Estimating the GHG Impact of City-Level Policies Across Canada

By

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Declaration of Committee

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Abstract

There is an ever-intensifying conversation regarding the role that cities have in response to climate concerns. Many local governments have set ambitious targets and climate action plans, especially within Canada's major metropolitan regions. I used CIMS-Urban, a land-use model linked to an energy-economy model, to estimate the potential impact local and senior government climate efforts can have on national greenhouse gas emissions. My research suggests that local-level policies, aggregated to a national scale, can achieve significant greenhouse gas reductions. However, they will not achieve the necessary deep reductions needed for announced 2050 targets without stringent policies implemented by senior governments.

Keywords: urban climate policies; fuel switching; energy efficiency; energy demand reduction; mode shifting; density; built environment; policy interactions; spatial modelling; national policy

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Chapter 1. Introduction

As Canada's economy changes, greenhouse gas emissions (GHG) from the top three emitting sectors, industry, transportation, and buildings, must be addressed. Currently, cities across Canada and globally push to develop emission reduction plans that align with or exceed targets proposed by their national governments (Global Covenant of Mayors for Climate & Energy, 2018). The interconnections between urban-level and senior government energy and climate-related issues provide a unique opportunity for policy research. Assessing the interplay between the various policies, city scales, regions, and energy systems across Canada will be critical for understanding urban-level emission reduction strategies.

There have been periods of ineffective climate policy by the provincial and federal governments. Naturally, this has motivated cities to act. It is only recently that senior governments have increasingly adopted stringently defined policy requirements for GHG reduction. In the wake of this movement, cities and metropolitan regions helped to further the momentum by declaring highly aspirational GHG targets. Regions such as Metro Vancouver and Greater Toronto have set carbon neutrality goals by 2050 (Metro Vancouver, 2019; Ministry of Municipal Affairs and Housing, 2020). While these regional districts and other cities begin to set ambitious targets, they do not necessarily have substantial policies to meet these targets.

Canadian metropolitan areas are providing leading strategies for addressing climate concerns within their respective jurisdictions. These rely on interconnections between urban subjects and how they interact, develop, and move within an urban environment. Policies within this respect can guide positive and sustainable change that attempt to address climate concerns. City regions have aligned themselves to a range of options that encourage action within their jurisdictional constraints. Analyzing key policy mixes in tandem with strategies applied at the regional level will be critical for designing a narrative forward.

In assessing the policies at various levels of government across Canada, I will address the research question: What is the likely national contribution of urban governments to Canada-wide energy demand and GHG emissions within the context of more or less stringent policy efforts by senior levels of governments?

To explore this question, I acquired an energy and emissions model that could integrate with a land-use and transportation-based model. Using an energy-economy model, I evaluated GHG emissions and energy consumption changes under various provincial and federal government policy scenarios. These models are unique in their ability to assess the capital stock turnover of a wide array of energy-using technologies. They can incorporate behavioural parameters to better replicate the decision-making by firms and households (Murphy & Jaccard, 2011). These models can further be integrated into spatially derived parameters to assess the impact that changes in geographical features stimulate, such as how changes in transportation route quality and land use impact the uptake of transit use. (Li et al., 2019). To input changes at the urban level, I used an energy-economy model with spatial resolution called CIMS-Urban to capture the unique dynamics of urban form and transportation infrastructure's impact on individual decision-making.

In the past, graduate researchers have applied CIMS-Urban to answer policy questions in the City of Vancouver and Metro Vancouver (Förg, 2020; Budd, 2019; Pardy, 2018; Zuehlke, 2017). However, my research proposes a novel application of this model by developing a set of standardized city archetypes to assess the impact of urban policies on a national level. Through this approach, I will address leading claims that city-level GHG actions can significantly reduce GHG emissions (Miller & McKibben, 2020). These types of claims can be misleading if they do not acknowledge the jurisdictional limitations and local context of cities within senior government action needed to meet national GHG targets (Kuramochi et al. 2020).

Considering the estimated impact of a collective effort by cities implementing GHG policies, using representations of urban patterns, or archetypes, offers insights into the relative aggregate effects on GHGs. Archetype-based energy modelling typically focuses on the neighbourhood level by using building and neighbourhood archetypes to get a general outlook on a study area with relatively limited data (Salter, Kellett & Girling, 2017). However, the level of detail these models use is far beyond the scope and relevance that applies to citywide climate policy. Neighbourhood models are generally based on highly sophisticated energy-use conceptualization—rather than capturing the economy-wide changes in technology use needed for this type of study.

This concept of standardizing buildings to make assumptions for the energy use in a neighbourhood could also apply to modelling municipalities with CIMS-Urban. By isolating a set of standardized archetypes that reflect averages in the real world a model could then make estimates on a much larger scale. The purpose of these archetypes is to capture common patterns and features found in Canada's built environments, such as transit systems and varying neighbourhood types. Through aggregating these representations of patterns, an estimate of the national contribution that urban level change can have on GHG emissions reductions can be derived. Bataille et al. (2010) applied this methodology in a study that used a set of city archetypes simulated within land-use and transportation models. These archetypes were then inputted into various policy scenarios within the CIMS energy-economy model to estimate the effects on energy use and GHG emissions at the urban level. I intend to update this research perspective by applying current climate policy and urban-level action proposed by many regions.

To further explore climate policies and actions at all levels of government, I simulated four scenarios. Each scenario reflects federal and provincial policies as well as metropolitan and city-level policies. For each, I assumed a mix of sincere and insincere senior government climate efforts, juxtaposed with contrasting growth patterns at the urban level. The senior government policy alternatives are based on the uncertain future of how climate policy will progress in Canada—and will thus provide the GHG emissions and energy changes under two opposing realities. The urban level action alternatives reflect the regional growth strategies (RGS) outlined by Canada's major metropolitan regions to simulate changes within an urban form, which are also exposed through two contrasting realities.

The smart growth scenario simulates the goals in Canada's three major metropolises – Toronto, Montreal, and Vancouver. In Chapter 2, where I provide an overview of the RGSs, I make the informed assumption that these strategies are largely similar when guiding urban growth and active transportation development. The consensus trend is that RGSs and smart growth planning by cities emphasize actions that avoid sprawl and create denser urban hubs. These centers are built around transit-orientated developments that promote localized amenities and services which encourage walking, cycling, and transit. Furthermore, this type of development planning also contributes to the reduction in overall travel demand and the distances that individuals generally travel. The table below outlines more specific smart growth perspectives that are often bundled into these planning strategies. I have noted certain ones that are included in the studies as they are the most critical to GHG emissions and energy uses. Most importantly, they are within the modelling capabilities of CIMS-Urban.

Land-use

- Mixed-land uses
- Compact building designs
- Range of housing and choices
- Preserve and rehabilitate critical environmental areas
- Strengthen direct development in already existing communities
- Development is fair, equitable and costs effective
- Encourage stakeholder collaboration

Transportation

- Walkable neighbourhoods
- Distinct, attractive communities that are easily accessible
- Variety of transportation choices
- Facilitate investment in improving public transportation in a range of income and neighbourhood types

My research will provide an updated analysis of the potential contributions that aggregated city smart growth will have on reducing GHG emissions within the context of varying efforts by senior governments. In the following chapter, I provide background on the role that metropolitan regions and cities have within senior government policy. In Chapter 3, I describe my methodology using CIMS and CIMS-Urban to simulate my modelling scenarios. In Chapter 4, I provide background on my policy scenario, additional information, and the respective assumptions. In Chapter 5, I present and discuss my results. Finally, in Chapter 6, I summarize the key findings.

Chapter 2. Background

In the following sections, I explain the role that cities can play within the context of senior levels of government action or inaction on a climate future. To frame the following discussions throughout each chapter, I will use contrasting terms to describe policies associated with climate goals at the city or metropolitan level. I consider the umbrella terms for these as *smart growth* and *dumb growth*— similarly, I describe senior-level approaches as either sincere or insincere.

I refer to city-level policies under the conventions of *smart growth* and *dumb growth*; both will be further detailed in the results and discussion section. The term *dumb growth* refers to inaction, generally unplanned, and business-as-usual approaches to growth. Alternatively, *smart growth* describes strategies that reflect the planned action strategies to avoid sprawl and advocate for compact, transit-oriented, walkable, active transportation and a range of mixed-use house development types.

Poli

I use the terms climate sincere and climate insincere to frame the contrast between senior government's approach to climate policy. These contrasting terms are defined by Jaccard (2020) to distinguish elected governments that enact policies and regulations that achieve ambitious GHG reduction targets from those that do not carry through with their promises.

2.1. Jurisdictional Context for Climate Policies

The climate policy landscape across Canada has varied through all levels of government. The previous 2008 elected federal government lacked sincerity on climate by pulling out of the Kyoto Climate Accord and setting intensity-based carbon targets, which do not set hard caps on GHG emissions. Current federal-level action on climate has been sincere through implementation of several key policies. For example, a national carbon tax acting as a backstop for insincere provincial responses, a coal plant phase-out for electricity generation, a reduction in industrial methane emissions, national strategies for zero-emissions vehicle policies and net-neutral ready building code for provinces to adopt by 2030. The federal government recently reaffirmed its interest in positive climate efforts by announcing a net-neutral 2050 target.

In 2008, the British Columbia provincial government responded to climate concerns by implementing policies, the first key policy being a zero-emission requirement for electricity (2007) and then pricing of carbon pollution (2008). These policies were followed by a zero-emissions vehicle standard, an increasing low-carbon fuel standard, increasing supply of renewable fuels and investing in low-carbon buildings innovation program through the government CleanBC plan (The Government of British Columbia, 2018). British Columbia continues to act as a leader in provincial climate policy and is the leading example throughout my study.

Relative to provincial and federal authority over climate policies, Canadian cities do not share similar jurisdiction to implement economy-wide policies—such as a carbon price or impose a zero-emissions vehicle mandate. However, municipal governments can levy certain taxes or fees to generate revenue—such as property taxes and parking fees. In addition, municipal governments have considerable jurisdiction over land use and how urban transportation infrastructure develops—Vancouver is an example, as illustrated in its Renewable City Strategy and Zero Emissions Building Plan (City of Vancouver, 2016, 2017). In Vancouver's case, it can impose building zone regulation for high-density mixed-use developments around transit stations. The city can also construct bikeways, car-free zones, and increase transit dedicated roadways to reduce road space of personal vehicles. Both transportation and infrastructure are dominant emitters in cities and are where opportunities for urban-level policy can focus on reducing GHGs (Jaccard et al., 2019).

Across Canada, there is a special relationship between municipalities, cities, and regional districts, which refer to joint-local governments or regional governance. These governments collaborate with local authorities, such as transportation boards, planning boards, and First Nation bands. They have legislative authority for land-use policies that are informed and worked on by local municipalities.

The three largest regional governance districts in Canada are Metro Vancouver, the Greater Toronto Area, and Greater Montreal. I will refer to them as Metro Vancouver, Metro Toronto, and Metro Montreal, respectively. These are considered regional districts with leading government bodies formed with their local authorities. The strategies in each region are generally characterized by action or planning items to anticipate future growth and are referred to as the Regional Growth Strategy (RGS). These plans are developed in collaboration with senior stakeholders who work on action items, turn them into policies, and decide where funding is needed. Afterward, they are translated into Regional Context Statements that outline the official community plans concerning the RGS. The results offer a clear indication of the land use plans and opportunities that developers and transit planners use to plan future projects.

These three Metro regions have a unique responsibility due to their population size and growth—and therefore, can influence energy and emissions consumption through their planning strategies. The RGS outline of each region is similar in its key pillars for *smart growth*. This shows that the terminology, planning goals, and direction of the major Canadian cities holding roughly a third of the nation’s population are on similar growth patterns. The jurisdiction these metro regions have over the municipalities varies slightly. However, the possible impacts on GHGs rely on land-use plans, and investment in transit and active forms of transportation are relatively consistent. Their urban form is also similar in respect to the portion of the population able to access transit lines, high-density urban hubs, and active transportation routes. And surrounding the densely populated urban areas are low-density suburbs that make up a large portion of the population—which the three metro regions share.

Outside of the top three metro regions, Canada consists of various sized cites with similar smart growth strategies, such as Calgary, Edmonton, Victoria, Hamilton, etc. These types of cities are included in the study as they too have the opportunity to be guided by municipal governments, aligning planning to similar strategies to that of the three major metro regions. While this is a generalization to say they all are following a similar route—I have taken this approach to consider scenarios where a collective national narrative for cities, follows smart growth practices of other major urban hubs. Much of the Canadian population live in cities and population projections for the coming decades show continued growth, meaning that these urban areas are becoming a key focus for climate and energy plans.

2.2. Urban Policies and Actions for GHG Mitigation

When discussing GHG policies, distinguishing between action and policies is key, in that policies are required to cause actions. A few actions that can cause a reduction in energy-related GHGs can be improvements in technology and building energy efficiency, urban form change that reduces energy service demand, fuel switching to less carbon-intensive fuels and direct air carbon capture and storage systems. The importance is that these actions may provide a similar level of service for energy demand while reducing associated GHG emissions. While such actions contribute to reducing GHGs, I emphasize that a low carbon energy future will rely on a combination of the above for sufficient deep decarbonization. In the case of cities, they can act as leaders by focusing on key sectors such as transportation and urban form (Axsen, J. & Wolinetz, M., 2019; Jaccard et al., 2019). Ultimately to achieve deep decarbonization, switching to low-carbon fuels or using fossil fuels with extensive carbon capture and storage will be needed in the following decades to meet national and global climate targets in tandem with climate-focused city policies.

The limited jurisdictional ability of cities and metro regions is not to say that there is no role or ability to reduce emissions by these urban areas. Rather, cities might best be considered as both *policy takers* and *policy makers* when it comes to GHG reduction policy (Braglewicz, 2018; Pardy, 2018). In other words, these urban areas' energy and emissions goals are inevitably going to be affected by senior government policy. However, they can utilize specific urban policy within the control of municipal governments to aid in the achievement of energy and emissions targets. In this section, I will explore the types of policies that cities often propose and in later sections, I will model these general policies on a Canada-wide level.

