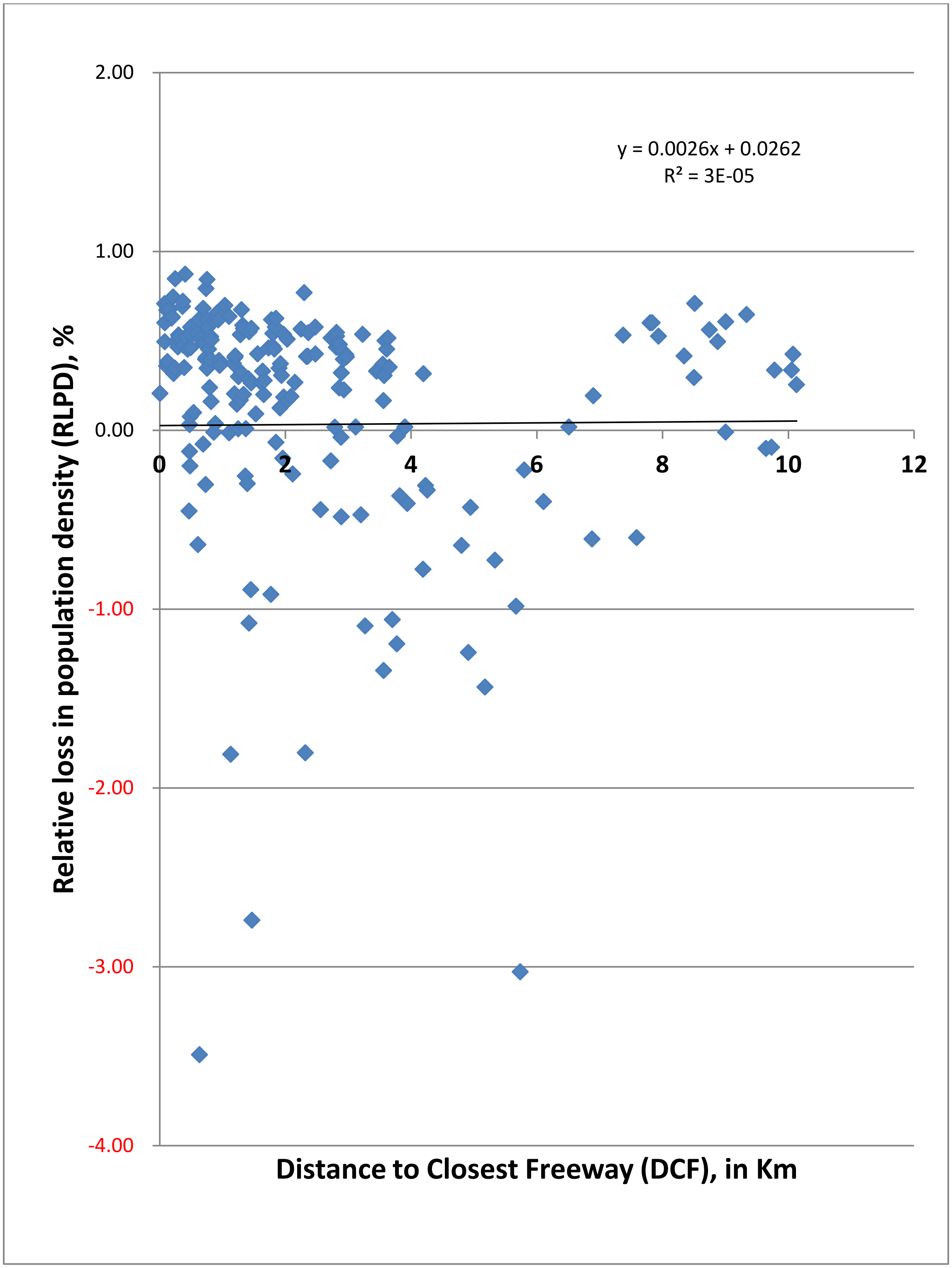


The data point -349 is from census tract 5350012 (2006 notation) with population of 23 in 1956 and 8,053 in 2006. It is located at the harbour south of Front street, between York and Bathurst streets.

Appendix 8b - RLDP and distance to freeway, without the outlier (data point: -349)

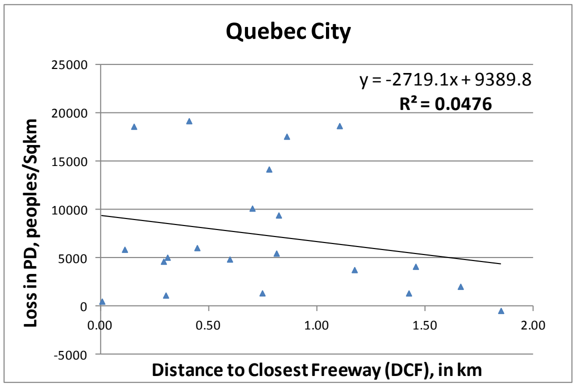


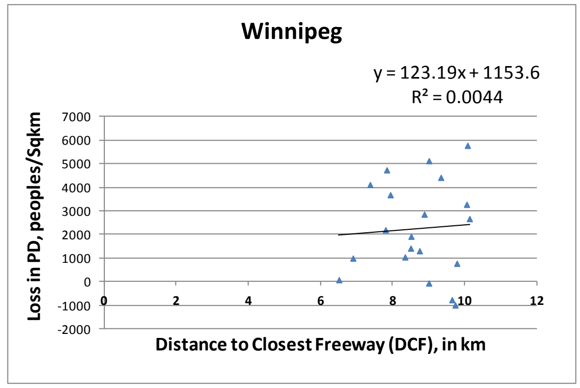
Appendix 8c - RLPD and distance to freeway with all data

