Urban sprawl in Canada: measurement, history, and implications of road network structure

Chris Barrington-Leigh[a,*] and Adam Millard-Ball[b]
[a]McGill University [b]UC Santa Cruz

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1 Introduction

This work is motivated by the idea that decisions about the placement of roadways may be among the most important environment- and climate-relevant investments humans are making.

The importance of urban policy decisions, is underlined by the scale of ongoing urbanization, worldwide. For instance, between 2010 and 2025, China is expected to build the equivalent of an entire United States of new city roads, homes, and infrastructure. Globally, with an urban population rising ~65% to about 6.4 billion by mid-century, we are building more "city" at the rate of more than one million people-spaces per week, every week between now and 2050 (United Nations, 2014). In Canada, where urbanization is nearly complete, urban and suburban growth continue at a high pace in response to growing population.

There are, naturally, numerous ways in which civic policy plays an important role in addressing global economic issues like climate change, in addition to the more obvious local ones. While cities continue to evolve after they are built, one thing that tends not to change is the layout of streets, especially in residential areas. In this report, we (i) explain how, through their permanence, street networks might be central to determining future efficiency, consumption patterns, and greenhouse gas emissions, (ii) explain why they may embody a path-dependent "lock-in" effect for urban form, thus further enhancing their importance, (iii) outline a research project to map urban form globally and, in the U.S., its evolution over time, and (iv) present a new analysis of the Canadian road network, covering all urban regions.

We find that our key measures of urban sprawl which relates closely to the archetype of North American suburbia and, more recently, negative health and environmental outcomes, has been on the decline in Canada for at least two decades. We find only mixed support for our long-term hypotheses concerning the densification and value changes of different urban forms.

2 Road networks and urban form

The physical layout of urban areas has a direct impact on vehicle travel, energy use and greenhouse gas emissions. Less sprawling areas — those characterized by higher densities, mixed land uses and a connected street network — tend to have lower energy use, climate and other environmental impacts. Indeed, urban economists, historically sympathetic to sprawl as a desirable market outcome, have begun to focus more on its negative externalities (Glaeser, 2011). To the extent that carbon and other taxes on private vehicle travel are set inefficiently low, the private market is likely to produce too much sprawl.[1]

Low fuel prices have long been seen as a major cause of sprawl. This is not to deny the validity of other explanations, such as tax regimes (Song and Zenou,

[1] Other sprawl-related externalities such as a reduction in social capital may exist as well, but are more contentious in the literature. See, for example, Brueckner and Largey (2008).

2009) and land-use regulations (Levine, 2005), but there is a weight of theoretical and empirical evidence that indicates the cheaper it is to drive, the more a metropolitan region will sprawl. The impact of fuel prices on development patterns is a direct implication of many analytic models where households trade off commuting costs against living space. Cheap travel encourages households to incur longer commutes in favor of a larger house and yard, perhaps in proximity to the urban fringe (Brueckner et al., 2001; Bento et al., 2006). Numerous empirical studies, meanwhile, have demonstrated a strong relationship between fuel costs and urban sprawl (Glaeser and Kahn, 2004; Tanguay and Gingras, 2012; Molloy and Shan, 2013), and also between fuel costs and the demand for suburban homes (Sexton et al., 2012).

However, urban structure changes very slowly once a network of roads is laid down. Thus, there will be a long lag between any increase in prices — for example following a carbon tax — and reduced vehicle travel, and inefficient sprawl may get locked in. Moreover, the existing level of sprawl is likely to affect how new development responds to a fuel price shock. In other words, sprawl may beget sprawl, in a path-dependent, self-reinforcing process.

The existence of such path dependencies is intuitive: lower-density, car-oriented development generates greater returns for developers if that matches the prevailing pattern of development. Even if fuel prices rise, it makes less sense to build a walkable neighbourhood if there is nowhere to walk to. Strong path-dependence would imply a more urgent policy impetus for a carbon tax or increased fuel tax. Alternatively, since even significant increases in fuel prices in the medium term may not overcome the frozen-in effect of existing urban form on adjacent new developments, carbon pricing may be insufficient to account for the externalities of current construction. If sprawl today leads to more sprawl tomorrow, then delay in enacting broad climate change or specific anti-sprawl policies makes it more difficult or costly to take action later. Analogous implications for optimal policy have already been found for technological innovation in the context of energy efficiency (Aghion et al., 2012).

2.1 Persistence

Given the importance of urban form in determining current efficiency and future development patterns, what is the right measure of urban form to capture the key element in this variation, and how can it be estimated across an entire country?

We consider the layout of the road network to be the key feature which affects future urban form and development choices. While other private and public investments may have depreciation time scales on the order of decades, the locations of roads typically persist for hundreds of years. This is much longer, for instance, than the time scale characterizing the use or even the structure of buildings located along those roads. One reason for this is that while individuals, firms, and coordinated groups have ownership over land parcels and buildings, and can therefore modify, rebuild, and subdivide their property, a given road segment tends to touch on numerous property owners. Therefore a much larger coordination problem is faced by any initiative to reroute roads from their original paths. The immutability of road networks once they are laid down is in evidence following major disasters. For instance, following the devastation of the 1906 fire in San Francisco, a striking reproduction occurred of otherwise-arbitrary road networks and discontinuities in road structure.

The persistence of roads means that future changes in other aspects of urban infrastructure cannot escape the network connectivity constraints of the original road layout. In Section 3 we provide a description of why low network connectivity of roads is likely to prevent the formation of local services, efficient use of capital, and high-density residential arrangements. We also elucidate how low-connectivity urban sprawl may be likely to self-propagate, creating a path-dependent lock-in, as mentioned above.

For the present study of Canadian urban areas, the key implication of road network persistence is that regardless of their initial density or zoning, urban sprawl neighbourhoods characterized by cul-de-sacs and low road connectivity are unlikely to "densify." According to the arguments in Section 3, urban sprawl neighbourhoods may be "density-proof" in that the non-automobile accessibility needed for provision of collective (private and public) services is forever hampered, thus limiting the benefit obtainable from changing the kind or size of dwelling, or the mix of services, in the neighbourhood. This means that areas of urban sprawl are predicted to remain relatively low density even as nearby land values rise, automobile costs rise, and, for instance, carbon prices become significant. Accordingly, land values in areas settled with low-connectivity roads are predicted to underperform those with more gridded road accessibility when price signals begin to favour high energy and material efficiency in domestic/urban production. The high productivity of dense urban areas comes in part from the efficient use of shared capital and a transition from home production/consumption to market (labour) production and consumption (ie, in addition to efficiencies due to business proximity, for instance; see Murphy, 2012). This is possible only in dense living arrangements, which are permanently hampered where people cannot efficiently travel locally without cars.