Many of the following policies are commonly used to meet a wide range of goals and achieve targets outside of GHG emissions targets. For example, actions, as mentioned before in the RGSs, seek to support affordable housing and healthy lifestyles through densification of mixed-use land development and encouraging active forms of transportation. Through bylaws and directed government actions, local governments have some influence over buildings, personal transportation, and waste heat. Other important sectors such as freight transportation, energy generation, agriculture, and industrial GHG emissions are difficult to impact through local and regional government policy. For this study, I focus on emissions from personal and commercial transportation and residential and commercial buildings.

2.2.1. Buildings

Densification through rezoning and bylaws is often used as a key planning option for municipalities to reduce urban energy consumption. By increasing dwellings per lot, constraining boundaries for urban growth, and incentivizing developers to focus on mixed-use densification, cities are actively shaping the distances people travel as well as the types of transportation they choose (Ewing & Rong, 2008). The general assumption is that these actions, because of planning policies, lead to a negative relationship between urban density and per capita emissions in residential buildings (Ewing & Rong, 2008; Gudipudi, 2016; Lee & Lee, 2014). Essentially, per capita emissions are a direct function of these types of planning strategies.

The highest density areas are in the top three metro regions' downtown cores and are generally made up of high-rise apartment buildings. However, as density is measured generally through people per square kilometre, this is only one dimension and does not capture the mix of building uses, neighbourhoods, and transportation network access. These various types of density directly impact how people make decisions that impact their overall energy and emissions. Personal transportation and the building sector are key. For example, dwellings that make up the highest density areas are more energy-efficient than detached single-family homes, due to shared walls, and thus less exposure to the outside (Ewing & Rong, 2008; Martilli, 2014). These types of components are important to understand when assessing densified development.

On the other hand, the differences in energy performance between detached and attached homes are directly impacted by floor space, building shells, and space heating technologies. Multi-unit building performance is also impacted by similar aspects. If all else is held equal, denser areas with a higher mix of mid/high rise multi-unit buildings can reduce energy consumption. The context for this will vary based on the location and age of the building, making it difficult to estimate precisely how densification is reflected in changes in energy and emissions. It is clear however that densification alone is insufficient to achieve the aggressive targets set out by many municipal governments (Pardy, 2018). Densification can also contribute to emission reduction associated with supporting infrastructure that lowers the cost of transit expansions and enables development and expansion of district energy systems (Jaccard et al., 2019).

Along with densification, transportation and district energy systems infrastructure, mixed-use developments can also be pursued in conjunction with city planning focused on reducing GHGs. Mixed-use development refers to buildings with residential and commercial properties in the same block or the same building. Research into the impact of mix-use developments on GHGs is varied and points towards an array of important contributing factors, such as walkability, accessibility to services, and density as all being needed to reduce vehicle usage and overall emissions in cities (Hachem, 2016; Potoglou & Kanaroglou, 2008). The important point is that a multi-pronged approach to the development of urban form is needed for smart growth, rather than a one solution strategy.

Local governments across Canada can directly influence densification through land-use policies within their jurisdiction. However, further energy demand reductions in the built environment can be brought in by national and or provincial building codes. BC's Step Code is a primary example of a provincial guideline outlining effective actions to improve energy efficiency requirements (The Government of British Columbia, 2019). This type of policy outlines actions such as requiring high-efficiency building shells, and heating and cooling systems as pathways to reduce energy demand in all building and dwelling types. The Step Code only outlines suggestive actions for the building code and does not link to actual regulatory policy at the provincial level. However, local governments have the option to require builder to build to a certain "Step". This is a reality across cities in Canada, where suggestive build code standards are not linked to direct building policies, but local municipalities may have options to enforce higher building code standards.

Cities may have the authority to control new buildings through by-laws. For example, the City of Vancouver has the authority to regulate the energy and carbon intensity of new buildings. Through a building standard outlined in the Zero Emissions Building Plan (ZEB) released in 2016, new buildings must adhere to energy efficiency and carbon-intensity targets. After 2022, all new heating systems will be required to be zero-emissions (City of Vancouver, 2016). Recent modelling by Pardy (2018) found that ZEB had the potential to significantly reduce emissions as more residents acquiring newly built residences would be forced to use low-carbon heating options. Similarly, the

City of Toronto has implemented a ZEB—which sets building tiers linked to energy efficiency and carbon intensity. The city set a similar target for new buildings to perform at a near-zero emissions level by the year 2030. (Ministry of Municipal Affairs and Housing, 2020).

2.2.2. Personal Transportation

Implementing land-use policies that encourage vehicle alternative infrastructure investment and transit-orientated developments are key actions cities can use to increase active transportation modes (walking and cycling) and transit. Building out infrastructure to add more walkways, safer bike paths and increased mixed-use developments can improve the accessibility of an area by making these modes more convenient while potentially discouraging driving. Local transit that connects these neighbourhoods and community hubs within a metropolitan region will also reduce the need to drive. Increasing amenities at key transit stops such as shelters, small businesses, and digital display boards could encourage ridership uptake.

Research into density impacts on travel demand and vehicle use is limited. It is often associated with a set of factors that determine travel behaviour in an urban environment. However, as mentioned above, mixed-use developments have been a key variable to reduce travel demand and lower vehicle use. For example, replacing car trips with active transportation modes can reduce overall energy demand. While mode shifting towards active modes can lower energy demand in transportation, deeper emissions reductions require a wholesale transition to low-carbon options. Fleets comprised of electric, biofuel, plug-in hybrid, or hydrogen buses are essential to further reduce city and metropolitan region GHG emissions.

Improved transit and increased densification can lead to a reduction in vehicle use and lower respective GHG emissions (McIntosh et al., 2014). However, coordinating this on a metropolitan level can be difficult as this requires cooperation from a variety of stakeholders (Filion & McSpurren, 2007). Moreover, how the impact relates heavily to localized factors such as topography, weather, income, age, health, and general behaviour preferences are highly important for mode choice decisions (Cervero & Duncan, 2003; Wang et al., 2016).

Variety in transportation options can be important for supporting a variety of context dependant travel demand patterns. An individual's ability to choose the transportation modes and routes most appropriate for their travel needs are key for density development and building infrastructure to support more active transportation and less driving demand. Research shows that satisfaction with travel options is at its highest when individuals have the most control over their trip (St-Louis et al., 2014; Thomas, 2014). Essentially, an individual's ability to be able to choose travel options that reduce time in traffic will contribute to a higher level of satisfaction—especially when the overall trip is not subjected to unexpected and constant delay.

For bus travel, options through infrastructure improvements that reflect increased frequency, reliability, and more up-to-date information on routes can help to increase overall satisfaction (Thomas, 2014). The level of satisfaction for this study can be thought of as the quality of that transportation service. In the case of buses, the quality of the service will increase as an improvement to the transit system occurs. Driving, alternatively, offers the highest level of service as it is the most convenient, comfortable, and generally the fastest mode, providing access to the greatest number of destinations. These factors of transit frequency and reliability are important to increasing the service quality and as a result, inducing more people out of cars. However, individuals generally are averse to moving to modes with less service quality. Biking and walking are also considered to have a low level of service provided in respect to driving as they require physical effort, are largely weather dependent, and are generally slower. While improved cycling routes and walkability may reduce private vehicle use, evidence of densification, increasing mix-land use, and high-quality transit shows higher rates of active transportation uptake, and in turn emissions reductions (Nielsen et al., 2013).

To achieve complete GHG emissions reductions, provincial and federal level government policies may be needed. The policies above touch on reducing energy use and causing some fuel switching in buildings. While reducing energy use can be part of the policy strategy to reduce emissions, fuel switching from gasoline and natural gas is necessary to achieve deep emissions reductions. Non-urban-specific policies at the provincial and senior government levels will be further explained in the following sections. Many of these key fuel switch policies, such as building codes, vehicle regulations, and pollution pricing fall into the senior government category. The overlap between urban-specific and non-urban-specific policies and their effects will be further explored in the results and discussion section.

2.3. Need for Analysis

There lacks an analysis of Canada-wide city-level policies that couples a spatially explicit land-use and energy-economy model to assess climate-focused policy scenarios at all levels of government. In this study I attempt to address this analysis gap by implementing a climate policy modelling study that covers approximately two-thirds of the Canadian population, that being those who live in the densest urban centers across the nation. These urban areas are set to steadily grow until 2050, for which I model future climate scenarios to assess GHG emissions and energy use. Below are guiding questions I use in the study:

1. How might the collective impact of country-wide city-level efforts in urban land-use change, transportation improvements, and other urban-level actions and policies contribute to national climate goals?
2. Given the likely GHG-reducing policies from senior levels of government, what will be the relative contribution of these and city-level efforts?
3. How do the urban-initiated policy mixes contribute to transportation mode shifting and energy use at the city level over a period of several decades?

Chapter 3. Methodology

I used the CIMS-Urban model to address my research questions. Previous research has applied CIMS-Urban to answer similar policy questions in the City of Vancouver and Metro Vancouver (Förg, 2020; Budd, 2019; Pardy, 2018; Zuehlke, 2017). This work has provided a foundation for expanding the geographic scale of estimating metro and city-level policies on both a provincial and national level.

Tools that can enable researchers and policymakers at the urban level to simulate changes to transportation and urban form and analyze the associated GHGs are key for informed policymaking. CIMS-Urban, is a tool that bridges the gap between energy-economy models and urban form evolution through simulating the economy with technologically explicit, behaviourally realistic, and spatial factors that influence changes at the urban level via a series of dynamic equations.

3.1. Background

The CIMS-Urban model was first developed by Zuehlke (2017). He developed a spatial extension of the CIMS energy-economy model to represent land use and transportation network changes in the City of Vancouver. On their own, conventional energy-economy models are not able to incorporate changes in spatial relationships. These relationships are especially important for assessing urban-specific policies, hence the development of the spatial extension. Without the dynamic feedback between these models, the ability to let spatial relationships influence behavioural change is negated. The study recognized the opportunity of combing both spatial relationships and energy-economy modelling for studying urban-specific policies.

Budd (2019) contributed to the methodological approach by incorporating new components in the model. Budd measured the effect that population density and changes to urban form have on travel demand and, developed a road congestion feedback algorithm to improve the spatial simulation of key transportation feedback effects. This research stimulated interest in developing a travel demand function based on population density. However, Budd identified that this approach would benefit from further research into a travel demand function that could integrate public preference, a person-kilometre travelled index, and network quality.

Recent CIMS-Urban research by Förg (2020) at the level of Metro-Vancouver's announced climate goals focused on updating the network quality algorithms through literature research to better inform the dynamics within the model. In particular, she improved the walking, cycling, transit, and driving distance decay functions to better inform the spatialization of intangible costs in CIMS-Urban. This research expanded the geographic scale of CIMS-Urban to a metropolitan level and has laid the foundations for my methodology to explore aggregate urban emissions at the national level.

3.2. Overview of Urban Land-Use Models

Understanding how GHG policies at the provincial and federal levels interact with emissions reduction strategies by cities will be essential for influencing the development of urban-level energy systems. Urban energy systems have primarily been defined as a functioning system that represents the process of using and supplying energy to satisfy demand in an urban area (Keirstead et al., 2012). Methods for researching urban-level energy systems have used energy-economy models that specialize in the capital stock turnover for end-use energy devices—which also may include parameters to simulate consumer behaviour (Murphy & Jaccard, 2011). In essence, these models estimate how individuals choose energy-using devices and shift to new technology. However, energy-economy models have generally not integrated spatial components, which has negated the ability of researchers to provide policymakers with insights at a high-resolution spatial level (Li et al., 2019).

The modelling approach for an urban-level energy system has generally been categorized into three alternative definitions:

Pure geographic: the approach looks solely at technology and energy consumption within the city bounds and jurisdictional abilities.

Geographic-plus: includes energy and technology consumption within the city's administrative bounds in addition to upstream energy consumption, such as electricity.

Pure consumption: measures all energy and technology consumption within the city's administrative bounds but subtracts the energy consumption associated with locations such as resorts and reallocates the emissions to the households from which the patrons came (Keirstead et al., 2012; Ramaswami et al., 2011). Models that attempt to simulate these conceptual bounds of the urban-level energy systems have largely used energy-economy models linked to geographical information systems (GIS) to emulate the supply and demand of cities' energy and emissions over time (Alhamwi et al., 2017).

Urban level models have primarily taken their conceptual modelling boundaries and generated specific models for systems within the city. Keirstead et al. (2012) conducted a literature review of these types of urban level models and found an array of approaches that included spatial perspectives in technology design, building design, urban climate, system design, policy assessment, and transportation. Within this study, I do not explore the nuances of each subsystem model design, nor how these specifically compare to CIMS-Urban. However, as a broader overview, I discuss the key categorization classes: simulation, optimization, and econometric (integrated land-use and transportation models) urban level modelling approaches. Then I explain how CIMS-Urbans fits within these various approaches.

Firstly, urban level simulation approaches have primarily been used to estimate the change in technology design, building design, and urban climate change action under various policy and economic conditions (Keirstead et al., 2012). Through variables that help estimate changes in behaviour, technology prices and urban form, this type of approach attempts to endogenously calculate the difference in energy demand at the urban level (Michalik et al., 1997). This approach disaggregates subsystems within a city. For example, it looks at energy use on a specific block within a neighbourhood, rather than integrating full city-wide estimated feedbacks such as influences from infrastructure upgrades, transportation route improvements, and technology change. In essence, this approach can be useful to policymakers and city managers because they can test the effects of policies such as demand-side management programs within a very specific part of the city.

Secondly, urban level optimization approaches have mainly been used for system designs, which integrate exogenously defined changes to the structure in urban form (Keirstead et al., 2012). Typical assessments under this approach would be to find the optimal mix of infrastructural upgrades or retrofits to meet the future energy demands of a city. For example, studies have used optimization models to assess the cost of a power outage in a city or to estimate the effect that a district heating system may have on the energy efficiency of a mixed-commercial and residential block (Mancarella & Chicco, 2009; Sundberg & Karlsson, 2000). This approach is generally useful for finding the lowest energy costs of a change at the urban level.

Thirdly, integrated land-use and transportation model (ILTM) approaches have predominantly been used for building in dynamic feedbacks from a variety of city functions to assess how some changes influence energy demand. This modelling approach category is described by Keirstead et al. (2012) as complex model systems that attempt to capture the relationships between urban processes. ILTM models were initially developed to estimate the change in transportation demand provided by vehicles, transit, cycling, and walking in response to differences in urban form. Some researchers have begun to identify the limitations of these types of urban level models and have utilized an approach that integrates an energy-economy model and a geographic information system (Jaccard et al., 2019).