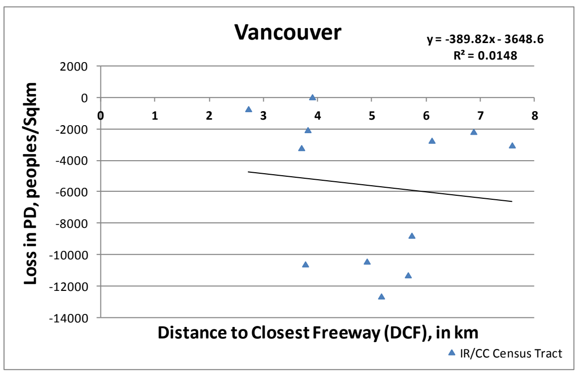


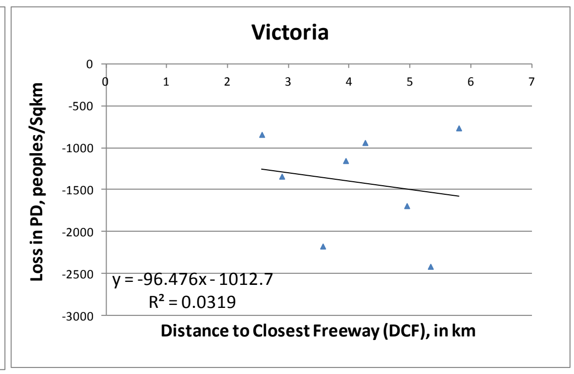
The graph cuts at RLDP=-4 to get a better visual for the majority of the losses