While we are not, using our Canadian data, able to test our predictions about path-dependence, in which new development follows the pattern of preexisting nearby communities, we are able to assess the densification and land appreciation predictions, below.

We next motivate and describe the specific measures of road network connectivity, by which we characterize urban sprawl, and which we are able to calculate directly for the entire Canadian road system.

2.2 Conceptualizing Sprawl

Urban sprawl is itself somewhat of a sprawling concept. It encompasses a range of phenomena that operate at a range of spatial scales, from the metropolitan region to the urban design of individual developments. Galster et al. (2001) identify eight distinct dimensions of land-use patterns that characterize sprawl, including density, centrality (the distance of development from the Central Business District or CBD) and nuclearity (whether a metropolitan area has a dominant urban center or is polynuclear in character).

In addition, concepts of sprawl are somewhat discipline-dependent, reflecting different policy interests and methodological traditions across disciplines. For architects such as Duany and Plater-Zyberk (Duany et al., 2001), sprawl is inherently about the rigid segregation of land uses, and urban design features such as the placement of parking in the front setback of homes. Economists, in contrast, have tended to focus on density, the scatteredness of urban development, and the size and spatial extent of metropolitan areas. In large part, this reflects the intellectual history of urban economics. In particular, the Alonso-Muth-Mills model, which posits a monocentric city where all employment is in the CBD and households choose their distance from the CBD by trading off housing and commuting costs, still has great influence (see, for example, Glaeser and Kahn, 2004; Burchfield et al., 2006; Tanguay and Gingras, 2012).

In this paper, we instead conceptualize and measure sprawl as a property of the street network. First, we construct measures of the degree[2] of intersections, and of the proportions of dead-ends and intersections with four or more edges. Second, we measure intersection density. Both of these measures are frequently used in the urban planning and transportation literatures, and are strongly associated with the amount of vehicle travel and mode split (Ewing et al., 2003; Ewing and Cervero, 2010; Guo, 2009). In Ewing and Cervero's (2010) meta-analysis, the impact of these street network measures on total vehicle distance travelled is three times that of population density.

Sprawl is characterized by a high proportion of dead ends and a low intersection density, which favor travel by the private car in several ways. Dead-end streets and low intersection densities typically increase the ratio of network distance to Euclidean distance, which reduces the generalized cost of driving relative to walking. Such street patterns typically involve wider arterials, and longer distances between signalized intersections – again favoring the private car. In contrast, a dense, gridded street network tends to be more attractive to pedestrians, allows more efficient service by public transit, and reduces travel speeds by the private car through requiring frequent stops.

Our measures of sprawl offer several important conceptual and empirical advantages over more traditional economic measures such as density, spatial extent and centrality. First, the structure of the street network is relatively fixed, and reflects decisions by cities and landowners at the time of initial development. Street rights of way are rarely vacated, and so four-way intersections usually remain that way. Opposition by homeowners fearing increased traffic, not to mention the costs of demolishing existing buildings, mean that dead-end streets also usually remain dead ends. In contrast to characteristics such as density, which can change over time, the street network indicates the degree of sprawl at the time it was laid down.

Second, our measures of sprawl offer extremely high spatial and temporal

[2]In graph theory, the degree of a node is the number of edges (in this case street segments) connected to the node.

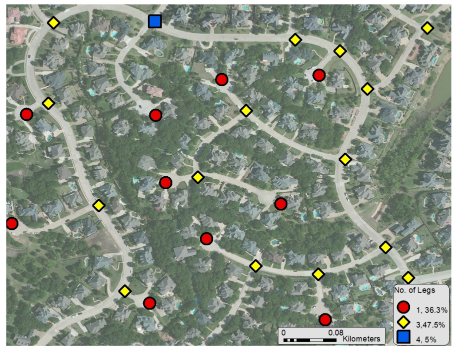

Figure 2.1: Assignment of nodal degree. Intersections are marked according to their degree of 1 (dead-ends), 3, or 4.

resolution. Our underlying units of analysis are street segments (edges) and intersections. This provides us with the ability to conduct analysis at any spatial scale, rather than being constrained by the aggregation units for census data or the resolution offered by remote sensing technologies. Our measures of sprawl vary within a city, in contrast to measures such as nuclearity and spatial extent which are a characteristic of an entire metropolian area.

Third, our measures relate directly to the most important externalities of sprawl — emissions, public health and other impacts from private vehicle use. As noted above, there is a direct theoretical link and strong empirical relationship between the structure of the street network and private vehicle use. In contrast, there is a tenuous externality from sprawl when measured by the amount of open space in the square kilometer surrounding a house(Burchfield et al., 2006); the size or spatial extent of metropolitan areas (Brueckner and Fansler, 1983; Brueckner et al., 2001; Su and DeSalvo, 2008; Song and Zenou, 2009); or the extent to which employment is located within a five-mile radius of the central business district (CBD) (Glaeser and Kahn, 2004). Even the commonly used measure of density has a less direct relationship to the external costs of sprawl than the structure of the street network; density often proxies for other characteristics of the built environment that affect vehicle travel (Ewing and Cervero, 2010).

figure 2.1 shows an example of a neighbourhood with the degree of each intersection labeled.

3 Path dependence: theoretical Model

The discussion below, taken from Barrington-Leigh and Millard-Ball (2014a), gives an account of how higher urban density is related to higher efficiency in both material and energy use and to an increased dependence on market production and consumption rather than home production. It also elucidates the relationship of the transport mode choice between private cars and alternative transport to the connectivity of the road network and possibility of dense settlements: walking, cycling, and shared transit are compatible with higher densities and require high connectivity of roads.

Our understanding of the externalities surrounding both fossil fuel burning and traffic congestion costs on limited roadways are conventional. However, our aim is to elucidate a new interaction which can exacerbate or alleviate these problems through a feedback from existing urban form to decisions about new developments. This spatio-temporal externality comes about through the interaction of the residential market and the markets for commercial services.

This section, offers two accounts of these spatio-temporal spillovers. The first is an outline of the salient interactions as we conceive of them, but it comes without a mathematical description due to its complexity. In 3.2 we formalize a highly simplified version of this theory which exemplifies the locking-in effect of existing urban form and its relationship to current fuel prices. Properties of this model motivate our reduced form empirical specification in the later sections of the paper.