3.3. The CIMS Energy-Economy Model

The CIMS energy-economy model functions as a simulator for energy and GHG emissions policies concerning energy and technology use. These interactions are constrained by the energy and supply and demand of each sector. The model is technologically explicit, meaning that it accounts for the changes in capital stock in technology over time. This capital stock turnover is simulated on a five-year turnover period to forecast the changes in technologies— such as household appliances vehicle types, and heating systems. CIMS incorporates econometrically estimated behavioural parameters to account for consumer preferences when making technology choices (Rivers & Jaccard, 2006).

How CIMS simulates choices in technologies and transportation modes is depicted in Equation 1. Lifecycle costs are annualized into *CC* capital cost, *MC* annual maintenance and operating cost, *EC* energy costs, *i* intangible costs, and *r* discount rate. The technology *j* competes with all other technologies *k* that can provide the same service. Parameters *i, v* and *r* are derived from revealed and stated preferences research. Revealed surveys assume preferences of consumers based on their buying habits, whereas stated preference methods involve asking individuals to infer their buying preferences based on hypothetical scenarios.

Equation 1: CIMS Market Share Algorithm (Jaccard et al., 2003)

$$MSj = \frac{\left[CC_j * \frac{r}{1-(1+r)^{-n_j}} + MC_j + EC_j + i_j\right]^{-v}}{\sum_{k=1}^{K}\left\{\left[CC_k * \frac{r}{1-(1+r)^{-n_k}} + MC_k + EC_k + i_k\right]\right\}^{-v}}$$

The market share algorithm estimates the new market share MS_j for each respective technology j that provides an energy service by comparing the lifecycle cost to all those other technologies competing. Capital costs CC of j is multiplied by a discount rate r equation to reflect time preferences and annualize the capital cost over n number of years.

The second layer to the behaviour parameters is the non-financial costs i. These can be considered non-monetary influences on technology choices. This parameter tries to capture some of the inherent perceived risks, differences in service quality, symbolic value, and aesthetics. An example could be the associated non-financial costs of choosing to take a bus or drive a car based on the difference in perceived comfort, convenience, and status of taking either mode.

The heterogeneity parameter v is the third behavioural parameter. This enables the model to simulate how the personal preferences of individuals are dissimilar in the market and when presented with identical technology choices may be dissimilar. Each behavioural parameter layer (*r, i, v*) in CIMS has been estimated by CIMS researchers through stated and revealed preference studies for multiple technologies (Axsen et al., 2009; Horne et al., 2005; Jaccard & Dennis, 2006; Rivers & Jaccard, 2006; Washbrook et al., 2006)**.**

CIMS further represents dynamic changes in the perceived and real costs of technologies by adjusting cost values through both a declining intangible cost function, as well as a declining capital cost. This endogenous change in the model allows the algorithm to incorporate the effects of economies-of-scale, learning-by-doing, and the neighbourhood effect (Jaccard et al., 2003; Bataillie, et al., 2007; Mau et al., 2008). Both economies of scale and learning-by-doing are reflected in the declining capital cost function. Along the same lines, the neighbourhood effect tailors the algorithm to reflect how an individual’s perception of these intangible costs’ changes over time. Essentially, this effect takes place as supporting infrastructure for various technology increases over time. The associated risk and assumption of service quality declines as individuals see this technology more incorporated into everyday life. For example, a more well-established, easy-access transit system may lower the reservations an individual holds for choosing that transportation mode over a car. This could be reflected through less walking time required, neighbours are noticed walking to transit hubs, transit hubs become faster and more direct to places of high employment. The same concept goes towards electric cars— as an individual associated risk with vehicle charging infrastructure is alleviated through more convenient charge stations. Neighbours who begin to buy electric cars, or the general sense of satisfaction sold to them by other owners, start to reduce the higher intangible costs.

3.4. The CIMS-Urban Model

CIMS-Urban begins to bridge the gap between energy-economy models and urban form through simulating the economy with technologically explicit, behaviourally realistic, and spatial factors that influence changes at the urban level in a series of dynamic equations.

CIMS-Urban focuses primarily on personal transportation and urban buildings as they often account for the most significant emissions in cities (Bataille et al., 2010). The building sector, for example, looks at technology choices and energy use in households based on the building shell, heating systems, appliances, and floor space. Transportation, on the other hand, estimates the technology choice and energy use for personal kilometres travelled based on the type of mode (private vehicle, transit, cycling, and walking) (Förg, 2018).

CIMS-Urban components are depicted below in Figure 1. The relationship between a base and policy year is used to inform the respective network coefficients. In other words, the current land use is analyzed and used to produce quality for each node in transportation networks, which is then compared to the land-use and transportation network changes in a selected policy year.

The components display that spatial estimates of intangible costs are calculated through network quality indexes. More specifically, CIMS-Urban calculates intangible costs that are converted into a set of indexes for each transportation mode choice. This spatial aspect of the model enables the simulation of factors such as distance to transit, cycling, walking networks in the city, employment, length or route and overall quality (Förg, 2018).

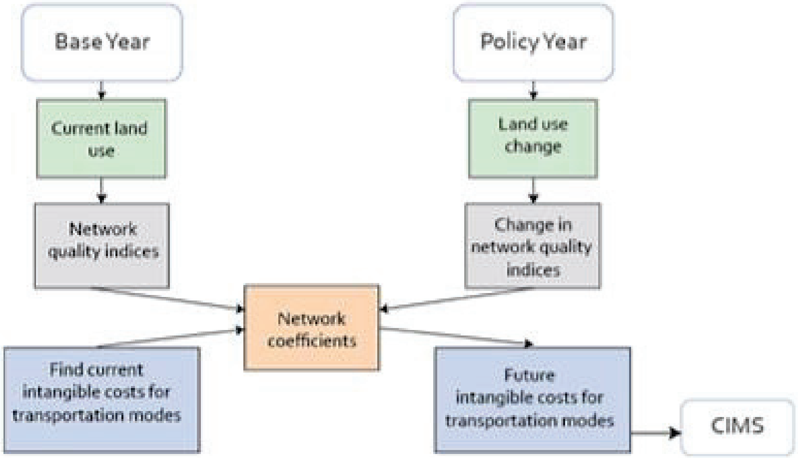


Figure 1: Structural components of the CIMS-Urban model Förg (2020)

To estimate the relationship between network quality indices and base year intangible cost by transportation mode, I have followed the methods and results estimated by (Förg, 2020; Zuehlke, 2017). The relationship between base year intangible costs and network quality indexes uses linear regression (least-squares method). Base year intangible costs for individuals in a particular traffic zone are based on 2016 Census data (Statistics Canada). The data provides transportation mode share split at the Dissemination Area geographical scale and converted into traffic zones (TAZ). Using the derived parameters from previous choice preference research, the census data can be used to drive the CIMS market share algorithm (Equation 1) for intangible costs. However, this method does not allow for the equation to be solved algebraically, since multiple intangible costs are needed for each transportation mode.

As a workaround, the Nelder and Mead optimization technique (1965) is used to solve the transportation costs in the traffic zones.

The optimization technique allows for an estimate of intangible costs in each traffic zone that is reflective of the mode splits provided by Census data. This leads to a scaling issue between traffic zones as the optimization method can lead to one traffic zone having high walkability while an adjacent one with an overlapping pathway could have low walkability. These pockets of variations in adjacent traffic zones are smoothed out by setting the intangible costs of each mode to zero in all traffic zones, mode by mode, which scales all other intangibles costs to the same level. The results of the scaling process are then averaged and cross-checked with the Census mode splits to ensure consistency.

Estimated intangible costs are related to the network quality indices through a linear log regression. The log transformation improves the fit of the equation as well as the explanatory power, as reflected in an improved R squared value. Socio-economic explanatory variables are also included as they are considered to have a substantial influence on travel behaviour (Ewing & Cervero, 2001; Ewing & Cervero, 2008). The log regressions relationship can then be used to calculate how intangible costs change as a result of land use and urban form change. Future intangible cost is derived from calculated network quality indices that are log-transformed, which are multiplied by the mode-specific network coefficients produced by the log regression.

Given CIMS-Urban ability to analyze the impact that changes in land use and transportation networks have on intangible costs, the model can assess interactions between urban-level and senior government policy. The model links these interactions in a way that is less complex than CIMS hard-linked with a conventional transportation model. CIMS-Urban produces intangible costs as an output, which is useful when using CIMS as these spatial outputs can be fed as direct inputs to the market share algorithm (via intangible costs) along with senior government policy information. Alternatively, if a conventional transportation model was used, the model outputs would exogenously set market share of each transportation mode in CIMS, which would make it difficult to see the interaction with senior government policies (e.g. on fuel price) using the CIMS market share algorithm. The benefit of CIMS-Urban in this case is that changes in costs (e.g. fuel price) and intangible cost feed into the same algorithm and can interact endogenously to determine mode share.

Previous research by Bataille et al. (2010) explored a similar question to my research but used a blend of multiple conventional land-use and transportation models. This mega-study and blend of multiple models required a large team of modellers to hard-link various components of each model. While this approach may add additional modelling components, it would add layers of complexity beyond the scope of this research. The combination of CIMS-Urban and CIMS struck the most suitable balance between modelling tools and complexity, while enabling me to effectively answer my research question.

3.5. Spatial Module Outcome Aggregation and Archetype Analysis

Previous research by Forg (2020) aggregated the intangible costs by traffic zone to a Metro Vancouver scale to generate regional changes in transportation mode choices. Each traffic zone was weighted by population, which assumes that as more residents living in TAZs with a high level of alternative transportation mode accessibilities, the lower the intangible cost they will experience. Driving intangibles costs by TAZ would ideally be weighted by the number of trips occurring through and within a zone. In response to a lack of data, Forg divided Metro Vancouver into sub-regions as defined by a 2011 Trip Diary document (TransLink, 2013). Weighted averages were created for each sub-region based on the Diary insights and then were converted to TAZ level intangible costs as a function of jobs in each zone.

Considering that the previous aggregation of adjusted intangible costs at the TAZ level was produced on a metropolitan scale, I then developed a method to use these insights to capture distinct urban form patterns and apply them to various cities and metro regions across Canada. The logic assumes that there are similarities between urban form within cities and metro regions that share downtown cores, commercial/mixed-use areas, and suburbs. While the physical make up of these pockets within a city or metro region will be different, their relative effect on people’s individual choices on transportation mode and driveability will largely be similar. I aggregate the national impact of major cities and the three metropolitan regions on energy and GHGs, under the primary assumption that relative patterns can capture segments of the population who live in very similar urban environments. I use drastic colour gradients in my archetype mapping to contrast between highly dense amenity rich urban form (oranges and reds) and low density amenity poor urban form (blues and greens). This type of gradient was chosen over typical bylaw zoning colours to distinctly represent where similar types of buildings exists. Zoning colouring often does not follow a gradient scheme and would lead to a speckled looking map rather than maps with noticeable pockets of opposing colours. While other colouring options were explored, I found contrasting gradients to be the most visually clear on the below maps.

The following sections will outline (1) the distinctions between each urban form archetype, (2) how I aggregate up each segment of the population in a respective city or metro region, and (3) how each city and metro region are aggregated to a national scale.

3.5.1. Selecting Urban Form Archetypes

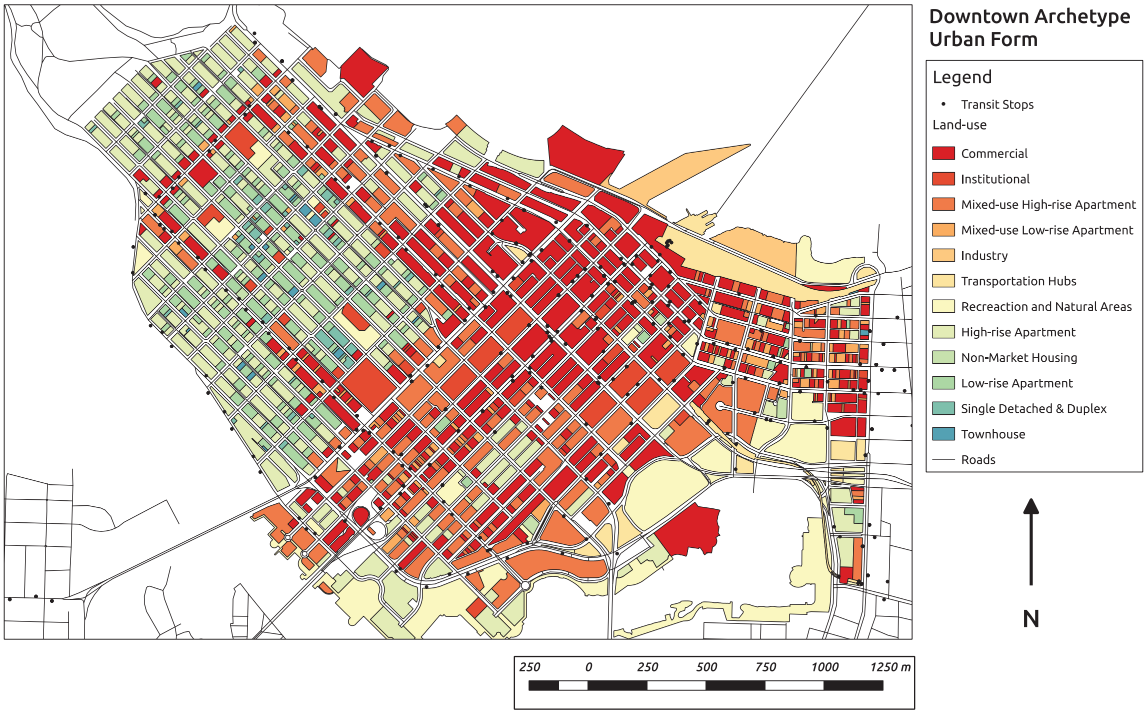


Figure 2: Land-use of downtown archetype urban form

Figure 2 is a map displaying the land-use of a downtown core archetype, which has been selected from the City of Vancouver's downtown area to represent similar urban form in cities and metropolitan regions nationwide. This area is primarily made up of large towers occupied by a mix of residents, commercial districts, highly accessible transit systems, high cyclability, and walkability. This is meant to reflect the assumption that other cores that are built on business districts, entertainment hubs, and low to high rise residential communities will reflect similar travel patterns.