Appendix 9 - Individual Cities - LPD vs. DCF



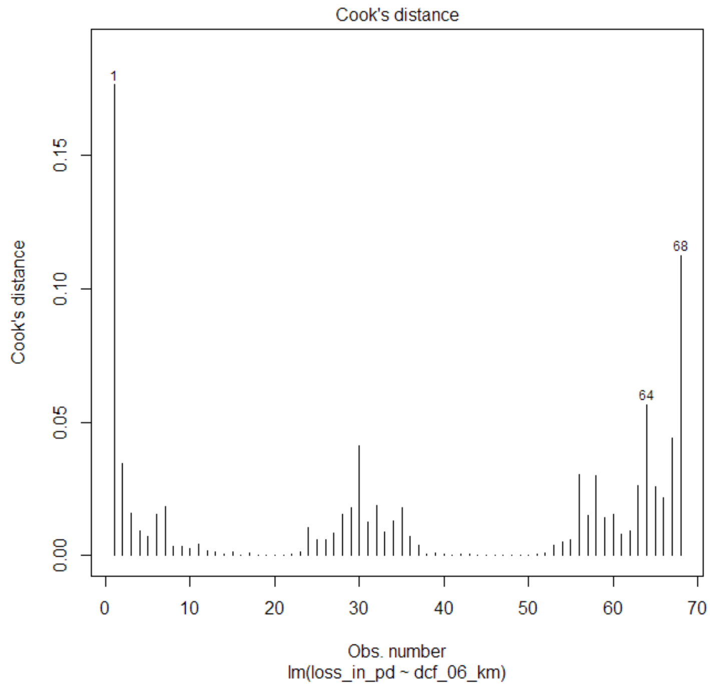


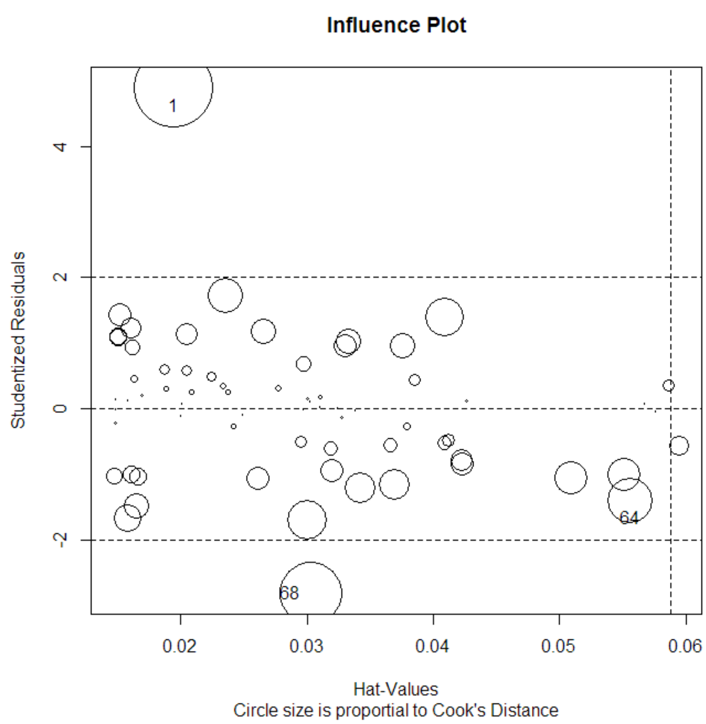


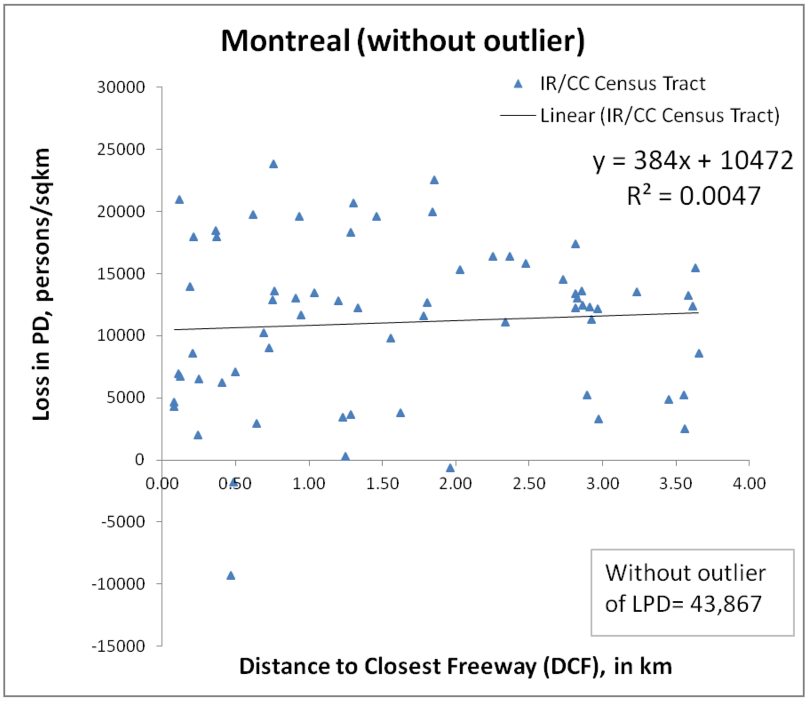


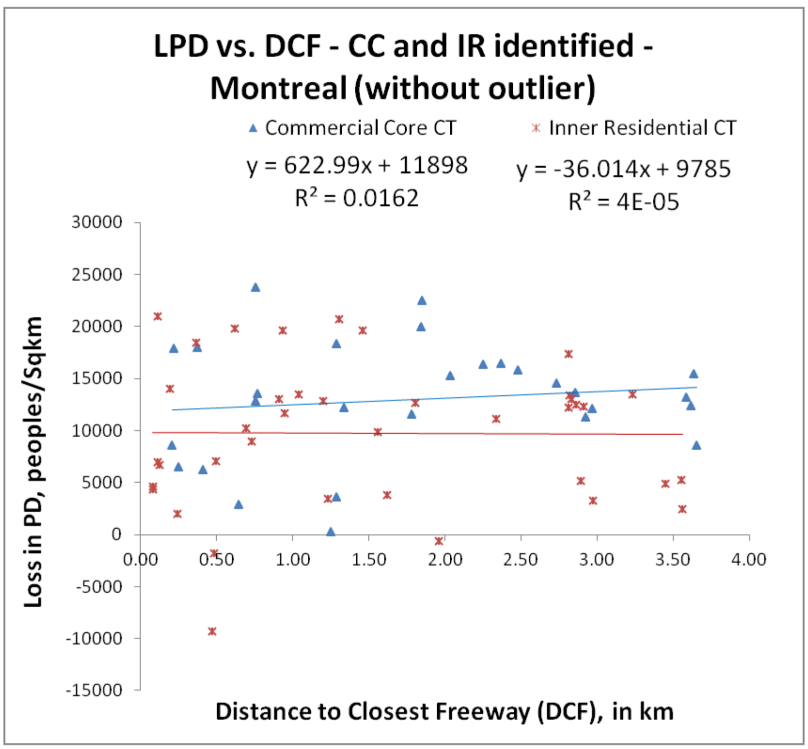
Appendix 10 - Testing for outliers at City Level