3.1 Qualitative account

We conceive of a model in which developers are responsible, directly or indirectly, for building the roads which service a new development. Developers therefore choose the degree to which new road networks embrace a gridded smart-growth or (suburban) cul-de-sac form. This choice of developers, reflecting that of eventual residents, is driven by the availability and accessibility of nearby services, and by the cost of transport. A key, semi-permanent feature of urban form which determines future incentives towards one or other of these extremes is the interconnectedness of the road network. When existing, nearby urban form is of the connected variety, characterized by a dense grid, new developments can benefit from the ease of car-free access to nearby destinations, making the creation of a compatible, gridded road network advantageous. By contrast, when access to existing services is already difficult without a car, new roads are more likely to be laid down favoring a car-oriented lifestyle — typified by a high proportion of culs-de-sac.

Underlying this relationship is a deeper tradeoff between home production on one hand and market or public good consumption on the other, as described by Murphy (2012). In our extension of this idea to include the dynamics of transportation mode choice, residents' choices over time use are broader: they choose between market labour, home production-consumption, market consumption accessed by car, and market consumption accessed by foot (which can be taken to include bicycle and public transit). Leisure activities are encompassed by the three consumption options. To give examples of the kinds of substitutions and complementarities implicit in these choices, consider two paradigms which characterize a low-density, car-oriented lifestyle versus a high-density, walkable living and working arrangement.

Household choices

Family A earns some income through market employment (which involves a car commute), but has also invested in a house large enough to supply certain services at home. Investments for home production and consumption include such things as a large kitchen and dining room useful for hosting guests, some fitness equipment in the basement, a pool in the backyard, a lawn, and complete laundry facilities. Some time is spent maintaining these investments (cleaning the pool) and using them enjoyably (swimming) and productively (doing laundry). A large pantry and refrigerator also facilitate storage of food, allowing for relatively infrequent, large shopping trips carried out by car. The availability of home production services diminishes the need for nearby commercial and public (e.g., swimming pool) services. Families place some value on living on a quiet, out of the way street, and Family A resides on a cul-de-sac in a sprawling residential suburb. Because there is nothing nearby, having to navigate by car out of the cul-de-sac development does not add much extra time to the typical trip, and the family does not suffer what would be a long walk to the nearest well-connected road.

Family B, on the other hand, allocates a little more of its time to wage-earning activities on the market and a little less to home production. This extra market income pays for the family's intensive use of nearby commercial services such as small grocery shops, restaurants for eating out with friends, laundry and drycleaning services, and a fitness club. Family B lives in a smaller home or condominium and is able to access these commercial services and other public goods easily by walking, cycling, and public transit through the highly connected (gridded) local street structure. Their smaller house requires more frequent but shorter local trips to replenish supplies and access services, and their home location offers less of the quiet, secluded characteristic of cul-de-sac communities.

Supply of services

In our conception, both of these patterns form part of self-consistent equilibria. Reinforcing the domestic situations described above are the commercial service provision markets as well as the public good service provisioning system. In a development characterized by low-connectivity roads such as a network of cul-de-sacs, small service providers would be unprofitable because very few consumers are able to access them cheaply enough, ie with a short trip. In addition, there will be little demand for certain kinds of services that are supplied through home production, outside of the market. Instead, in order to accomodate and reach a critical level of demand, services required by these residents are likely to be offered in large shops, clustered in highway oriented retail areas, and accessed solely by car.

By contrast, in highly gridded street networks many potential consumers can easily reach a given point, even if they are distributed no more densely than those living on low-connectivity streets. As a result, a larger number as well as a wider variety of shops is likely to arise throughout a gridded development. This makes it possible for local residents to avoid owning either a car or the extra home features which substitute for the outside services.

In summary, more intensive use of the market represents more shared use of resources, while the higher home-production equilibrium represents more replication of capital investments and therefore lower intensity of their use. That is, in the case of the gridded road network, more services are supplied and used collectively nearby but outside the home, which is smaller as a result. In the case of the car-oriented road network, by contrast, more needs are met by non-market, home production. Commercial services are more restricted both in scope and in geographical frequency, and homes and private spaces are larger as a result.

Although there may be some economies of scale in large (highway-oriented) retail facilities, there can also be an inefficiency involved in the duplication of domestic resources when they are underused. Even putting aside the problem of traffic congestion, it seems likely that if petrol prices are high enough or environmental effects of burning petrol are high enough, the sprawling equilibrium will be less economically efficient overall.

How does such an inefficiency come about? It represents a collective action problem wherein individual households are motivated in part by the private benefit of being hard to reach on a cul-de-sac, but they do not bear the costs imposed on others by the lack of connectivity in the road network (in addition to the conventional externalities of traffic congestion and emissions).

Spillovers to future development

In addition to the static externalities which may make the sprawling equilibrium inefficient, our focus is on intertemporal spillovers which occur when new developers make decisions in sequence about new roads to build. Because service suppliers are sensitive to the connectivity (and walkability) of roads throughout the entire potential demand catchment of any given shop, the influence of the road network extends beyond that of the subdevelopment in which a service chooses to locate. This means not only that the provision of services will adjust when a new neighbouring development is built, but also that prospective residents of a new development will form expectations over their future transportation mode choices based in part on the existing availability of nearby services and the existing connectivity of nearby streets. These expectations, in turn, will generate their preferences over the kind of street network that is optimal for their new development. If the street network adjacent and nearby to a new development site is all cul-de-sac sprawl, for instance, then not only are there likely to be few nearby services already accessible by walking or public transit when the new homes are built, but such services are never likely to arise in the future in the midst of the existing cul-de-sac neighborhoods.

In our description of the dynamics of sprawl, therefore, local one-off decisions have intertemporal and spatial externalities which may multiply over time, with long term implications for the lifestyle and environmental impacts of future residents.