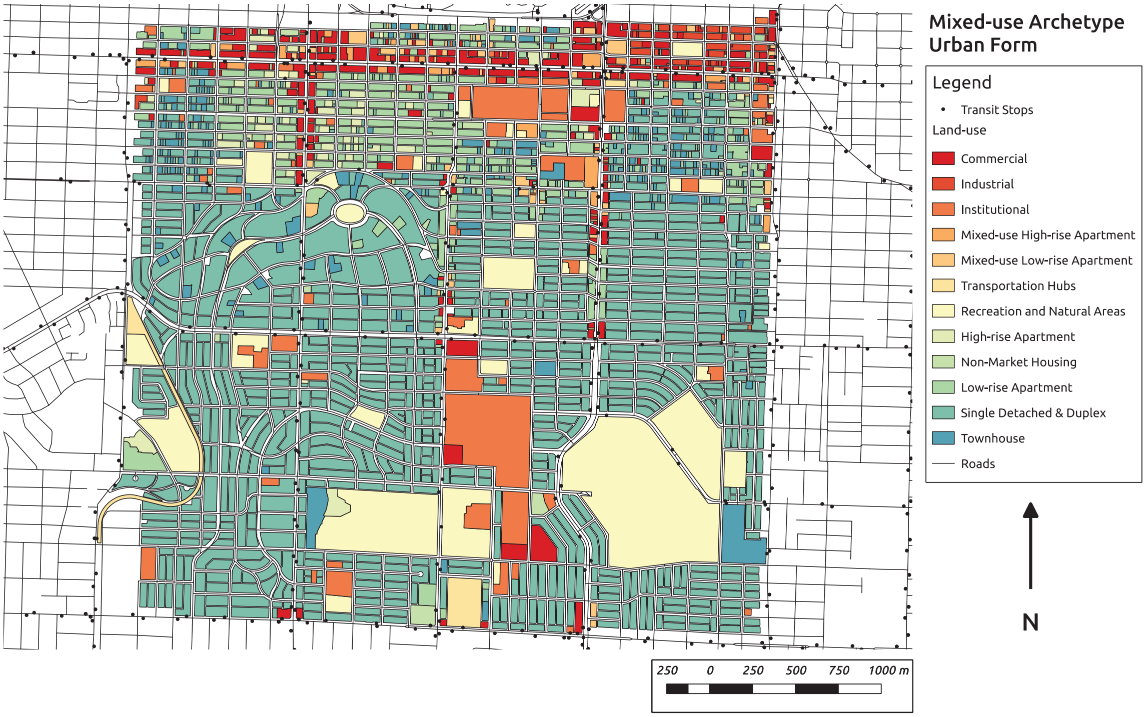


Figure 3: Land-use of mixed-use archetype urban form

Figure 3 is a map displaying land-use of a commercial and mixed-use archetype, which has been selected from an area within the City of Vancouver where there are clusters of commercial districts along an arterial street and peripheral areas of detached and attached row homes. By including a mix of suburban and commercial mixed-use along a main street, this section is meant to simulate travel behaviour that draws people to the commercial hubs. This area also can represent the downtown of smaller to medium-size cities by simulating a main street acting as the hub for commercial districts. The intention is to represent a variable transit, cycling, and walkability-based area adjacent to commercial hubs and transportation route options.

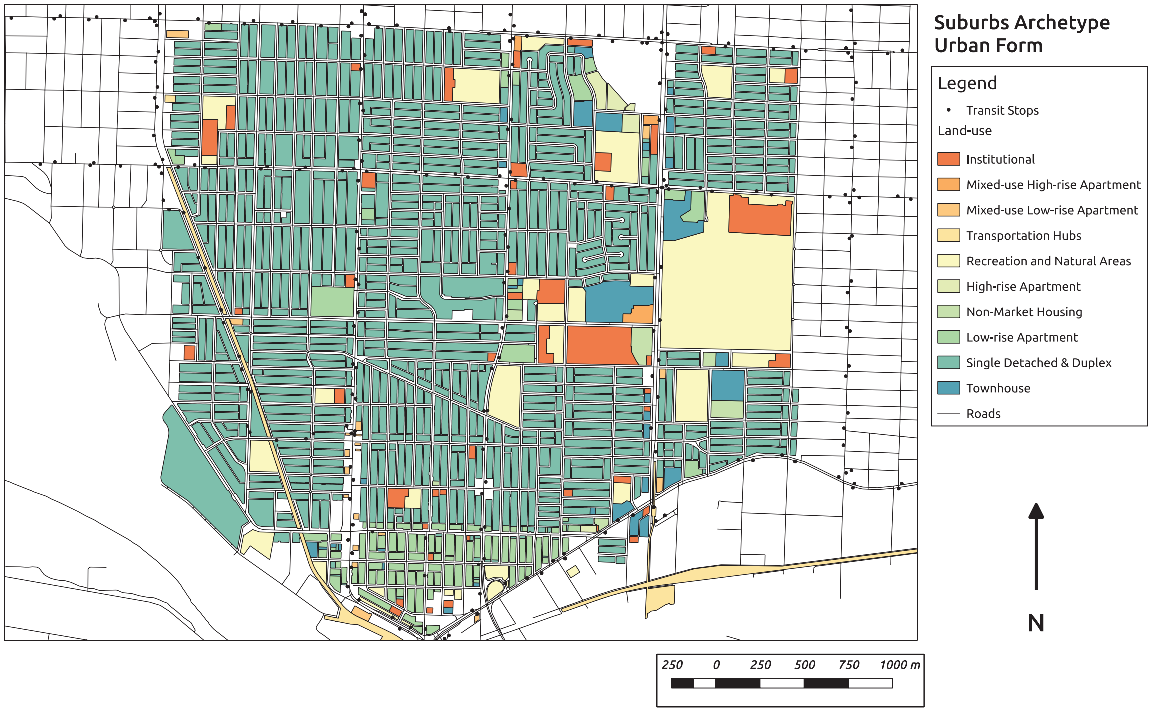


Figure 4: Land-use of suburbs archetype urban form

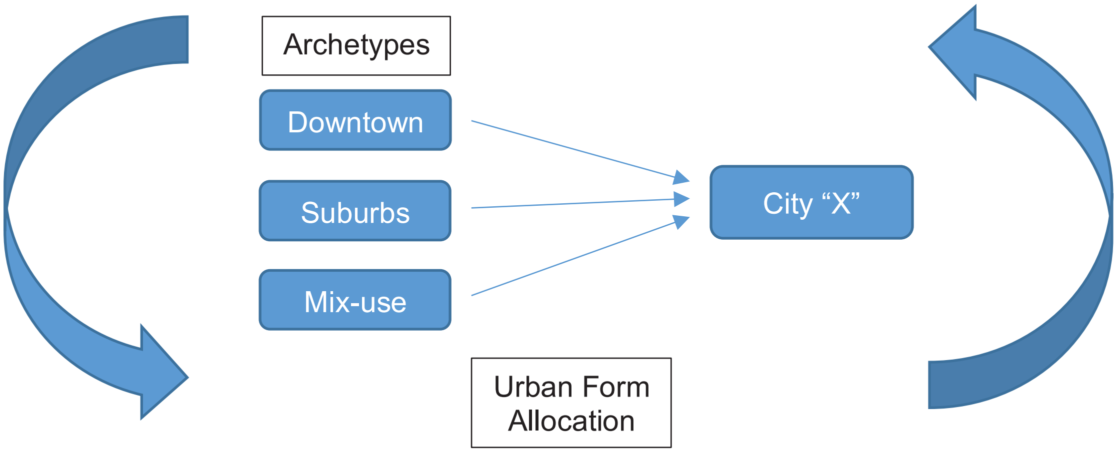
Figure 4 is a map displaying land-use of a suburban archetype within the City of Vancouver where the residential area is primarily made up of single-family detached homes, limited commercial land-use, poor transit, and access to a highway. This represents the neighbourhoods within metropolitan regions and cities with lower population densities—which generally requires individuals to commute to commercial districts by driving. These areas generally have low transit, cyclability, and walkability as mode choices for travel. The Marpole neighbourhood in the City of Vancouver was chosen as the suburban archetype due to its layout of single family homes, recreation space and low-density housing. The neighbourhood blocks are representative of typical suburban areas that surround downtown and mixed-use areas across the cities included in the study. The small commercial areas have been removed in this archetype to further represent the lack of amenities and services in suburban areas.

3.5.2. Aggregating Urban Form Archetypes

To reflect the make-up of various cities and metropolitan regions, I allocated segments of the urban population to each urban form archetype. For example, by taking the downtown core section and assigning a certain percentage of the population to that area, I can estimate the per person impact on intangible costs and its impact on mode choice. As illustrated in the figures above, each archetype represents a typical urban pattern found in Canadian cities and were assigned to a percentage of the population in each city. Determination of how many people live in “suburbs” versus a “downtown” archetype was based on municipal reports, various maps, and expert opinion for each city.

As previously mentioned, the data for each TAZ, which makes up each archetype, is from Forg’s (2020) 2015 base year in Metro Vancouver analysis. Each TAZs includes data that may be outside of the selected archetype area. Features such as transit lines and cycling routes that continue outside of the selected area are included. Ensuring that their inherent quality to the specific TAZ within the selected area is preserved.

Figure 5 Archetype Aggregation



The logic of the archetype aggregation is a straightforward iterative process of assigning a certain percentage of the city’s population to each urban form type. Figure 5 displays each archetype type. In the Urban Form Allocation, each of the archetypes is assigned a relative weighting to the total population living in the city or metro region. Through this approach, I have segmented the population in metropolitan regions and cities to reflect the assumed distributions of types of urban form. This process is then repeated based on the number of cities included in the study.

Assigning portions of the population to each archetype in a metro region builds on the assumption that patterns in urban form often produce similar travel behaviours. Patterns in this type of systemic assignment of archetypes help to explain general behaviours in the cities and can be used to enhance the transferability of modelling concepts (BenDor & Kaza, 2012; Wolstenholme, 2003). In other words, the patterns established in Metro Vancouver are applied elsewhere based on similar urban form archetypes in other cities.

See below for split makeups but note that this does not include the entirety of the Canadian population, as those included in cities were defined by 2016 Statistic Canada census data. I estimated each metro region and city archetype split from my analysis of public reports such as OCPs and planning strategies. In addition, I used municipal GIS systems to analyze current zoning and land-use policy as means to estimate urban form patterns.

Table 1: Archetype splits for metropolitan regions and cities (Statistics Canada, 2016)

CITIES	ARCHETYPE SPLIT OF TOTAL POPULATION IN BASE YEAR			
	Downtown	Mixed-use	Suburbs	Total
METRO VANCOUVER	7%	18%	75%	2,550,000
METRO MONTREAL	25%	15%	60%	4,100,000
METRO TORONTO	30%	10%	60%	6,600,000
ALL OTHERS (MEDIUM/SMALL)	Med 1% / Sm 0%	Med 6.5% / Sm 2.7%	Med 92.5% / Sm 97.3%	11,250,000

Together, Canada’s three major metro regions hold roughly a third of the Canadian population and were modelled individually to capture their relative differences in urban form. For example, Metro Toronto has a higher percentage of the downtown archetype than Metro Vancouver. First, archetype aggregation started by calibrating the Metro Vancouver results to that of Forg (2020) research on the entire Metro Vancouver region. This was to ensure that the aggregation of distinct urban patterns could reasonably estimate the results of a model that included all TAZs in Metro Vancouver and was used as a test of the modelling approach. Metro Montreal and Metro Toronto were adjusted by looking at population estimates in downtown urban core areas in addition to informed estimates made through regional maps. All other major cities were adjusted to show a primarily commercial and mixed-use suburban archetypical urban form. The splits for each region and collective cities are displayed in Table 1.

As mentioned, the Metro Toronto, Montreal, and Vancouver areas were modelled separately to capture variation in their urban form characteristics. For the small and medium-sized cities, the same segmentation of population logic was applied to estimate the aggregate effect of the respective cities. Within those cities, a small portion includes a downtown core archetype while the rest is suburban and commercial/mixed-use urban form archetypes. The major metropolises and various sized cities were then summed to estimate overall results, which are further discussed in Chapter 5.

Table 2: Population range by type of city (Statistics Canada, 2016)

TYPE OF CITY	POPULATION RANGE OF CITIES	TOTAL POPULATION	% OF TOTAL POPULATION OF CITY-DWELLERS	# OF CITIES
SMALL	12,000-220,000	4,731,000	19%	94
MEDIUM	340,000-1,600,000	7,317,000	29%	8
MAJOR 3 METROS	2,500,000-6,500,000	13,100,000	52%	3

Small and medium-sized cities included in the study were represented through mixed-use and suburban archetypes as illustrated in table 1. A small portion of the urban form was allocated to mixed-use to replicate the “downtown” of small/medium cities. While these cities do not have the same downtown type of Vancouver, they do generally have main streets that resemble that of the mixed-use archetype. For example, the “downtown” area of a city such as Victoria shares more similarities with mixed-use, rather than the accessibility and density of the downtown archetype. The suburban archetype made up the bulk of urban form for small and medium cities. While not all suburban patterns are uniform, the archetype chosen includes general patterns seen elsewhere, such as single-family lots that are close to arterial streets, limited amenities and services and low-quality transit. Ultimately, this may overestimate the accessibility of urban form in small and medium cities, due to factors such a sprawl spreading out the pockets of residential neighbourhoods. Despite this overestimation in some areas, I considered the split reasonable for estimating city climate policies at a national level.

Overall, I represent approximately 70% of the total Canadian population in my study. The population range for each type of city was based on my interpretation of common city sizes in addition to how Canadian Census defines cities. Canadian Census defines the majority of these very large cities as central cities of a census metropolitan area (CMA). A central city is defined as the city that is within a census metropolitan area. All other cities not within a CMA, are called peripheral cities. The buckets between a small and medium type of city is based on the largest gap in population size on the list of peripheral cities. The cut off for small cities is based on Census Canada dataset referring to urban areas below 12,000 as towns.