Appendix 10a - Montreal

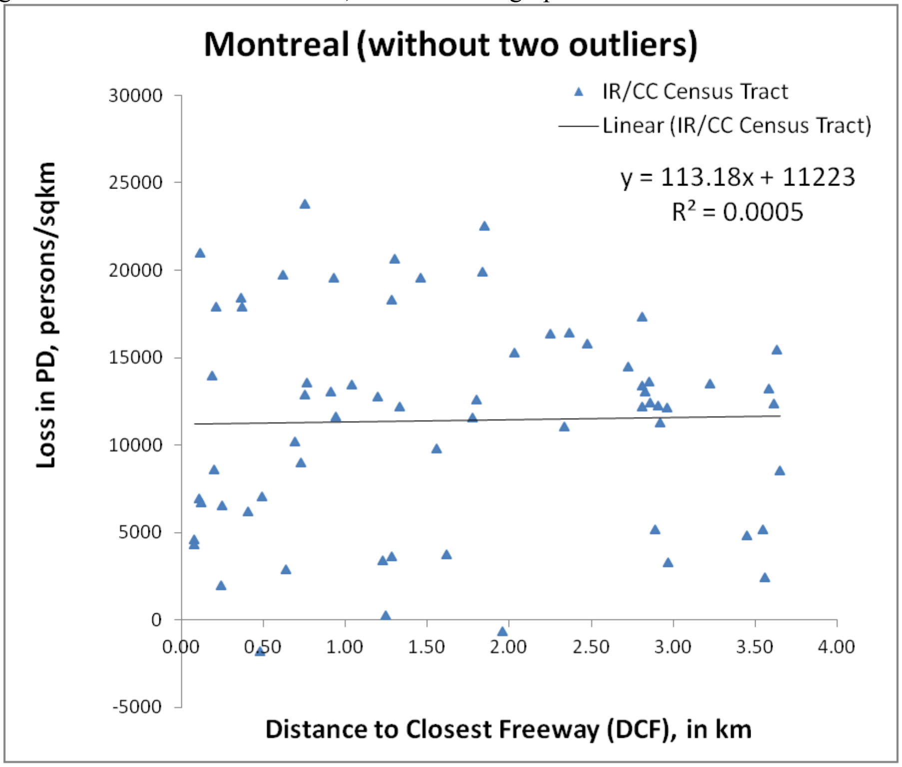


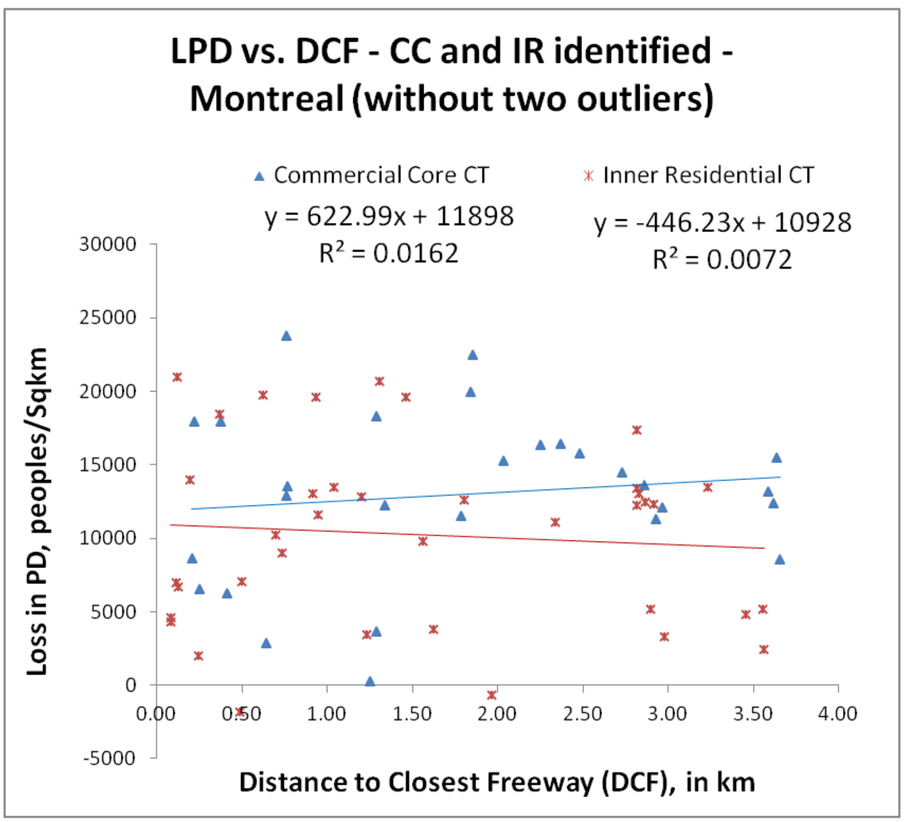




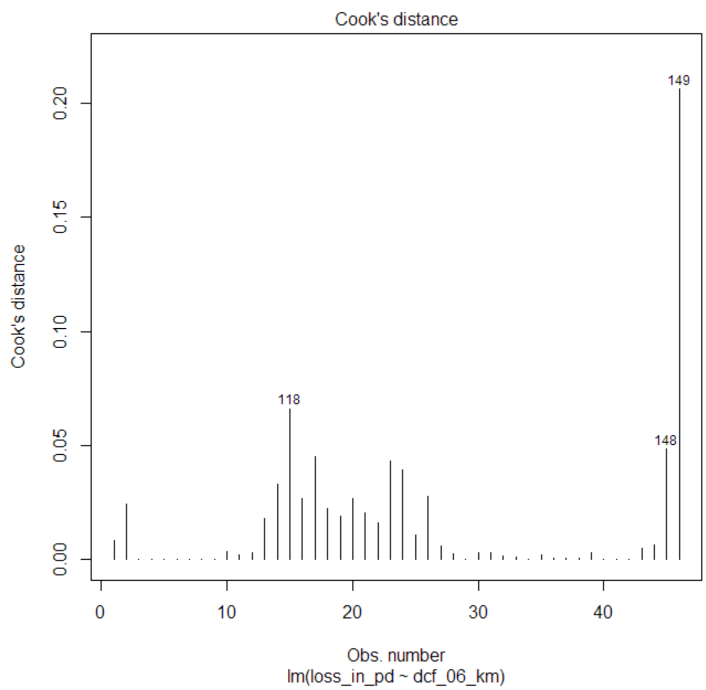


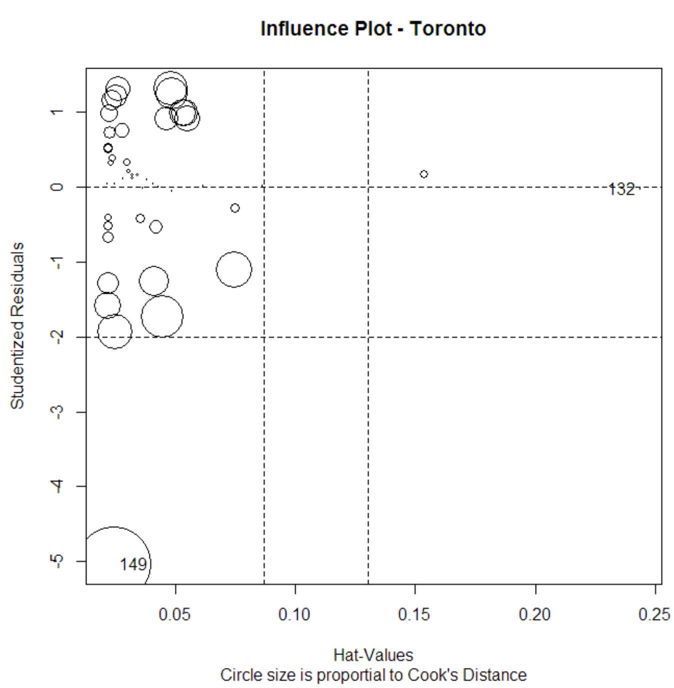
Outlier = data point 1 identified in Cook's distance/Influence plot above, i.e., LPD = 43,867 persons/sq.km; Note: A Cook's Distance value larger than absolute value of 2 needs to be investigated. Here the distance is just over 0.15. The influence plot, however shows data point 1 and another point, 68 (LPD = -9321), and is greater than the abs 2. Therefore, another set of graphs shown below without both the outliers.