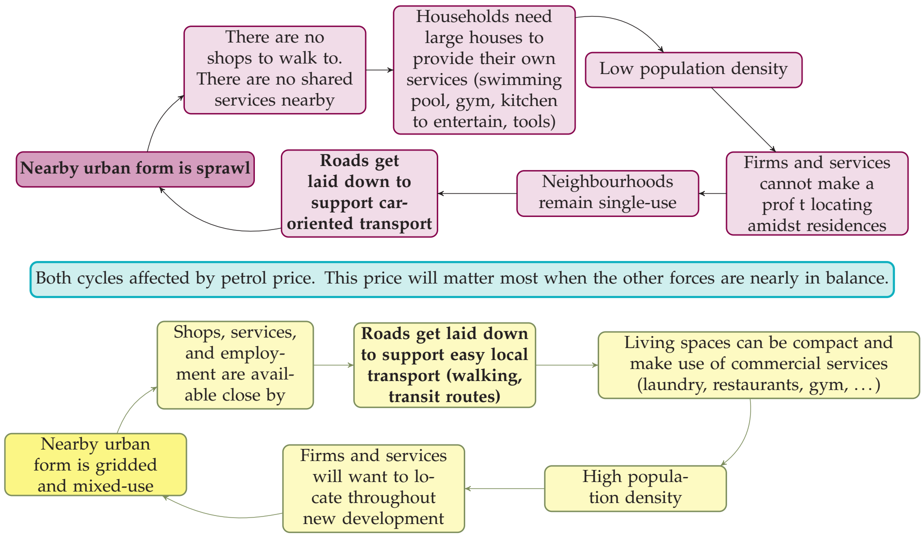

Figure 3.1: Self-reinforcing urban form, and the private/shared capital tradeoff

Transport prices and the "freezing-in" of development patterns

At the same time, home buyers and hence developers can be expected to take into account current transport energy prices in choosing their neighbourhood (Molloy and Shan, 2013; Sexton et al., 2012). Thus, in times of low petrol prices, demand for new developments will tilt towards a cul-de-sac, secluded, large-home style because the cost of making most commute, shopping, and social trips by car is low, and may even be low enough to overcome the influence of nearby gridded developments which have a variety of easily-accessible services. Conversely, a period of high fuel price would tend to encourage gridded, denser development, all else equal.

We expect these two influences — the spatial spillovers and the current fuel price — to interact most strongly where and when the tradeoffs between car-oriented and dense/walkable forms are nearly balanced. When fuel price levels are high or low enough, they result in a "freezing-in" of their signature low or high connectivity road networks. During times of intermediate fuel prices, existing road networks will have a dominating effect on decisions about new roads, and the urban form will self-propagate. Figure 3.1 summarizes the two self-reinforcing cycles for sprawl and gridded road networks.

3.2 Simplified case

The story laid out in section §3 implies a model involving a spatial equilibrium for service provision. Providers choose their participation and locations based on distributed spatial features. Households choose their transport mode, time use, investments, and street network type, also based on distributed spatial features. Parameterizing all these decisions becomes involved.Instead, in order to formalize the simplest quantitative model that captures the spatio-temporal externality due to well-networked or poorly-networked urban form, we consider a one-dimensional world. In addition, we focus for the moment solely on the household, or developer, problem, abstracting from production and the commercial provision of services. The features of interest in this system are the effect of existing urban form and prevailing fuel prices on choices about new urban form. For the sake of clarity and in order to address our empirical description, we consider a dichotomous choice over urban form: to build a new residence or development either on a cul-de-sac or on a gridded street.

To illustrate the dynamics of successive choices, consider a "linear city" consisting of discrete, contiguous locations (cells) which may be developed. Newcomers select an empty cell adjacent to one or two developed cells. Taking into account the need to shop and work nearby, developers select either a cul-de-sac or a gridded road system with which to integrate with the adjacent road network. This decision is based on new residents' expectations to walk or to drive for their commuting and shopping needs.

Fundamentally, cul-de-sac sprawl favours transport by car, while gridded street networks are more conducive to walking (or cycling or collective transport). We parameterize the payoffs in this decision as follows. Due to its low connectivity, there is a cost σ to departing from a cul-de-sac location by foot, and the same cost for arriving at one. By contrast, there is cost π for parking in a gridded road area. This reflects the relative lack of driveways and parking spaces and, moreover, the existence of one-way streets and traffic calming measures, in locations designed for pedestrians.[3] Trips by car incur a fuel cost ϕ, while none is assumed for the other mode(s).

Beyond the differences in amenities and land price typical for homes in suburban sprawl, there is a direct benefit to creating a non-connected roadway. We call this attractive quality "quiet" to represent the seclusion and safety which buyers may believe comes with cul-de-sac life. The value of this benefit is χ.

Services and employment are uniformly distributed throughout developed areas. In order to meet their needs, residents expect to travel equally to the one or two immediately adjacent cells. Therefore, when building on a new cell, developers consider the expected costs of travel, taking into account that they will have the option for each trip to travel by car or by foot.[4] Based on these costs, the developer's optimization problem is to choose to lay down a cul-de-sac (S) or a gridded street (G), in order to minimize the cost of the cheapest way to access each neighbouring developed cell, and taking into account the direct benefit χ.

According to this description, expected costs of travel are as shown in table 1. The second and third rows are identical, as costs are symmetric between origin and destination types. It can be seen immediately that for positive parameter

[3]In a more spatially realistic model, it would also reflect the higher density that is typical of gridded street network locations, but this feature ought to arise endogenously.

[4]Beyond the irrevocable choice about the road network, there is no investment in cars or other infrastructure, so there is no direct lock-in to a given mode choice.

Destination	Origin (new development)	Cost of walking	Cost of driving
sprawl	sprawl	2σ	ϕ
sprawl	grid	σ	$\pi + \phi$
grid	sprawl	σ	$\pi + \phi$
grid	grid	0	$2\pi + \phi$

Table 1: Costs of travel in one-dimensional cell model.

values, walking is always optimal when travelling from G to G. In the case of heterogeneous urban form types (S $\rightleftarrows$ G and G $\rightleftarrows$ S), one or the other transport mode will be preferrd depending on the sign of $\pi + \phi - \sigma$.

Empty cells may have either one or two developed neighbours, each of which could be a cul-de-sac or a gridded street; there are thus five possible environments for a new development. Since our primary interest is in the path-dependence of urban form in a growing city, and since spillovers are strictly local, the critical features of the system are determined by what happens to cells at the edge of a developed region — that is, to developing cells with only one developed neighbour. These represent the edge of expanding development. If extant cul-de-sacs lead to new cul-de-sacs, and extant gridded roads lead to more of the same, then the system has strong path-dependence. We therefore examine the requirements for developers adjacent to S to build S and those near G to build G, and denote these decisions as S $\Rightarrow S$ and G $\Rightarrow G$.

It is useful to consider three ranges for the value of the fuel price ϕ: we will call these contiguous price ranges $\Phi_1 \equiv (0, \sigma - \pi)$, $\Phi_2 \equiv (\sigma - \pi, 2\sigma)$, and $\Phi_3 \equiv (2\sigma, \infty)$.[5] They are illustrated in figure 3.2. Below, we describe the decisions in each range of ϕ, before considering a special case.