Chapter 4. Policy Mixes and Assumptions

I built hypothetical scenarios to test new methodical changes made to CIMS-Urban to estimate the research objectives. By aggregating urban form archetypes, I developed scenarios to estimate the impact that relative changes in buildings, density, land use, and transportation modes and energy forms can have on Canada’s top three cities as well as on Canada’s other cities and towns. The scenarios are designed to estimate energy use, GHG emissions, and travel demand of certain mode choices under metropolitan and city-level policies. This is simulated in tandem with senior government climate policies. In the following sections, I describe the test policy scenarios and key assumptions I made for each simulation.

4.1. Policy Simulations

I depict two sets of opposing alternatives using simple expressions to label the GHG-reducing efforts of senior levels of government as either “sincere” or “insincere” and their policies as either “smart growth” or “dumb growth”. “Smart growth” is a frequently used term which implies that other types of urban growth are dumb, while the last three decades have shown that many elected officials have been insincere in their GHG promises while a much smaller number have demonstrated their sincerity by implementing policies that actually reduce emissions. These contrasting depictions generate four scenarios for testing the relative effects on transportation behaviour and urban GHG emissions. These simulations are applied independently to the top three metro regions and then collectively to the cities and towns. Each scenario was simulated to the year 2050. Below outlines a matrix of each scenario (Table 3).

Table 3: Policy scenario matrix

		URBAN FORM GROWTH	
		Dumb Growth	**Smart Growth**
SENIOR GOVERNMENT CLIMATE ACTION	**Insincere**	*dumbGrowth+ insincereSen*	*smartGrowth+ insincereSen*
	Sincere	*dumbGrowth+ sincereSen*	*smartGrowth+ sincereSen*

4.2. Urban Scenarios

The two urban policy scenarios (dumb and smart) were sourced from previous EMRG research (Förg et al., 2021) that developed two contrasting growth scenarios in the context of Metro Vancouver.

Under the dumb growth scenario, I assumed that there is a limited collective effort by municipalities and metropolitan regions to concentrate growth into higher density and mixed uses aligned with non-vehicle mobility options. This includes shopping malls and suburbs that favour the ongoing dominance of personal vehicles and single-family detached dwellings. In contrast, a “livable community approach”, or smart growth, commits to preventing low-density sprawl. I also assume that general population trends, as estimated by Statistics Canada for each respected region, would remain constant in each downtown, commercial/mixed-use, and suburban urban form archetype. I assumed the service quality and accessibility of personal transportation mode would stay relatively unchanged. This is represented in the model by holding the non-financial costs constant for walking, cycling, transit, and driving. Additionally, percent shares of building stock would remain constant, and splits would be representative of typical Canadian metropolitan regions. Thus, I assume that in 2050 26% of all dwellings would still be single-family detached homes, 31% attached homes, 26% low-rise multi-unit residential buildings (MURBs) (less than five stories), and 17% high-rise MURBs.

4.3. Senior Government Scenarios

I assume sincere senior government action on GHG emissions involves similar approaches and stringency to that of the policy list indicated below. Insincere, on the other hand, assumes senior governments turn climate insincere and roll back key policies that have been a part of current sincere government climate strategies for aggressive 2030 and 2050 climate targets. The intention is to display the contribution that national climate policy has on GHG emissions at the city level.

All sincere scenarios include the following provincial and federal policies and were modelled through the CIMS energy-economy model (Chapter 2), whereas the insincere scenarios do not include these and the already legislated federal carbon pricing backstop is assumed to be eliminated in 2025.

- Existing carbon tax of 30$ per tonne of CO2 in 2012 rising to 50$ in 2021 and then 170$ as announced by the Canadian federal government.
- The federal Passenger Automobile and Light Truck GHG Emissions Regulation: these regulations set a certain fuel efficiency and carbon-intensity level for new vehicles sold. A similar policy also applies to heavy-duty vehicles, referred to as the Heavy-duty Vehicle and Engine GHG Emission Regulations. Both sets of regulations are generally referred to as vehicle emissions standards and in the model reflect a stepwise energy efficiency and carbon-intensive standard over time.
- Low Carbon Fuel Standard (LCFS): this policy requires a minimum renewable fuel blending of 4% in diesel and 5% for gasoline in addition to a 10% reduction in transportation fuel carbon intensity by 2020 compared to 2010 and rising to 20% reduction by 2030 (Greenhouse Gas Reduction (Renewable and Low Carbon Fuel Requirements) Act, SBC 2008, c. 16; B.C. Reg. 394/2008). The LCFS is a market-based flexible regulation that operates through a credit trading system. The LCFS was modelled at the provincial level. Low-carbon transportation fuel shares, which were a result of Doan's (2020) simulation of the LCFS in CIMS BC were input for the metro-level CIMS model.
- Zero Emissions Vehicle mandate (ZEV): this policy sets a required minimum percentage of vehicle sales sold to be zero emissions. Starting at 10% of total new vehicle sales in 2025, rising to 30% by 2030 and 100% by 2040. Vehicles counted as ZEVs are electric, plug-in hybrids, and hydrogen-fueled. Similarly, to the LCFS, this policy operates in a credit marketplace where car suppliers can trade credits between one another. Again, this policy was modelled at the provincial level by Doan (2020) and vehicle share results were used as inputs for the minimum requirements in the metropolitan CIMS model.
- Subsidy for light-duty electric vehicles (plug-in hybrid and full electric): $6,000 subsidy for all plug-in hybrid and electric vehicle purchases, (an

approximation of progressive contributions by the provincial and federal government). The simulation is available until 2040— assuming the federal or provincial ZEV mandate requires 100% ZEV sales by that year.

- Provincial subsidies for heat pump conversion: the program provides $2,000 for electric baseboard heating systems or retrofitting fuel-fueled heating system upgrades to a heat pump.
- Renewable Natural Gas Standard requires a minimum content of 15% biogas content in natural gas supply by 2030.
- Building code requirements modelled after BC's Building Code and mandatory steps of the BC Step Code: In 2022, mandatory requirements for all new homes and commercial buildings must be 20% more efficient than the current building code. In 2027, energy efficiency requirements increase to 40%, and in 2032 increasing up to 80% efficiency. The model assumes that efficiency requirements would increase linearly to align with mandated efficiency targets. This is simulating by controlling the market share of new less energy-efficient technologies being purchased. I use this policy design to assume what other provinces and municipalities would follow to be aggressive on building emissions. This also covers major cities such as Vancouver and Toronto who have imposed ZEBs that are along the lines of efficiency standards outlined in the BC Step Code.
- Federal energy efficiency standards for building equipment and common household appliances are simulated by making less efficient technologies phase out over time.

Chapter 5. Results and Discussion

To assess my research objectives, I display estimated GHG emissions and energy consumption results for each of the four scenarios. I break down these scenarios into the aggregate results, the three metro regions and all other small and medium cities. Next, I show the fuel switching-based breakdowns. Results are further broken down into estimates of GHG emissions and energy use reductions associated with transportation mode choice to show relative fuel switching and expected changes in urban form and population growth. Displaying emissions in this respect show end-use energy consumptions of vehicles— no upstream emissions associated with fuel production are captured in the model. All energy and emission results pertain to the four key sectors important to urban-focused climate policy: personal and freight transportation, as well as commercial and residential buildings.

5.1. Greenhouse Gas Emissions

5.1.1. All Cities and Metropolitan Regions

The estimated total GHG emissions results for each of the four scenarios of all of Canada's relevant urban areas are displayed in Figure 8. This includes Metro Toronto, Metro Montreal and Metro Vancouver as well as the small to medium-sized cities. This result covers 70% of the Canadian population. In the following sections, I disaggregate the results into the respective metropolitan regions and all other cities and agglomerations. The aggregate GHG results support the assumption that changes in urban form through policy and action can contribute to GHG reductions, however these effects are moderate when compared to the effect of sincere senior government policies. When comparing the year 2015 to 2050, *dumbGrowth+insincereSen* and *smartGrowth+insincereSen* GHG emissions may reduce 25% and 36%, respectively. The noticeable reduction under the *dumbGrowth+insincereSen* is largely due to the continued current carbon pricing policy until 2025 when it is assumed to be eliminated. Comparatively, with the addition of sincere government action in the *dumbGrowth+sincereSen* and *smartGrowth+sincereSen* scenarios, GHG emissions may reduce 86% and 88%, respectively. The narrative illustrated is that if senior governments decarbonize the economy, actions of cities and metropolitan regions do not significantly reduce GHG emissions or play a contributory role to senior government policy. At the municipal level, emissions could potentially be lower because of the increasing population at urban hubs which utilize the existing transit, amenities, and accessibility infrastructure.

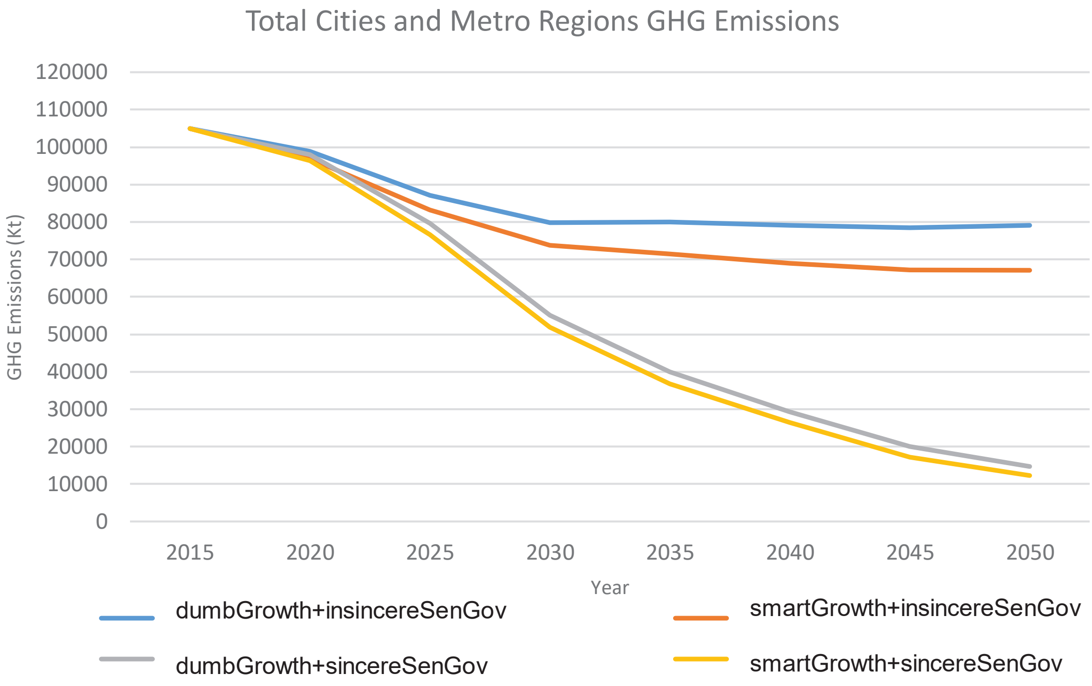


Figure 6 Total Cities and Metro GHG Emissions

In comparison to adding smart growth policies and actions, the estimations display the relative impact cities and metropolitan regions could have in response to insincere action. This raises the point that smart growth policies will largely help to lower overall GHG emissions but are unable to cause deep GHG reductions. Smart growth actions and policies may encourage a reduction in energy demand through travel demand, mode switching and slight efficiency improvements but are extremely limited in causing fuel switching.

Sincere senior government policies cause fuel switching for a rapid transition away from fossil fuel-based energy sources and lowers the carbon intensity of heavily integrated fuels such as natural gas and gasoline. The two sincere-based scenarios display far greater emission reductions than the scenario solely relying on smart growth policy.

5.1.2. The Three Major Metropolitan Regions

The estimated total GHG emissions for Metro Toronto, Metro Montreal, and Metro Vancouver are displayed in Figure 9. This portion of the aggregated results covers approximately 38% of the Canadian population. When comparing the year 2015 to 2050, *dumbGrowth+insincereSen* and *smartGrowth+insincereSen* GHG emissions may reduce 26% and 39%, respectively. Comparatively, with the addition of sincere government action in the *dumbGrowth+sincereSen* and *smartGrowth+sincereSen* scenarios, GHG emissions may reduce 82% and 85%, respectively. The estimations for the three major metropolitan regions are largely like that of the national aggregation, however, there is a larger spread between dumb and smart growth scenarios. This is a result of the lower intangible costs established in these metro regions, which is due to having a higher make up of downtown and commercial/mixed-use archetypes. Ultimately commanding a higher active transportation use and densification rate than small to mid-sized cities. Ultimately, the estimations of the metropolitan regions dictate much of the aggregate emissions results because of their population comprising slightly over half of the population included in the modelling.