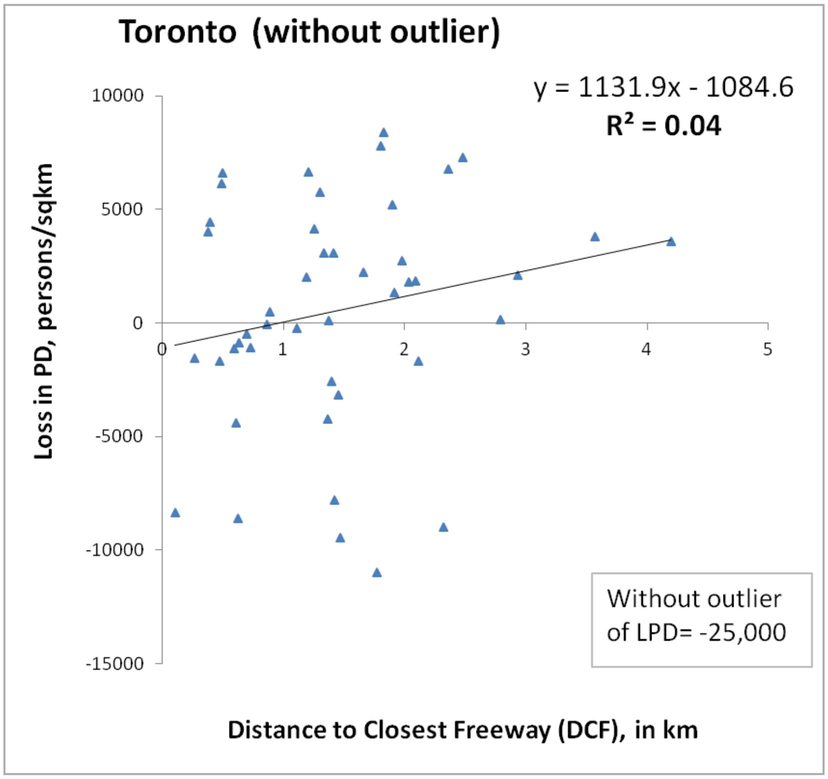


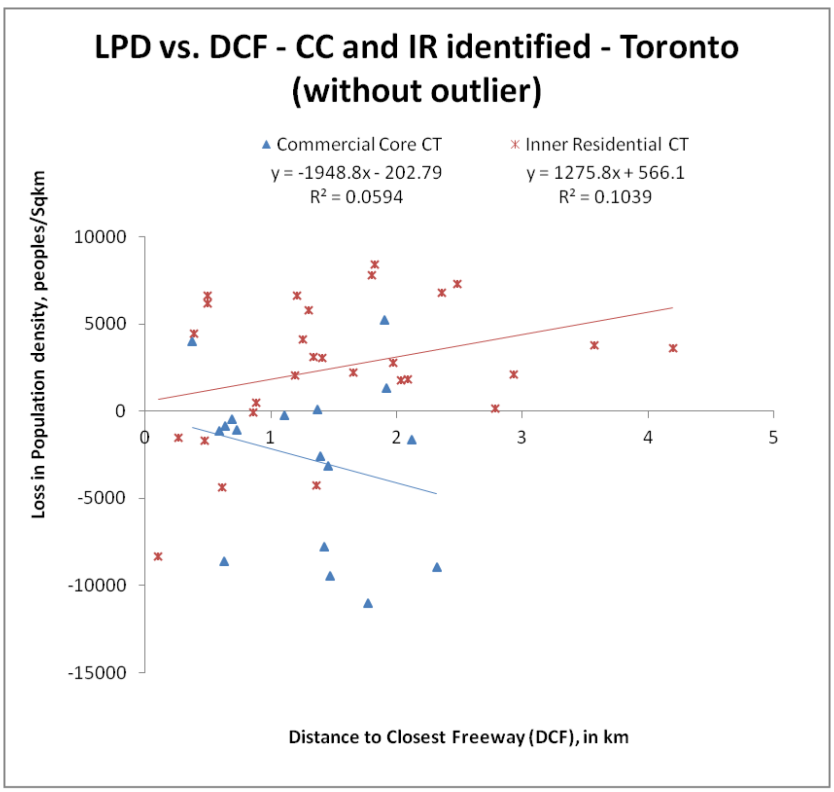


Appendix 10b -Toronto



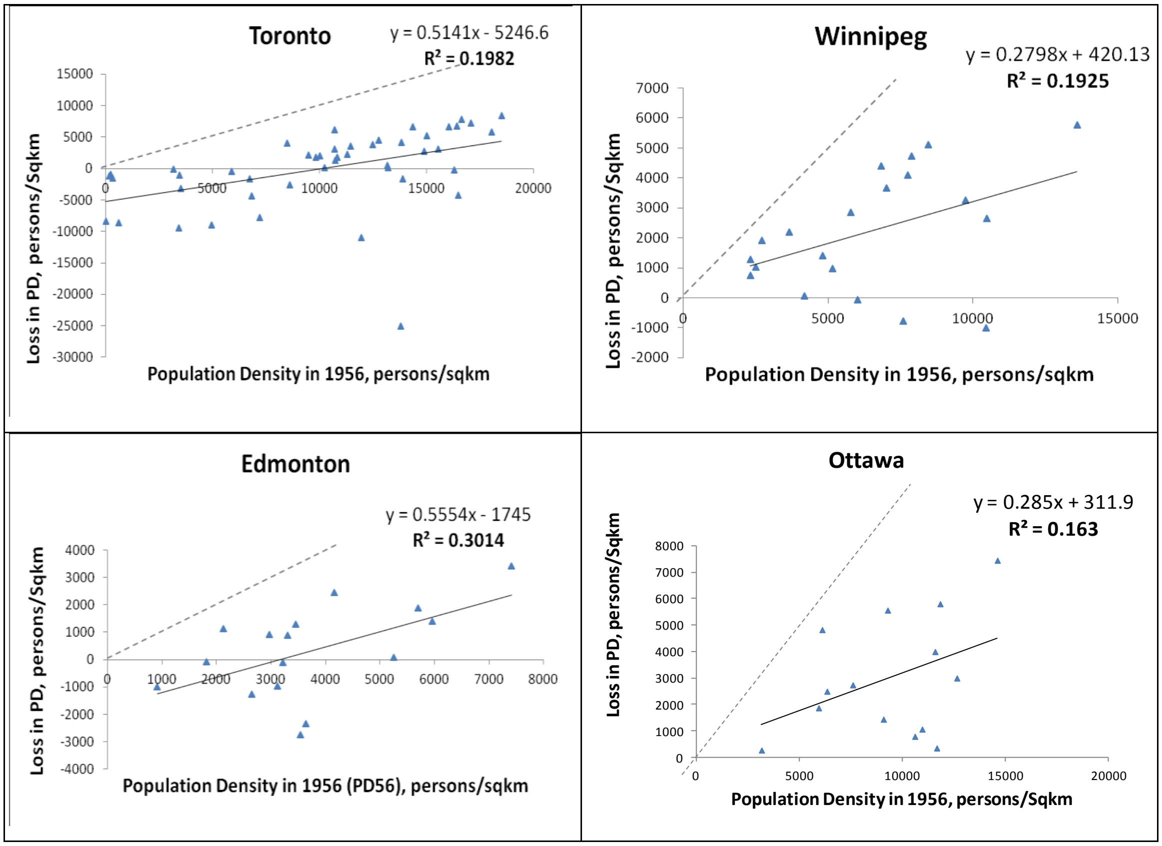