3.2.1 Low fuel price Φ_1 ($\phi < \sigma - \pi$)

When $\phi < \sigma - \pi$, the optimal modes of transport become as follows:

To$\rightleftarrows$From	Cost of walking	Cost of driving
S$\rightleftarrows$S		ϕ
S$\rightleftarrows$G		$\pi + \phi$
G$\rightleftarrows$S		$\pi + \phi$
G$\rightleftarrows$G	0	

Note that the value of σ does not affect urban form choices in this range. Developers will always choose to build new sprawl S next to existing S because transport costs are less ($\phi < \pi + \phi$), even before the added benefit χ of sprawl is counted.

Next to existing G, new sprawl S will also be built whenever the benefit outweighs the difference in costs, ie when $\chi - \pi - \phi > 0$, and new gridded road will be built otherwise. This condition amounts again to a constraint on fuel costs being low: $\phi < \chi - \pi$ in order for G$\Rightarrow$S.

[5] We consider only inequalities, ignoring knife-edge values of parameters.

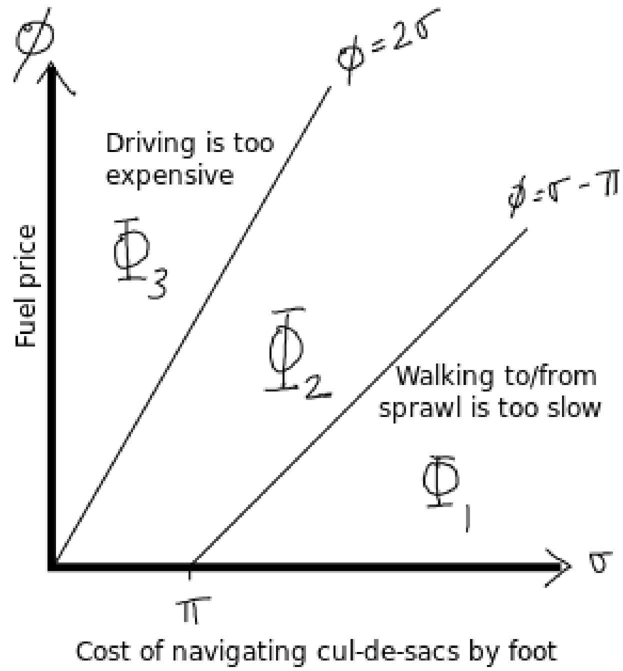

Figure 3.2: Fuel price regions

3.2.2 Middle fuel price Φ_2 ($\sigma - \pi < \phi < 2\sigma$)

In this price range, minimum transport costs are as follows:

To⇄From	Cost of walking	Cost of driving
S⇄S		ϕ
S⇄G	σ	
G⇄S	σ	
G⇄G	0	

All three urban form patterns are possible in this case, depending on parameter values: tendency to G, tendency to S, or path-dependence. Figure 3.3 shows the relevant ranges. For high enough values of "quiet" ($\chi > \sigma$), sprawl prevails regardless of the adjacent urban form. For low χ and low σ (in particular, $\chi < \phi - \sigma$) the opposite holds, and G dominates. For other values, $\phi - \sigma < \chi < \sigma$, new development exhibits perfect path dependence.

3.2.3 High fuel price Φ_3 ($\phi > 2\sigma$)

In the case of high fuel price, the value of π plays no role since walking is always preferred, as shown in the minimum transport costs below:

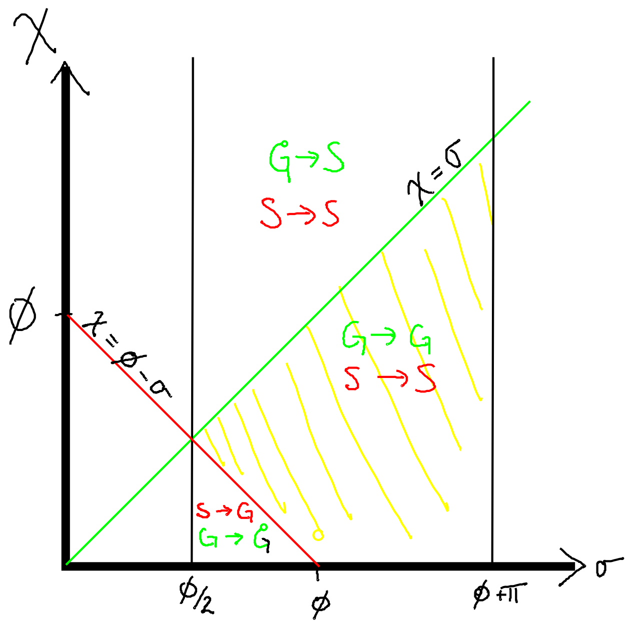

Figure 3.3: Sketch of three possibilities for mid-range fuel price.

To⇄From	Cost of walking	Cost of driving
S⇄S	2σ	
S⇄G	σ	
G⇄S	σ	
G⇄G	0	

In both cases of preexisting G or S, the difference in resulting transport costs between building S and building G is σ. Therefore, even though residents will always choose to walk, S will be built if $\chi > \sigma$ and G will be built if $\chi < \sigma$, regardless of preexisting urban form.

Proposition. *When fuel price is sufficiently high or sufficiently low, the urban form of new development bordering a single developed site is independent of the existing urban form. For intermediate fuel prices, new development may instead always match the existing urban form. In particular, under the conditions that* $\chi < \sigma$ *and* $\pi < \sigma$*:*

- development tends towards sprawl for fuel prices $\phi < \chi - \pi$,
- development is entirely path-dependent for intermediate fuel prices, $\chi - \pi < \phi < \chi + \sigma$,
- and development always tends towards gridded streets for high fuel prices, $\phi > \sigma + \chi$.

Proof. When $\pi < \sigma$, all three of the regions Φ_i are nonempty. From the analysis above of decisions in each range Φ_i, it suffices to point out that:

- The first price range in the proposition, $\phi < \chi - \pi$, is a subset of Φ_1 if $\chi < \sigma$. Therefore the description in Φ_1 holds, and in particular the special case of $\phi < \chi - \pi$, which is the case that S is always built.
- Under the condition $\chi < \sigma$, the second price range includes subsets of both Φ_1 and Φ_2. In Φ_1, $\chi - \pi < \phi$ ensures path dependence, while in Φ_2, the two inequalities $\phi < \chi + \sigma$ and $\chi < \sigma$ also ensure path dependence.
- The third price range, $\phi > \sigma + \chi$, is a superset of Φ_3 if $\chi < \sigma$. The portion in Φ_3 follows the special case of $\chi < \sigma$, which is the case that G is always built. The remaining portion, $\sigma + \chi < \phi < 2\sigma$, is a subset of Φ_2. In Φ_2, this condition $\sigma + \chi < \phi$ is sufficient for G to dominate.