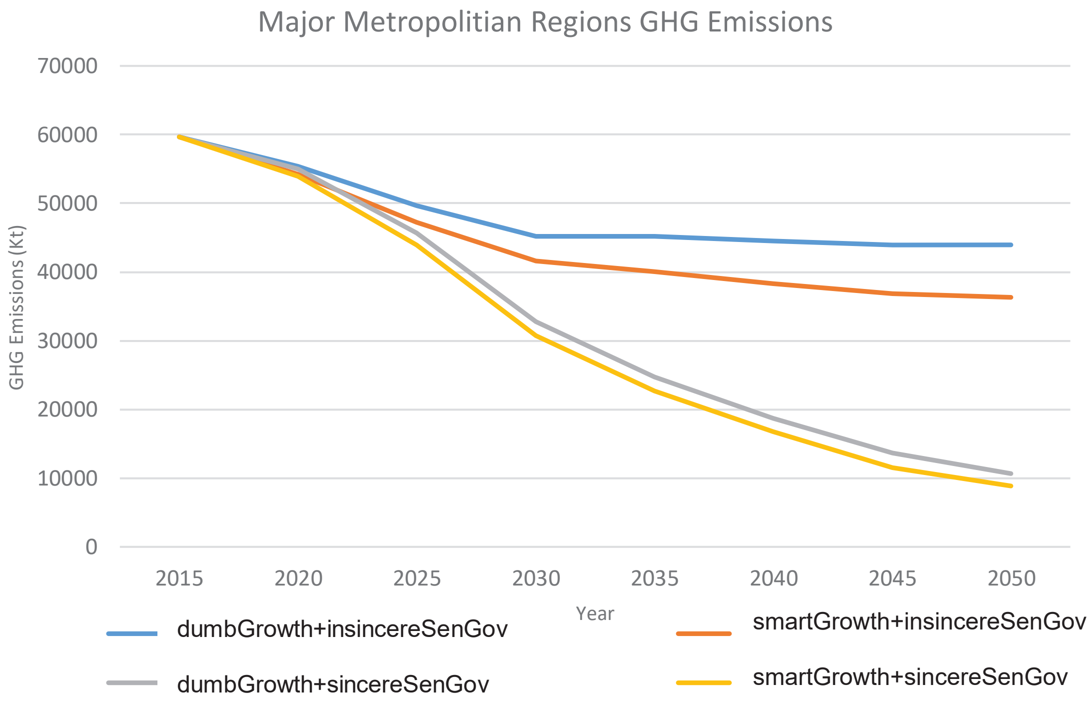


Figure 7 Major Metropolitan Regions GHG Emissions

5.1.3. Small and Medium Cities

The estimates for small to medium-sized cities are displayed in Figure 10. When comparing the year 2015 to 2050, *dumbGrowth+insincere* and *smartGrowth+insincere* GHG emissions may reduce 22% and 32%, respectively. Comparatively, with the addition of sincere government action in the *dumbGrowth+sincereSen* and *smartGrowth+sincereSen* scenarios, GHG emissions may reduce 91% and 92%, respectively. The relative split between dumb and smart growth development is smaller than that of the metropolitan regions. Not surprisingly, this is a direct result of these areas not having a downtown core that is as extensive as that in Montreal, Toronto, or Vancouver. However, there are either main streets, downtown centers, or highly dense mix-use areas that are on a smaller scale. These provide an opportunity for increasing active mode shares and following aggressive building policies that encourage densification. The estimations under sincere government action present a unique insight into how deep GHG reductions can occur because of senior government action. In particular, the nature of urban form in these areas generally are less densified, more kilometres are travelled per person and there is less access via active mobility. This favours the senior government in terms of emission reductions opportunities because these policies target technology and fuel switching objectives, which are the primary drivers of deep emission reductions. The relative 92% reduction under the most aggressive scenario displays the impact that fuel switching through technology change across Canada’s small and medium cities can have on GHG emissions.

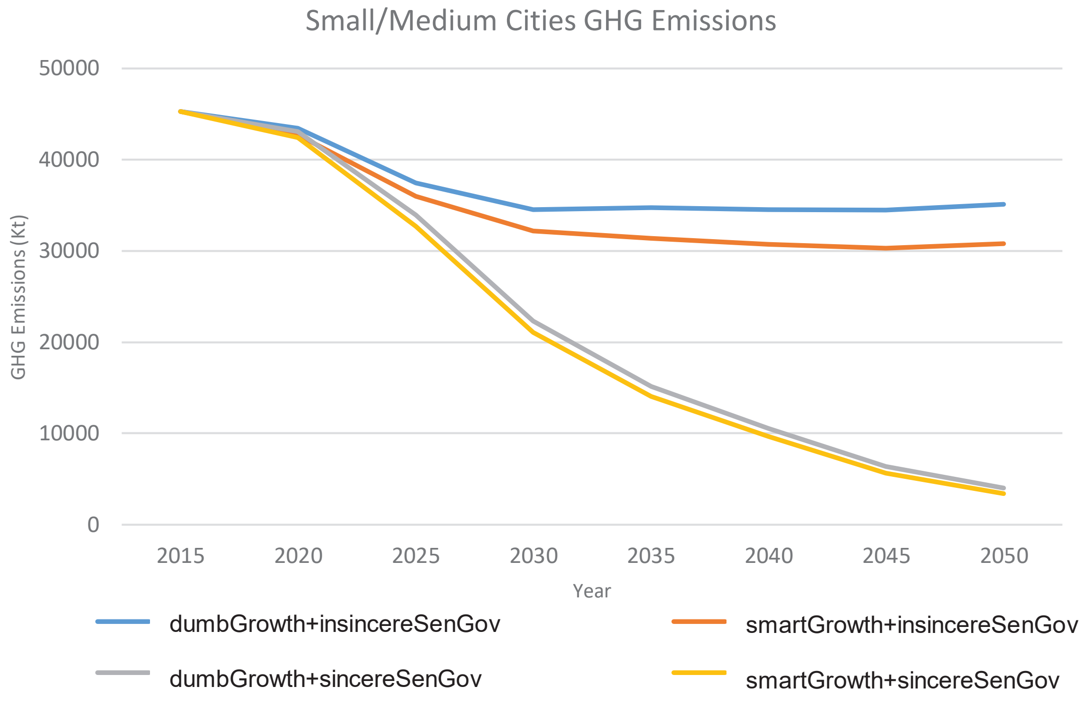


Figure 8 Small/Medium Census Defined Cities GHG Emissions

5.2. Energy Consumption and Fuel-Switching

The estimated total energy consumption for the aggregate of all cities in each of the four scenarios is displayed in Figure 9. Much like the GHG emissions results, the energy savings by smart growth actions and policies contribute more to reductions under insincere senior governments and less so under sincere. The energy trends of all scenarios show the capacity for energy savings in response to population increases in cities and metropolitan areas, which helps explain why deep GHG emission abatement pathways can occur despite continued population growth.

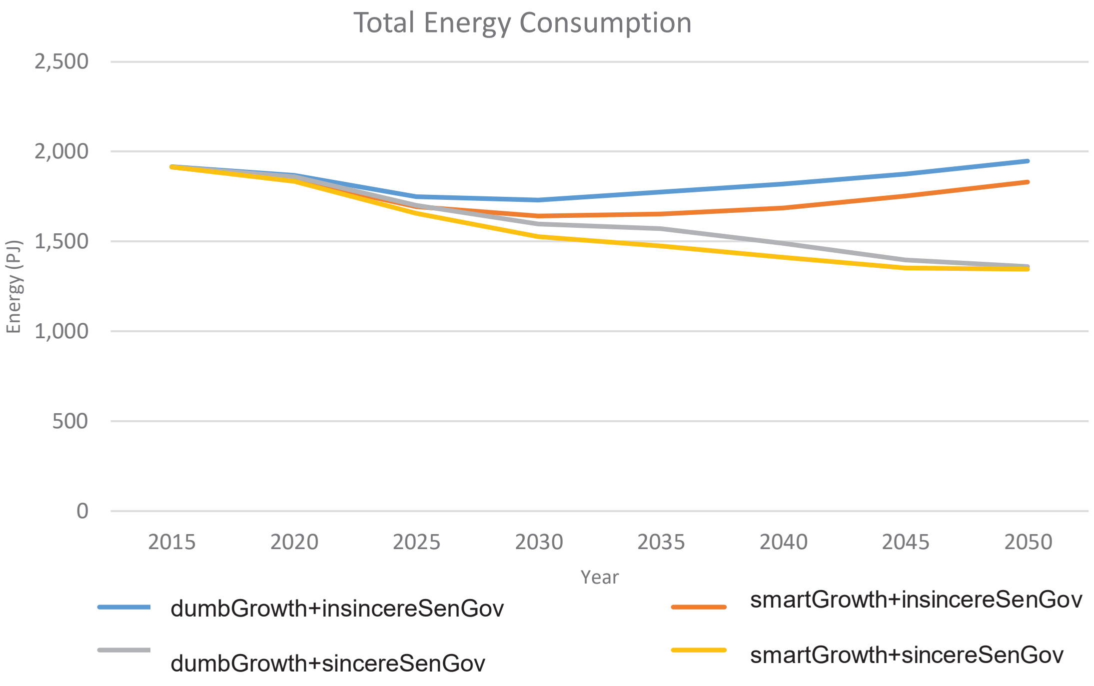


Figure 9 Total Energy Consumption by Scenario

Under *dumbGrowth+insincereSen* scenario, total energy consumption does not fall between 2015 and 2050. As the population increases in this scenario, energy demand is held relatively stable due to general energy efficiency trends in technologies. Energy consumption reduces the most under *smartGrowth+sincereSen,* by 38% between 2015 and 2050, which is primarily due to senior government policies encouraging faster uptake of more energy-efficient technologies. Likewise, smart growth under the sincere scenario facilitates further reductions in energy consumption, which will be further depicted in reductions in travel demand and transportation mode switching. Specifically, the smart growth policies reduce the required travel demand and mode switching to active forms of transportation— which greatly reduces the amount of energy required in the transportation sector. This is highlighted between the smart growth and dumb growth scenarios, where insincere government and smart growth reduces energy consumptions by 17% between 2015 and 2050 relative to dumb growth.

Changes in population densities produce similar effects on energy use as were displayed in the GHG results broken out for the three major regions. Higher population densities are due to more of the population and growth being experienced in downtown and commercial/mixed-use areas than that of other small and medium cities. This encourages more uptake of active modes of transportation and less travel demanded due to changes in urban form.

Energy consumption for all cities and metropolitan areas in all four scenarios are shown in Figures 10 and 11. See Appendix for a breakdown of the percentage shares of each fuel. As I previously stated, energy consumption is from personal and freight transportation as well as residential and commercial buildings. Diesel, gasoline, and other refined petroleum products are grouped (RPPs).

Figure 10 Energy use (PJ) yearly breakdown by scenario

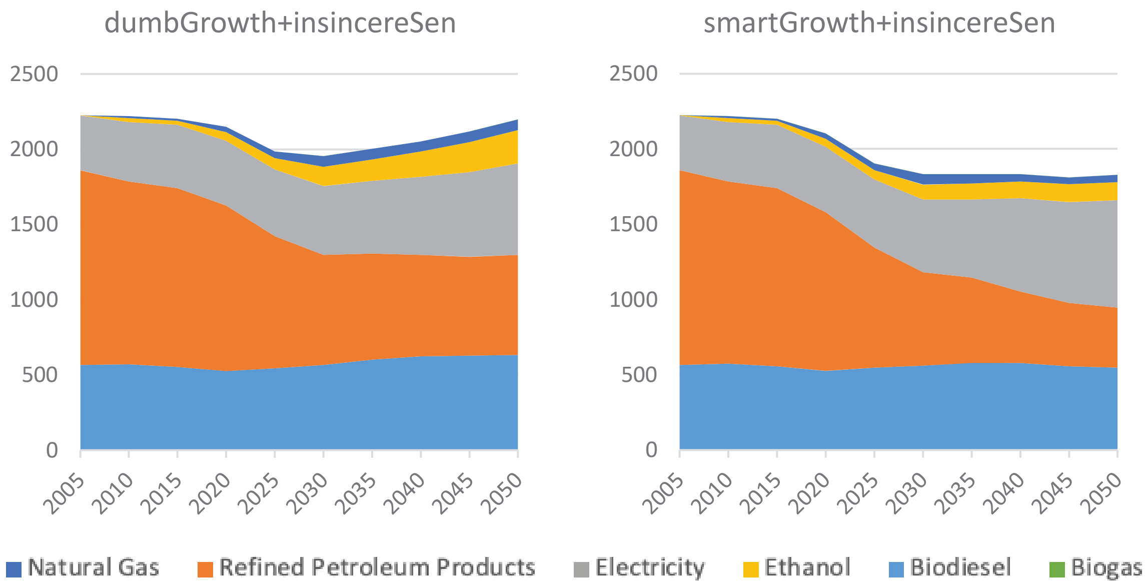
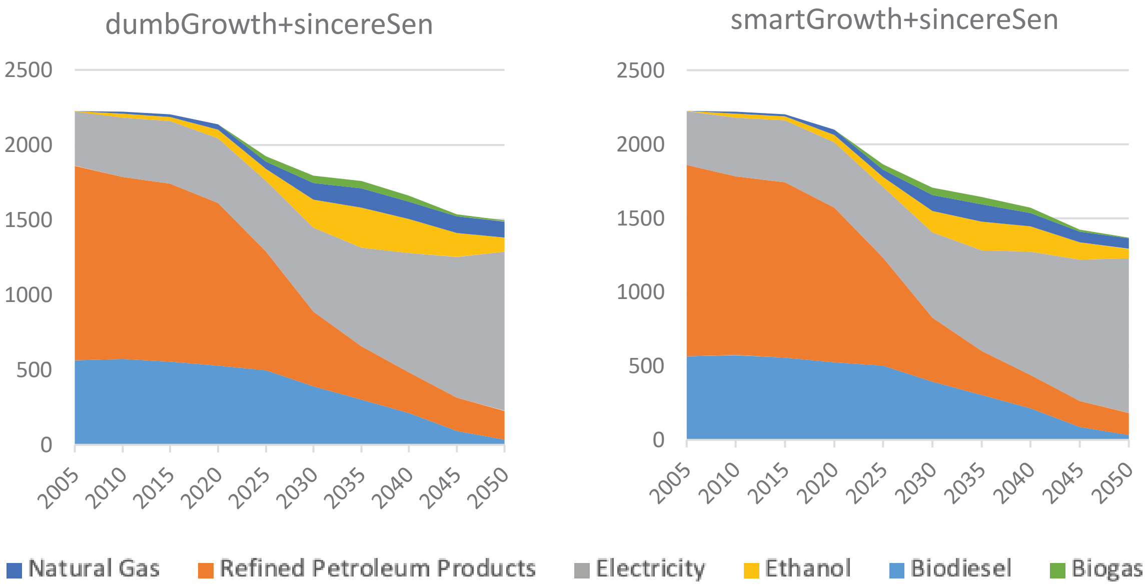


Figure 11 Energy use (PJ) yearly breakdown by scenario



When comparing *dumbGrowth+insincereSen* and *smartGrowth+insincereSen* scenarios (Figure 10), smart growth does encourage modest fuel switching through local land-use policies simulating shifts on transportation mode choice. Mode shifting most notably slightly decreases the share of RPPs, which can be attributed to fewer people relying on personal vehicles for their travel demand.

The addition of sincere government action, implementing stringent fuel switching, causes significant reductions in fossil fuels. The high stringency of policies such as the ZEV, LCFS, and RNG standards lower the overall energy consumption and stimulate fuel-switching to low-carbon options. The comparison between *dumbGrowth+sincereSen* and *smartGrowth+sincereSen* (Figure 11) displays similar results as local land-use policies that encourage fuel switching are overlapped by senior policies. However, under the smart growth scenarios, fuel switching away from RPPs and natural gas is slightly larger than without action by cities and metropolitan regions.