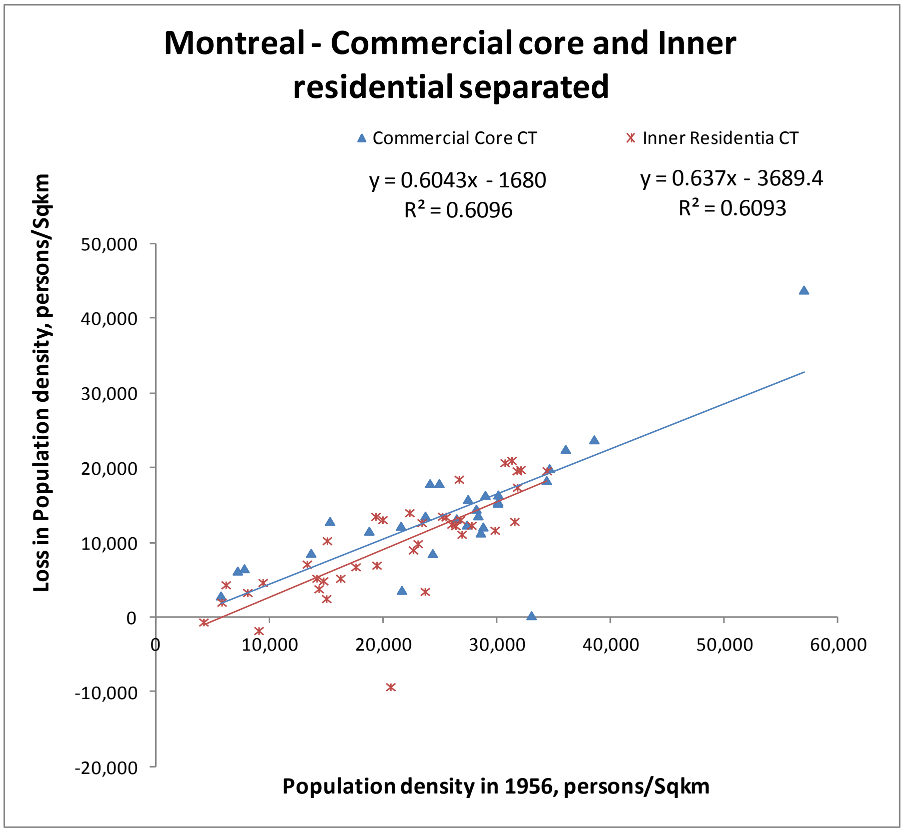


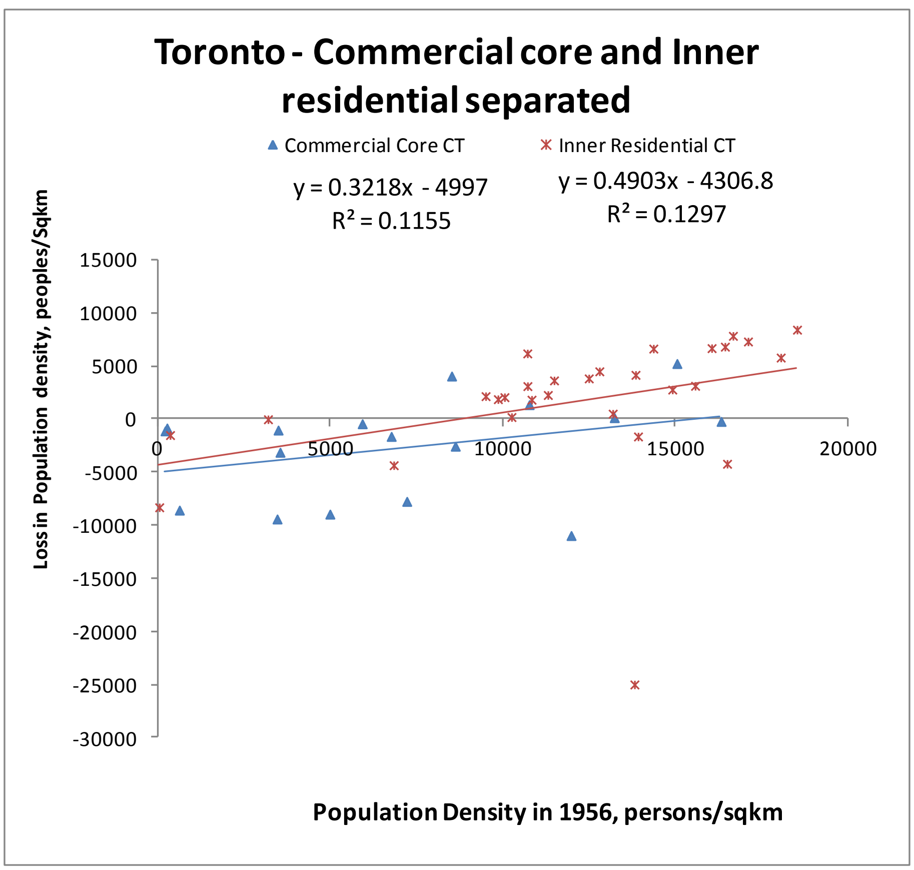


Outlier = point 149 identified in Cook's distance/Influence plot above, i.e., LPD = -25,001 persons/sqkm