□

These qualitative properties encompass our primary predictions. During a period with high or low fuel prices, new developments will tend to be built based on the prevailing fuel price and will not be influenced decisively by existing urban form. For intermediate fuel prices, however, the form of preexisting structure will determine what gets built; this constitutes path dependence. If these dynamics are in play, we would expect the following empirical features in aggregate data:

1. Past urban form predicts new developments' urban form, even after controlling for fuel price.
2. As a function of fuel price, this relationship is strongest for mid-range prices, and weaker for higher and lower ones.

As compared with our more conceptual model, described earlier, this model lacks a description of the supply decisions of service providers. It also does not account for a link between urban form and the density of population or services. However, we believe that these features may not be essential to capturing the key link between transport mode and urban form. 42% of trips (by all modes) made by households in the U.S. are for shopping, personal business and errands FHWA (2011, p. 20) . People also make mode choices for getting to schools and workplaces and for visiting friends and family. These destinations do not represent locations chosen to match residential demand in a market optimisation context.

4 Sprawl in Canada: a national panel database

The main contribution of this paper is the development of a Canada-wide database of urban sprawl, measured as properties of road intersections, along with a coarse panel time series of average nodal degree measured at the scale of census Dissemination Areas. Below we describe the method and in Section 5 we present analysis of the findings.

4.1 Empirical approach

We have built a Canada-wide dataset of road network connectivity based on the same conceptual approach we apply to the USA Barrington-Leigh and Millard-Ball (2014b) and to the rest of the world (work in progress). Below we explain the source of our spatial data on street connectivity and our method of generating a time series of urban sprawl from it.

4.1.1 Street connectivity calculations

We identify each paved road intersection (node) in Canada and compute its degree. These calculations are carried out as part of a project covering the rest of the world, starting from openstreetmap (osm.org) road data. Openstreetmap (OSM) is a crowd-edited global mapping database with good-quality data for Canada.[6] Statistics Canada, Natural Resources Canada, and Canada Post all have national road databases (Pat Adams, personal communication), but only the Statistics Canada one is publicly available, and the openstreetmap (OSM) data are likely to have had that one as their starting point. Our analysis showed no difference in quality for our purposes between the OSM and the Statistics Canada data.

We calculate our measures of street-network sprawl at the level of individual nodes and edges. Where two nodes are within 15 m of each other, we treat them as a single node for purposes of calculating nodal degree. This procedure accounts for offset intersections (i.e. "dog-legged" or adjacent T-intersections) that functionally are the same intersection, as well as allowing for misaligned streets and other potential imperfections in the OSM geometry. The 15 m distance is approximately the width of a typical two-lane urban street, including on-street parking and sidewalks. We ignore edges that are completely contained within an intersection (defined as a 7.5 m radius from each constituent node), so that short edges that connect within an offset intersection, expressway ramps and similar elements of the street network do not inflate nodal degree. Our calculations are carried out using an open-source, scalable, database-driven geographic computation system, PostGIS.

We identify 1.3M nodes in the Canadian road network, with half of these located in urban areas covered by Statistics Canada's Census Tracts. 2 shows the distribution of nodal degree overall and in urban areas. Three-way intersections account for more than half of all intersections. This reflects in part the suburbanization of Canadian cities. We next address the question of when these different styles of road networks were built.

[6] Conceptually, one may understand OSM as a blend of the innovations of Wikipedia and Google Maps.

	Overall	Urban areas
N	1329652	572862
Dead-ends	23.7%	16.9%
Degree 3	55.8%	58.9%
Degree 4+	20.5%	24.2%
Mean degree	2.73	2.90

Table 2: Network properties of road intersections in Canada.

4.1.2 Dating past construction

In analogous work for the U.S.A., we use three different approaches to assign dates to our intersection-level data. Only one is feasible for Canada, and none will be feasible for our effort to map urban form globally. In the U.S.A., tax assessor information on residential land parcels is often collected at the county level, and in some cases is freely or cheaply available to the public. These data sometimes contain dates of construction for any building(s) on the property, and it is these dates which Barrington-Leigh and Millard-Ball (2014b) use to constrain the date of developers' decisions regarding road layout at the scale of individual edges or nodes. In Canada, such data are much more closely guarded by local governments, and in some cases have actually been privatized to firms with no commercial interest in research or public disclosure.

A second method for dating urban developments which we use for the U.S.A. is also feasible in Canada. However, the spatial resolution comes from the aggregated census profile regions and is therefore limited to census Dissemination Areas (DAs) in Canada. In the present work, we assign each node to the DA in which it is located, and make use of the distribution of reported "year of construction" across dwellings in order to derive an approximate date for the development of the entire DA. Statistics Canada describes the DA as a small, relatively stable geographic unit composed of one or more neighbouring dissemination blocks, with a population of 400 to 700 persons. All of Canada is divided into dissemination areas. The boundaries of DAs are particularly stable within Census Tracts (CTs), although they tend to be split or revised when the population exceeds the target maximum. DAs only exist in the 2001, 2006, and 2011 censuses. The Census long form and, in 2011, the National Household Survey (NHS), include a question on the date of construction of respondents' dwellings. In 2006, this was worded as follows:

> When was this dwelling originally built? Mark the period in which the building was completed, not the time of any later remodelling, additions or conversions. If year is not known, give best estimate. ○ 1920 or before ○ 1921-1945 ○ 1946-1960 ○ 1961-1970 ○ 1971-1980 ○ 1981-1985 ○ 1986-1990 ○ 1991-1995 ○ 1996-2000 ○ 2001-2006

In data releases as "profiles" aggregated to the DA scale, the year built data "1960 or before" as the earliest category. Based on experience with U.S.A. data in which we can compare time series constructed from the high-resolution, parcel data method outlined above with the coarser census method used for Canada, we apply the following agorithm in order to develop a panel of urban form at the DA level:

1. Aggregate nodes into DAs defined for 2011, and calculate mean urban form metrics (nodal degree, fraction of deadends, and fraction of 4^+ nodes) for each DA. Also evaluate the land area of each DA, in order to estimate densities.

2. Using the distribution of years built for each DA, reported in the 2011 NHS:

    (a) Assign "1960" if more than half of responses are in the lowest category.

    (b) Otherwise, interpolate the median year built assuming a uniform distribution within each year category.

The resulting panel gives an indication of the kind (and location) of urban form which was being built as a function of time.

There are other approaches to categorizing nodes which may be fruitful in the future. Statistics Canada is revising its "Settlements Database" which is a high resolution geographic database, derived algorithmically from remote-sensing data, that describes land use at each point in time (Pat Adams, personal communication). These data were not yet available when the current study was conducted.