5.3. Travel Demand and Mode Switching

The estimated total person kilometres travelled (PKT) for all cities in each of the four scenarios is displayed in Figure 12. The PKT of both growth scenarios under sincere and insincere senior government only differs by a few percentage points. In contrast, the overall PKT between dumb and smart growth scenarios differ significantly. *dumbGrowth+sincereSen* and *smartGrowth+sincereSen* show a relative increase in PKT of 52% and 28% from 2015 to 2050, respectively. Under smart growth, land-use improvements that increase the accessibility of commercial land parcels to individuals reduce the PKT demand as the population continues to grow to 2050.

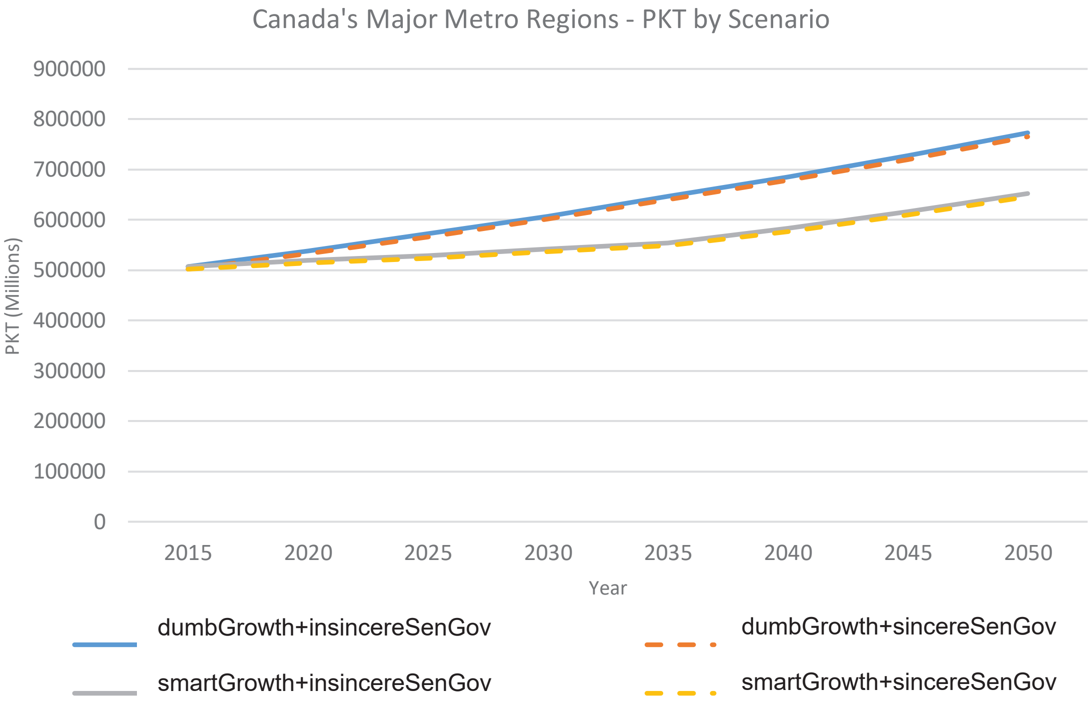


Figure 12 Total Cities and Major Metro Regions - PKT by Scenario

As mentioned, the relative impact of PKT under smart growth shows the influence that population densities increasing in downtown and commercial/mixed-use archetypes can have on overall travel demand. High-density hubs and accessibility traffic zones within these archetypes are increased under smart growth policies. This indicates that the overall travel demand can be restricted by land-use changes despite the population continuing to grow. The major contributor to decreasing the travel demand is the existence of mixed-use land zoning and the accessibility of commercial districts that residents can easily access. Without these smart growth actions, travel demand by population growth is not curtailed as aggressively and already existing infrastructure facilitates roughly a 63% increase in PKT.

Between 2015 and 2050, the smart growth policies and actions stimulate a greater overall reduction in PKT in each transportation mode, while the active modes, cycling and walking, only experience a slight uptake by 2050. This suggests that few people shift from vehicle transportation despite improving the quality of routes. Fortunately, the increase in PKT was captured mostly by transit between 2015 and 2050 because of improved transit quality nudging individuals out of vehicles.

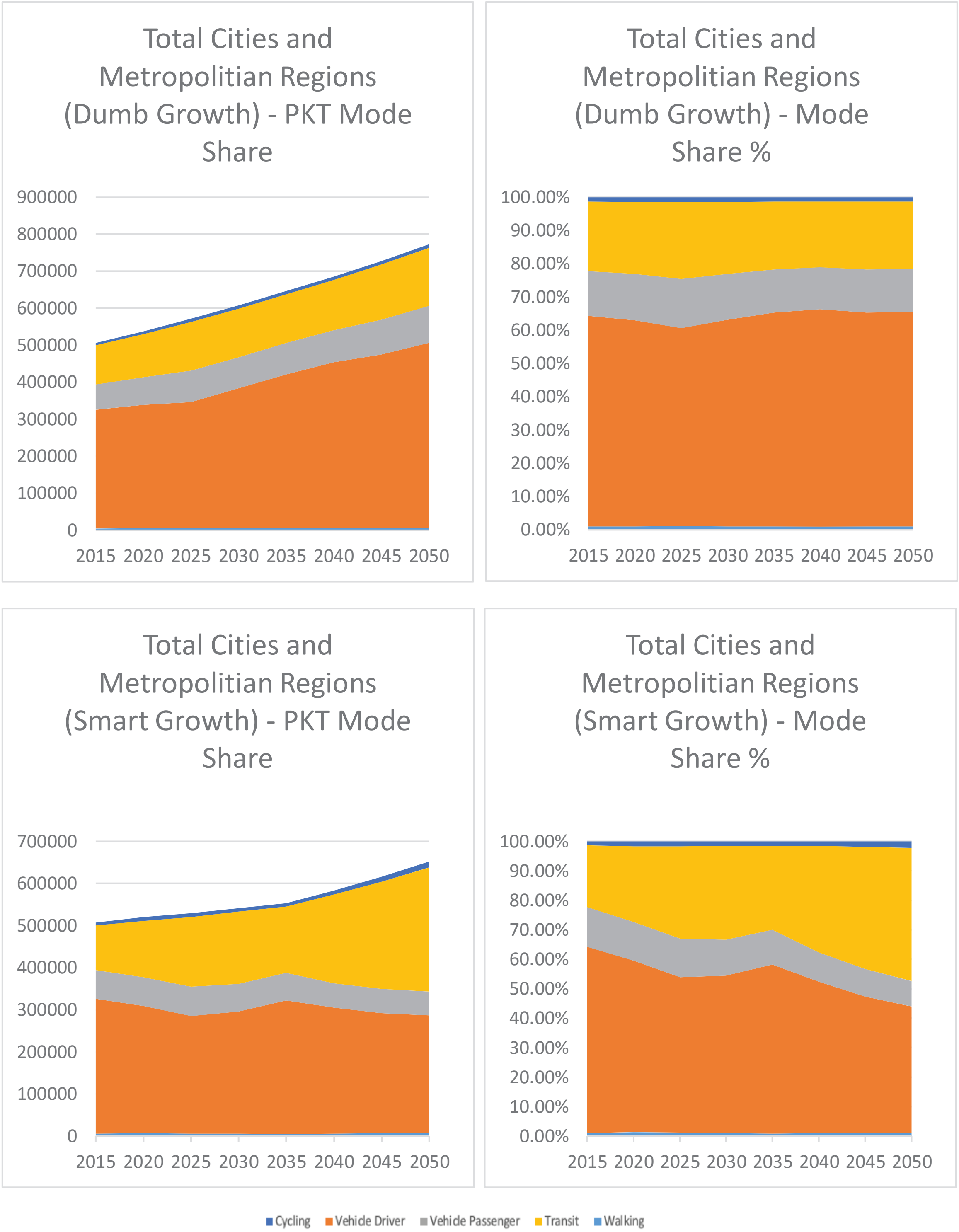


Figure 13 Mode share splits by PKT and % for all scenarios

The results indicate in Figure 13 that mode-shifting and travel demand constraints occur under smart growth policies and actions that introduce land-use changes and improvements in alternative transportation. Despite these changes, total travel continues to climb as population and infrastructure grow. These types of urban policies associated with smart growth are key initiatives that can be used to constrain anticipated growth in vehicle travel in urban areas within cities while supporting growth in transit and reductions in the overall vehicle share by 2050. The values estimated within this portion of the model indicate that vehicle use will remain an important aspect of mobility, which supports the need for fuel switching policies at senior government levels to encourage movement away from fossil fuel vehicles and towards ZEVs. Notably, in the smart growth scenario, there is a peaking of PKT in 2035. This represents the point where transit market share begins to offset the growth in personal vehicle use as a result of smart growth policies. In 2035 individuals begin to respond to the lower intangible costs associated with taking transit as a result of improved network quality from smart growth. This indicates that smart growth has a noticeable impact on mode shifting within cities in addition to lowering overall PKT as displayed in Figure 12.

Chapter 6. Conclusions

6.1. Summary of Findings

I used the CIMS energy-economy model to determine how changes in urban GHG and energy policy could assist with senior government policies addressing GHG emissions for all city-dwellers in Canada. This involved conventional energy-economy modelling supplemented with the spatial components of CIMS-Urban that incorporate policies that affect land-use, density, and transportation and mobility infrastructure. I contributed to the application of methodology by incorporating archetype-based urban modelling to estimate the aggregate effect of similar developments in other Canadian cities and metropolitan regions. Utilizing this approach, I was able to test and explore the research objectives of estimating the incremental energy demand and GHG emission reduction resulting from a Canada-wide effort of smart growth planning by cities to avoid sprawl and create denser urban hubs.

The combination of smart growth and sincere government action reduces emissions 88% in 2050 compared to 2015. These results exceed both Metro Vancouver and Greater Toronto's 2020 climate goals of reducing GHG emissions 80% by 2050. Even without the smart growth policies and action under the *dumbGrowth+sincereSen* scenario, reductions still reach 85% for all cities and metropolitan regions. The addition of smart growth policies only marginally reduces emissions but does decrease per person travel demand and increase transportation mode switching towards transit use as PKT increases with population growth.

Under insincere government, the GHG emissions and energy use difference between smart growth and dumb growth is significant. This indicates the overlap senior government policies have with smart growth policies. The scenarios without senior government policies shows that cities and metropolitan regions can make up for more of the emissions reductions. However, they alone are certainly not able to meet their aggressive GHG emissions targets by 2050, at least not with the package of policies I simulated in my smart growth scenarios.

I further find that for the three major Canadian metropolitan regions to decarbonize, they would have to be given the ability to impose stringent policies similar to that of provincial and federal governments, such as pollution pricing and regulations.

In this case, Metro Vancouver does hold the unique authority to regulate air pollution—which could operate as a policy pathway for controlling emissions through pricing or fuel-switching regulations.

I found overlap between local and senior government policies in addition to policies at the same level of government. Smart growth policy scenarios with insincere government action were more effective on energy and GHG emissions reductions than sincere government action. While the study did not test the overlap between climate sincere policies, this policy overlap between senior and local level government should not necessarily be considered an issue. Local policies offer further reductions in a region on top of senior government policy and can further facilitate actions such as mode-shifting away from vehicle use.

6.1.1. Results in Context

While smart growth policies are not key drivers of deep GHG emissions reduction in the scenarios, it is worth noting the additional benefits they provide to an urban population. Smart growth is often related to urban form development that improves the quality or satisfaction one experiences in their urban area, neighbourhood, or city. This experience is largely subjective but can be thought of as an individual preferring certain attractive or desirable features in a city, such as improved cycling and walking routes, access to amenities, and selection in transportation mode over a city development (Tian et al., 2015). However, these aspects change over time and are subject to socio-economic and cultural characteristics (Ruth & Franklin, 2014).

On the other hand, it is noteworthy that not everyone prefers high-quality cycling routes, mixed-use neighbourhoods, and transit hubs with access to amenities. Some people prefer single-family homes with a backyard. As this demand exists in metropolitan regions, so does the pressure on housing markets to meet a range of expectations and demands. As these metropolitan regions grow the sprawl of traditional suburban neighbourhoods may be constrained through the land-use policies inherent in smart growth.

The relationship between affordability, social equity, and smart growth is highly complex, but a critical perspective for cities and metropolitan areas moving in this direction. There are opposing perspectives on how smart growth may impact affordability, as some raise the concern that this type of growth will reduce affordability and equity, while others claim the opposite (Förg et al., 2021)

A primary pillar of smart growth is to facilitate walking, cycling, and transit use for mobility, which can be important for lower-income people as car ownership is more expensive per kilometre traveled. The ability of such people to access efficient and frequent transit hubs can enhance their ability to reach destinations needed for socializing, employment, or services (Ermagun & Tilahun, 2020; Lucas, 2012).

Overall conclusions for the positives and negatives of smart growth on affordability and equity are difficult to quantify but do not necessarily negate the role that it can play in supporting these objectives. Smart growth policies and actions implemented by local governments across Canada have an opportunity to play a contributory role in aiding climate targets. While GHG emissions reductions from city policies are likely to be relatively small compared to what sincere senior governments can achieve, cities and metropolitan regions can nonetheless contribute to the transition of Canada towards GHG emissions targets in addition to supporting urban equity, sustainability, healthy lifestyles, and varying transportation modes for our growing population.

6.2. Study Limitations

Modelling studies are built on representative scenarios of a complex world. Each simulation is structured around parameters, equations, and assumptions that contain inherent uncertainty. In this section, I will discuss the implications of the judgments and methods for modelling complex urban systems at a national scale.

The spatial module and the results I extracted provide a simplified assessment of the built environment and could be further improved. Previous EMRG research has improved the model's applicability for assessing key spatial relationships such as willingness for people to travel based on the type of transportation mode chosen. Most fundamental to the urban CIMS-Urban model are the spatial indexes, which rely on straight-line distance between points, which is to some extent a distortion of the actual distances people would travel, meaning that the parameters are not perfectly accurate. Other urban network factors not included were the availability of sidewalks or inter-line transit connections as well the direction of traffic flow on major transportation routes.

Additionally, landscape and climatological factors, such as topography and weather limitations, were not explicitly included as inputs. The ultimate objective of the study is to strike a balance between what is required to assess complex aspects of real-world city functions.