Appendix 11 - Individual cities - LPD vs. Density in 1956



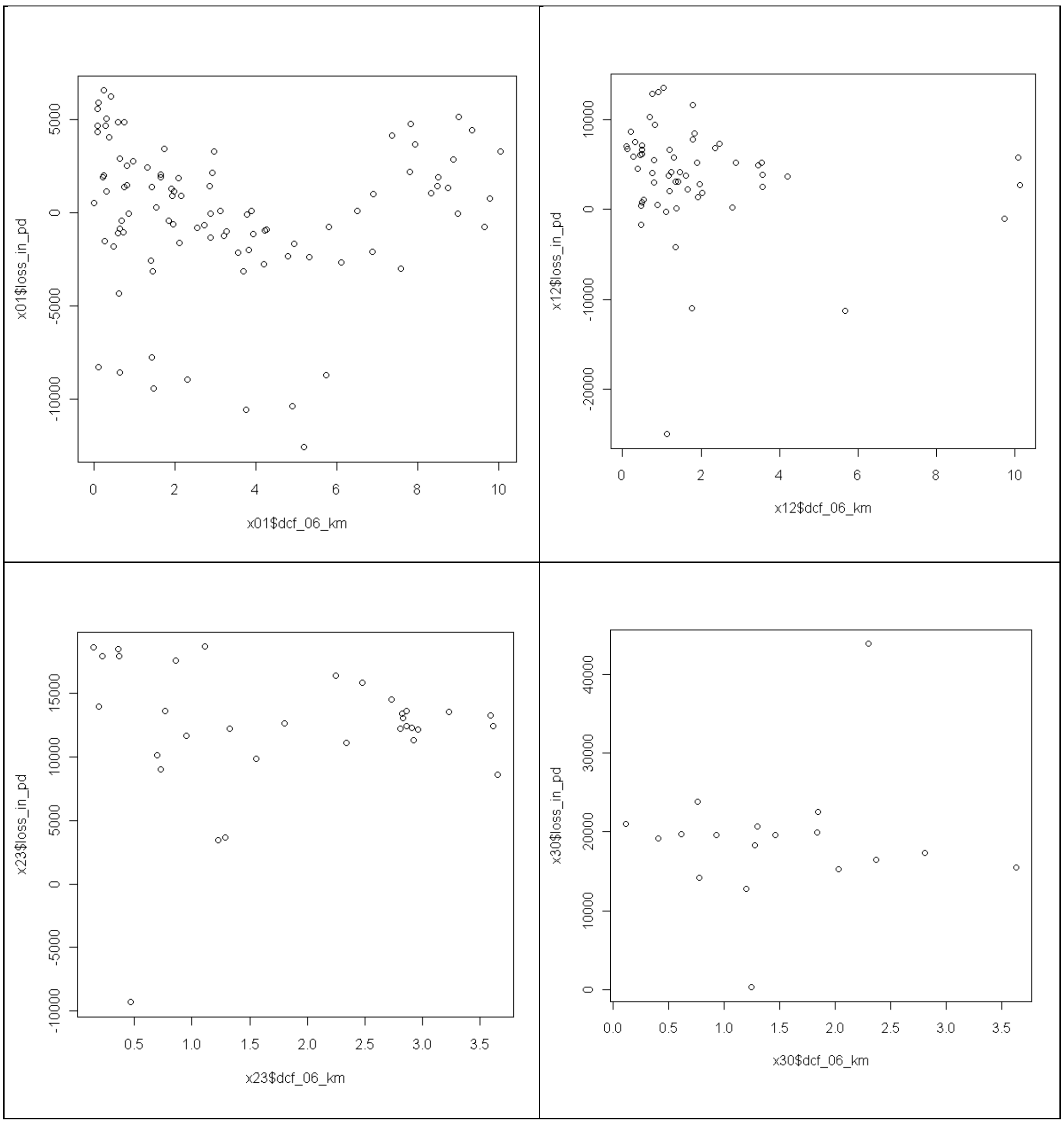

Montreal - Commercial core and Inner residential separated
Commercial Core CT
Inner Residentia CT
y = 0.6043x - 1680
R² = 0.6096
y = 0.637x - 3689.4
R² = 0.6093
Loss in Population density, persons/Sqkm
50,000
40,000
30,000
20,000
10,000
0
-10,000
-20,000
0
10,000
20,000
30,000
40,000
50,000
60,000
Population density in 1956, persons/Sqkm


Toronto - Commercial core and Inner residential separated
Commercial Core CT
Inner Residential CT
y = 0.3218x - 4997
R² = 0.1155
y = 0.4903x - 4306.8
R² = 0.1297
Loss in Population density, peoples/Sqkm
15000
10000
5000
0
-5000
-10000
-15000
-20000
-25000
-30000
0
5000
10000
15000
20000
Population Density in 1956, persons/sqkm

Appendix 12 - Plots for subsets of data

x01: pd_561<10000)
x12: pd_561>=10000 & pd_561<20000)
x23: pd_561>=20000 & pd_561<30000)
x30: pd_561>30000)

Below are plots are for each subset with response variable Loss in Density (loss_in_pd) and explanatory variable Distance to freeway: dcf_06_km)



R^2 for different subsets:

x01= Multiple R-squared: 0.0007894

x12 = Multiple R-squared: 0.02424

x23 = Multiple R-squared: 5.225e-07

x30 = Multiple R-squared: 0.006527