4.1.3 Additional census and NHS information

For DAs and CTs, numerous other means are of course available from census and NHS profiles. We make use of population estimates as well as responses to the following questions:

> If you were to sell this dwelling now, for how much would you expect to sell it?
>
> How many rooms are there in this dwelling? Include kitchen, bedrooms, finished rooms in attic or basement, etc. Do not count bathrooms, halls, vestibules and rooms used solely for business purposes.

The first question is asked only of home owners.

In the analysis described next, we investigate changes over time, in particular of areas which were already developed in the past. Therefore we make use of answers to the questions above from the 2001 and 2006 long-form responses, and use them to look at changes in DAs or CTs which were developed prior to 1980.

5 Economic implications of road network sprawl

In Section 3, we outlined reasons why the degree of street network connectivity may determine, in an enduring way, the kind of private and public investments which are made by households, businesses, and the government. In addition, we explained why these effects should feed back to future investment decisions involving additions to the street network itself. A simple qualitative corollary from this same causation is that areas with low street connectivity are likely not to "densify" readily even as the general value of land increases. Furthermore, because of the increasing returns (due to the dynamics we and Murphy (2012) describe, as well as the conventional ones) to agglomeration, we predict that areas initially settled with a more grid-like road network should appreciate faster than those where the roads were laid out with low nodal degree, i.e., low connectivity. Of course, such an apparent state of arbitrage should not occur under stable conditions, or if homeowner mobility is high, but the context of our investigation is one in which awareness of future effective and explicit prices on carbon, old-fashioned transportation, and environmental inefficiency is growing.

Here we provide exploratory evidence on the changes occurring over the last decade. First, and most importantly, however, we begin by assessing the major trends in urban sprawl across Canadian urban regions.

5.1 Trends in development form

Barrington-Leigh and Millard-Ball (2014b) report for the first time that across the U.S.A., the measures of urban sprawl we use here have already peaked, mostly around the mid 1990s to 2000, with a subsequent decline in measures such as mean nodal degree. This decline is significant enough that roads in new developments are on average as connected as in 1960, despite the major and steady decline in connectivity from early to late in the century.

Using our Canadian panel series, we find an even more remarkable situation in Canada. In this country, our measures of road network sprawl show a decline, and measures of connectedness like mean degree show a rise, since nearly a decade earlier than in the U.S.A. For urban neighbourhoods with median construction age in the 1990s and more recently, road networks have become progressively more connected and grid-like, with higher mean nodal degree.

Figure 5.1 shows these changes. While the original road networks in the cores of Canadian cities, developed before private automobiles were ubiquitous, tend to be highly gridded (degree close to 4), we cannot resolve dates earlier than 1960 using our method. The overall mean nodal degree in urban DAs with median construction prior to 1960 across Canada is 3.09 (heavy black line in the top left panel of figure 5.1), while the average degree over the entire stock of nodes extant in 2011 is considerably lower, at 2.90 (see 2). During much of the Twentieth Century, the average nodal degree in new developments was likely dropping, as it was in the U.S.A. Barrington-Leigh and Millard-Ball (2014b), and the continuation of this decline is evident in figure 5.1, where, until the 1980s, mean degree decreases and the fraction of deadends increases.

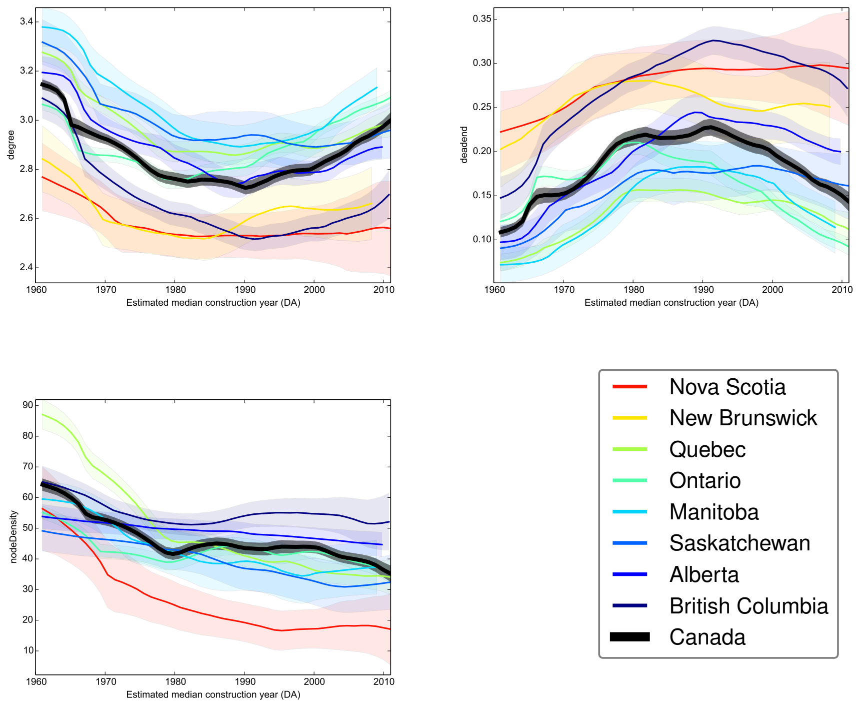

Figure 5.1: Trends in development form. Shaded regions show 95% confidence intervals.

These measures represent the flow of new development, i.e. additions to the stock of roads, over time. During the 1990s, the trend reverses, and in recent years new construction is more grid-like (degree ~2.95) than the average of the entire urban stock. This means that no only has the sprawling trend of new construction reversed (in the 1990s), but that in the last decade the overall stock of roads reversed its trend of becoming increasingly characterized by low-degree sprawl.

Figure 5.1 also shows the area density of nodes in DAs as a function of their median construction year. This is also a common measure of urban form. However, unlike our preferred network topology measures, the trend of nodal density has continued to decrease over the last decade. This suggests that while suburban lots may still be large (sprawling, by some definition), they are becoming better connected. According to our description of the dynamics of densification, our topology measures are the key enduring ones. A coarse gridded road network can be subdivided later to a finer grid, and thus, on the long term, nodal density may increase where the original network is gridded. However, original roads are unlikely to be moved, for reasons described earlier, and a low-connectivity development arranged on an irregular cul-de-sac and degree-three network cannot easily increase its nodal density. The combination of low nodal density with increased nodal degree in recent developments suggests a change in the *style* of new additions to the road network, rather than a change towards higher density in the kinds of locations being developed.