The regression between census base year intangible costs and the estimated network quality indices is built on partial, limited data. Census data is conducted in spring and summer, which likely puts a bias on transportation mode choices. Similarly, the regression assumes that the relationship between urban form and transportation choices is constant. Considering that some of the patterns and results extracted were from Metro Vancouver, this assumption likely overestimates preferences for weather-vulnerable modes of mobility, especially in colder Canadian climates. For transportation, census data only provides travel to work trips, data which were calibrated to trip diary information at an aggregated level to adjust for other than work trips.

The archetype-based analysis further exacerbates the assumptions made when describing and estimating the changes in urban form. The population percentage in each metropolis was informed through best judgement. This archetype approach relies on patterning to make assumptions for large urban areas, for example, that individuals living in the downtown core of Metro Vancouver would reflect similar patterns to people in the downtown core of Metro Toronto or Metro Montreal

The ZEV and LCFS were not endogenously simulated in the CIMS model as there is a credit trading market that needed to be modelled at the provincial level. The function of this market was modelled at a provincial level by previous EMRG research, which provided specific mode share and fuel splits inputs for the CIMS model. This assumes that these inputs would be similar in the other provinces of cities and metro regions included in the study.

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Appendix. Supplemental Figures

Network Quality Index for Walking

$$Q_w = Q_{w\,work} + Q_{w\,ComInst}$$

$$Q_{w\,work}\ for\ taz_i = \sum_{1}^{taz_j\ within\ dist.\ r} \frac{emp}{e^{\beta * dist.\ d_{ij}\ to\ emp}}$$

$$Q_{w\,ComInst}\ for\ taz_i = \sum_{1}^{ComInst_j\ within\ dist.\ r} \frac{1}{e^{\beta * dist.\ d_{ij}\ to\ ComInst}}$$

$dist. = Distance$ $\quad$ $\beta = distance\ decay\ parameter$

$ComInst = Commercial\ and\ institutional\ districts$ $\quad$ $emp = Employment$

Walking quality Q_w is calculated for a single traffic area zone (TAZ) as a function of two sub-quality indices which describe the accessibility to jobs $Q_{w\,work}$ as well as commercial and institutional areas $Q_{w\,ComInst}$ which are destinations for service and leisure (Förg, 2020). The work accessibility index is a function of the number of jobs *emp* surrounding traffic zone *i* and the respective distance *d* to those jobs. The index then sums up available traffic zones that are within the maximum defined walking distances *r* and discounts them by distance *dij*, which results in the distance between zone *j* and zone *i*. This acts as a weighting system for the index to weight jobs that are in closer traffic zones higher than ones further away. The index for points of commercial and institutional districts works similarly to the work index. All districts *j* within distance *r* from traffic zone *i* are summed up and discounted by the distance between *i* and *j.* In both sub-indices, the straight-line Euclidean distance is used and assumed that all roads and networks have pathways that are accessible to pedestrians.

The assumptions for the distance decay parameter *β* stays consistent with Förg's (2020) research on empirical findings by (Larsen et al., 2010; Yang & Diez-Roux, 2012), whose findings developed an understanding for peoples willingness to walk in the United States and Montreal, Canada.

Network Quality Index for Cycling

$$Q_c = Q_{c\,work} + Q_{c\,other} + Q_{c\,route}$$

$$Q_{c\,route}\ for\ taz_i = \sum_{1}^{bike\ route_j\ within\ dist.\ r} \frac{l_j * q_j}{e^{\beta * dist.\ d_{ij}\ to\ bike\ route}}$$

$dist. = Distance$ $\qquad$ $\beta = distance\ decay\ parameter$

$l_j = length\ of\ bike\ route_j$ $\qquad$ $q_j = quality\ of\ bike\ route_j$

The cycling network quality index is made up of three sub-indices, 2 of which $Q_{c\ work}$ and $Q_{c\ other}$, function identically to the employment and commercial accessibility previously explained in the walking index function (Förg, 2020). The key difference between the walkability and cycling indexes is in the maximum distance *r* of being 4km for walking and 10 km for cycling in addition to a smaller distance decay parameter *β*— which implies that individuals are willing to cycle further distances than walk. The distance decay parameters for cycling were derived from literature research by Förg (2020) who pulled an empirical research study by (Larsen et al., 2010).

The third sub-index $Q_{c\ route}$ measures the total length *l* of bike routes *j* within distance *r.* To account for variation between the types of bike routes and their respective quality *q* is multiplied by length within the maximum distance. Förg (2020) developed a quality score *q* for each bike path segment based on a preference study done in Metro Vancouver by (Winters & Teschke, 2010). The quality ranges from an off-street path, neighbourhood shared lane, major street painted bike lane, paved shoulder, and major street shared lane with a designated bike path. Likewise, to jobs and commercial districts for walking, bike path segments that are closer to zone *i* hold more weight to the index than segments further away.

Network Quality Index for Transit

$$Q_t = Q_{t\,regular} + Q_{t\,rapid}$$

$$Q_{t\,regular}\ for\ taz_i = \sum_{1}^{stops_j\ within\ dist.\ r} \frac{1}{e^{\beta * dist.\ d_{ij}\ to\ stop}} * fr_{tl} * line\ access_{tl}$$

$$Q_{t\,rapid}\ for\ taz_i = \sum_{1}^{stops_j\ within\ dist.\ r} \frac{e^{(a - b * dist.\ d_{ij}\ to\ stop)}}{1 + e^{(a - b * dist.\ d_{ij}\ to\ stop)}} * fr_{tl} * line\ access_{tl}$$

$$line\ access_{tl} = acces\ to\ work + access\ to\ commercial\ districts$$

$$access\ to\ work_{regular} = \sum_{1}^{stopsj\ in\ a\ line_{tl}} \left(\sum_{1}^{taz_y\ within\ rad.\ p} \frac{1}{e^{\beta * dist.\ d_{jy}\ to\ emp}} * emp\right)$$

$$access\ to\ work_{rapid} = \sum_{1}^{stopsj\ in\ a\ line_{tl}} \left(\sum_{1}^{taz_y\ within\ rad.\ p} \frac{e^{(a - b * dist.\ d_{jy}\ to\ emp)}}{1 + e^{(a - b * dist.\ d_{jy}\ to\ emp)}} * emp\right)$$

$dist. = Distance$ $\beta = Distance\ decay\ parameter$ $fr_{tl} = Frequency\ by\ transit\ line\ tl$

$rad. = Radius$ $emp = Employment$

The network quality index for transit is made up of three components: how accessible regular and rapid transit stops are from dwellings; the amount of jobs and commercial districts that can be accessed through each transit line; and how trips on the transit line per day (Förg, 2020). The index results only include walking to and from transit stops and do not include mixed-mode travel (transit travel with driving, biking, or walking to transit stop). The index differentiates rapidly as rapid bus lines, sky train/rail lines, and regular as standard transit with less frequent schedule times.

Regular transit $Q_{t\ regular}$ distance decay function uses the same form as the negative exponential function used for walking and cycling. Förg (2020) based the β parameter on a study conducted by (Zhao et al., 2003) that estimated people's willingness to walk to transit stops. Rapid transit $Q_{t\ rapid}$ distance decay function uses a negative logistic function in the form of form exp(a – b*d)/(1+exp(a – b*d)), where *d is* distance, *a* is the intercept and *b* is the slope. The function form was based on Kimpel et al. (2007), who estimated the values of each parameter through a willingness to walk to rapid transit stops. The resulting assumption is that people’s willingness to walk to rapid transit stops declines less rapidly than regular stops. More specifically, walking to a regular transit stop dropped to 50% at 200 meters and 650 meters for rapid transit—however, the maximum distance r for walking to either stop is roughly 1 km.

Similarly, the walking and cycling index, $Q_{t\ regular,}$ and $Q_{t\ rapid}$ describe how accessible transit stops are from individual dwellings by counting the number of stop j in buffer distance r around traffic zone i, which is then discounted by the distance decay function. The formula treats all transit stops as independent in respect to the specific line that they serve. This uses transit stops at the same location to differentiate between the variation in accessibility and frequency that one location can offer. The index accounts for transit stop level of frequency fr_{tl} (total trips per day). This supports the notion that transit network quality is influenced by people's perceptions of wait times and travel flexibility (Cirillo et al., 2011; Eboli et al., 2012; Kittelson & Associates et al., 2003). Frequency is also coupled with the accessibility measure $line\ access_{tl}$, which is similar to those used for calculating the jobs and commercial district access for walking and cycling. However, the line access indices are calculated by transit line, not by traffic zone. Each stop j along transit line $tl,$ will account for all jobs and commercial district within radius p around the stop and discount by distance d. Line access incorporates both jobs and commercial district accessibility of rapid $access\ to\ work_{rapid}$ and $access\ to\ work_{regular}$ to account for the variation in transit quality. This is reflected as changes in dwellings' proximity to jobs, commercial areas and other destinations are guided by city planning efforts.

Network Quality Index for Driving

$$Q_d = \frac{road\ network\ index}{(0.01 + traffic\ level\ index)}$$

$$traffic\ level\ index\ for\ taz_i = \sum_{1}^{taz_j\ within\ dist.\ b} \frac{(emp_j + drive\ share_j * pop_j)}{taz_j\ area}$$

$$road\ network\ index = average\ road\ quality\ index + road\ length\ index$$

$$road\ length\ index = \sum_{1}^{road\ seg.\ within\ dist.\ b} road\ segment\ length$$

$$average\ road\ quality\ index = \frac{\sum_{1}^{road\ seg.\ within\ dist.\ b} road\ type\ quality\ measure}{number\ of\ road\ segments\ within\ b}$$

$dist. = Distance$ $\beta = Distance\ decay\ parameter$

$seg = Segments$ $emp = Employment$ $pop = Population$

$$taz\ value = \sum_{1}^{DAs\ intersecting\ with\ a\ taz} DA\ value * \frac{DA\ \&\ taz\ intersection\ area}{DA\ area}$$

The driving network quality index is designed to reflect road capacity, travelling speed, and traffic levels rather than the walking, cycling, and transit indexes which are focused on accessibility to jobs or commercial districts. Distance plays a negligible role in people's willingness to drive—considering there is virtually no physical effort, constant shelter from weather changes, and the ability to travel at much higher speeds. To reflect these nuances of driving, the function consists of an estimation of traffic levels as well as a road network index (Förg, 2020). The *traffic level index* operates as a function to assess the level of traffic in a particular zone. Through summing the number of jobs with a buffer area *b* (2km) around traffic zone *i,* in addition to the population in each zone and drive to work (*population * drive share*). The result is then divided by the total area of the zone to provide a measure of density. This estimation lends to a better accounting of the traffic levels in each zone, rather than relying solely on population density in each zone.

Drive share per traffic zone is derived from 2016 Census data, which is provided at the dissemination area (DA) – highest geographical resolution provided. The DA level data is then transformed into traffic zones (TAZ) with the *taz value* equation. Drive share in this case is assumed to be held constant over time, while this assumption is simplified it does not result in significant changes in GHG emissions (Budd, 2019). Previous research by Budd (2019) tested a driving congestion feedback loop that adjusted the intangible costs to a higher and lower level of traffic. This study was conducted in the City of Vancouver and showed that emissions were nearly 2% higher with the incorporated feedbacks in addition to policies that encouraged mode shifting away from personal vehicle use. Incorporating this process into the analysis is extremely time intensive. Despite the geographic scale, there may be a small bias towards overestimating the amount of GHG reductions associated with driving network qualities, therefore it was not included.

The *road network index* is a function of the *average road quality index* and the *road length index*. The quality index provides an average for all road quality scores within the 2km buffer *b*. Qualities are assigned by the type of road in respect to the maximum speed, width, and the average number of lanes. Scores range from highest to lowest (highest being most suitable for driving and lowest being least suitable): highway, arterial, collector, and local road. The road length index sums all roads within the 2km buffer and weighs the roads by their lengths to give an estimation as to the availability of roads in the area—fewer roads, more traffic to cluster on roads. Both of these sub-indices functions creating the road network index are normalized between 0 and 1 in addition to the traffic level index. The logic formulated through the aggregation of these indexes is to assign higher drivability due to situations where there are higher travelling speeds, fewer drivers, multiple lanes, and more roads to choose from.

All Cities and Metros by Fuel Shares

dumbGrowthinsincereSen	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Natural Gas	25%	24%	28%	29%	30%	30%	30%	29%
Refined Petroleum Products	54%	51%	44%	37%	35%	33%	31%	30%
Electricity	19%	20%	22%	23%	24%	25%	27%	28%
Ethanol	1%	3%	4%	7%	7%	8%	9%	10%
Biodiesel	1%	2%	2%	4%	3%	3%	3%	3%
Biogas	0%	0%	0%	0%	0%	0%	0%	0%

dumbGrowthsincereSen	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Natural Gas	25%	25%	26%	22%	17%	13%	6%	2%
Refined Petroleum Products	54%	51%	41%	28%	20%	16%	14%	13%
Electricity	19%	20%	24%	31%	38%	48%	61%	71%
Ethanol	1%	3%	4%	10%	15%	14%	10%	6%
Biodiesel	1%	2%	3%	6%	7%	7%	7%	7%
Biogas	0%	0%	2%	3%	3%	2%	1%	0%

smartGrowthinsincereSen	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Natural Gas	25%	25%	29%	31%	32%	32%	31%	30%
Refined Petroleum Products	54%	50%	42%	34%	31%	26%	23%	22%
Electricity	19%	21%	24%	26%	28%	34%	37%	39%
Ethanol	1%	2%	3%	5%	6%	6%	7%	7%
Biodiesel	1%	2%	2%	4%	3%	3%	3%	3%
Biogas	0%	0%	0%	0%	0%	0%	0%	0%

smartGrowthsincereSen	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Natural Gas	25%	25%	27%	23%	18%	14%	6%	2%
Refined Petroleum Products	54%	50%	39%	25%	18%	14%	12%	11%
Electricity	19%	21%	26%	34%	41%	53%	67%	76%
Ethanol	1%	2%	4%	8%	12%	11%	8%	5%
Biodiesel	1%	2%	3%	6%	7%	6%	5%	5%
Biogas	0%	0%	2%	3%	3%	2%	1%	0%