5.2 Inter-provincial differences

In addition to the national averages across urban areas, shown in black, figure 5.1 shows means over time for each Province. Interestingly, these differences are quite persistent, even though they refer to new development rather than legacy stock. In Canada, there are relatively few metropolitan areas in each Province, and a small number of them dominate the national average. table 3 lists the mean degree of the 2011 road network in the largest metropolitan areas in Canada. While Manitoba's high average nodal degree reflects only the road layout of Winnipeg, the low British Columbia average is due to numerous low-connectivity urban areas outside of the Vancouver region.

While the trend reversal described above for mean nodal degree of new developments across Canada is reflected also in most Provinces, there are some differences in the timing of this change. For instance, nodal degree appears to have continued dropping significantly in British Columbia until 1990, while in Ontario the increase in connectivity begins as early as the 1980s.

Further research into differences in economic and regulatory influences across the country would be helpful to understand the observed variation. However, it is clear, and a primary finding, from our data that the full splendour of the suburban cul-de-sac maze is a thing of the past. The spread of more modern ideas about urban planning, contemporary demand for access to collective urban services, as well as demand for alternatives to complete reliance on automobile transport, are all likely factors in the changing network properties of new roads.

It is also worthwhile reiterating that this shift occurred earlier in Canada than the United States. According to our model (see Section 3), existing patterns of urban sprawl built up through the Twentieth Century are only likely to lose their influence on new, adjacent developments if the price of fuel is sufficiently high. It may be that the considerably higher cost of fuel in Canada helped to precipitate the reversal earlier there than in the neighbouring United States.

5.3 Metropolitan areas

Decreasing our level of aggregation further, we show in 3 the mean nodal degree of roads in the largest Canadian metropolitan areas. The third column of the table shows the means for the entire stock of roads in each metro area, according to the 2014 OSM data. The fourth column shows means over only those nodes that are located in DAs with median year built more recent than 1999. The colour coding simply reflects the point estimates, with dark blue signifying the highest connectivity (nodal degree) and dark red the lowest. There are regional differences that defy easy prediction. Winnipeg is largely gridded, with nodal degree far above the national average, while nodal degrees in the Vancouver region (in spite of the gridded streets in the city of Vancouver itself) and Kamloops, for instance, lie well below it.

Moreover, there is considerable persistence across regions, in the sense that recent developments tend to mirror the stock accumulated since each city area's founding. While there could be numerous reasons for such geographic differences, it seems likely that path dependence of the form we have proposed accounts for some of the persistence evident in our data.

5.4 Changes in population density

We next make use of data on population, dwelling size, and dwelling value from the census long form in 2001 and 2006 to look for correlations between changes in these settlement characteristics and the properties of the road network. In order to look for long-term effects of road network properties, we restrict our attention to DAs with mean construction year prior to 1992.

Because gridded streets foster walkability and the critical density for local services to flourish and to substitute for home production (see Section 3), we predicted that areas with higher connectivity road networks are likely to be better able to densify on the long term, as general population growth and urban agglomeration increase demand. Our non-parametric estimates[7], shown in figure 5.2, do not lend strong support to this idea. The left panel shows the average change in population of pre-existing dissemination areas as a function of the nodal degree of the modern road network there. The right panel shows the average change in population area density. The heavy black line shows the national average, with coloured lines showing Provincial estimates when they are sufficiently constrained.

5.5 Changes in dwelling value

According to our hypothesis, a changing trend towards better-connected road networks should benefit extant high-connectivity areas most. Although a more detailed treatment is needed to address properly this idea, we present in 5.3 the relationships — again estimated nonparametrically — between nodal degree and changes in three other census-derived measures.

The first plot shows the change in the size of dwellings among census tracts in between 2001 and 2006. The average number of rooms in a dwelling was apparently still increasing substantially during this period, at least for all but the highest nodal degree neighbourhoods.

The census long-form also asks respondents who own their homes to estimate the current value of their dwelling. The top right panel shows how answers to this question, averaged at the census tract level, changed during the same period. The bottom left panel combines the previous data to estimate changes in the cost

[7] We use kernel-weighted local polynomial smoothing with an Epanechnikov kernel.

CMA name	Province	Mean nodal degree 2011 stock	2000+
Toronto	Ont.	2.982±0.003	3.093±0.006
Montréal	Que.	3.094±0.003	2.974±0.008
Vancouver	B.C.	2.760±0.005	2.687±0.013
Edmonton	Alta.	2.851±0.005	2.752±0.011
Calgary	Alta.	2.955±0.005	2.967±0.010
Ottawa - Gatineau	Ont./Que.	2.886±0.005	2.965±0.011
Québec	Que.	2.927±0.006	2.798±0.018
Winnipeg	Man.	3.132±0.007	3.064±0.018
Hamilton	Ont.	2.878±0.008	2.887±0.020
St. Catharines - Niagara	Ont.	2.908±0.008	2.876±0.038
Halifax	N.S.	2.597±0.009	2.550±0.030
Victoria	B.C.	2.497±0.010	2.480±0.035
Kitchener - Cambridge - Waterloo	Ont.	2.959±0.008	2.960±0.018
London	Ont.	2.922±0.009	2.811±0.023
Saskatoon	Sask.	3.061±0.010	2.937±0.025
Windsor	Ont.	2.954±0.012	2.887±0.034
Oshawa	Ont.	2.924±0.011	2.997±0.021
Regina	Sask.	3.060±0.011	2.868±0.029
Sherbrooke	Que.	2.818±0.011	2.789±0.032
St. John's	N.L.	2.559±0.013	2.501±0.025
Kelowna	B.C.	2.539±0.014	2.484±0.029
Saint John	N.B.	2.539±0.013	2.532±0.062
Greater Sudbury / Grand Sudbury	Ont.	2.656±0.014	2.558±0.157
Saguenay	Que.	2.812±0.014	2.424±0.185
Kingston	Ont.	2.667±0.014	2.885±0.050
Moncton	N.B.	2.789±0.013	2.645±0.032
Trois-Rivières	Que.	2.958±0.012	2.784±0.050
Abbotsford - Mission	B.C.	2.553±0.016	2.426±0.043
Peterborough	Ont.	2.698±0.016	2.746±0.073
Thunder Bay	Ont.	2.868±0.016	2.707±0.124
Barrie	Ont.	2.853±0.014	2.854±0.028
Brantford	Ont.	2.957±0.015	2.861±0.050
Guelph	Ont.	2.977±0.014	3.053±0.029

Table 3: Average nodal degree in major Canadian metropolitan areas. Regions are listed according to the number of nodes in their road network. The two numeric columns show the mean nodal degree across all nodes and the mean across nodes in recently-built dissemination areas. Colours correspond simply to the point estimates.

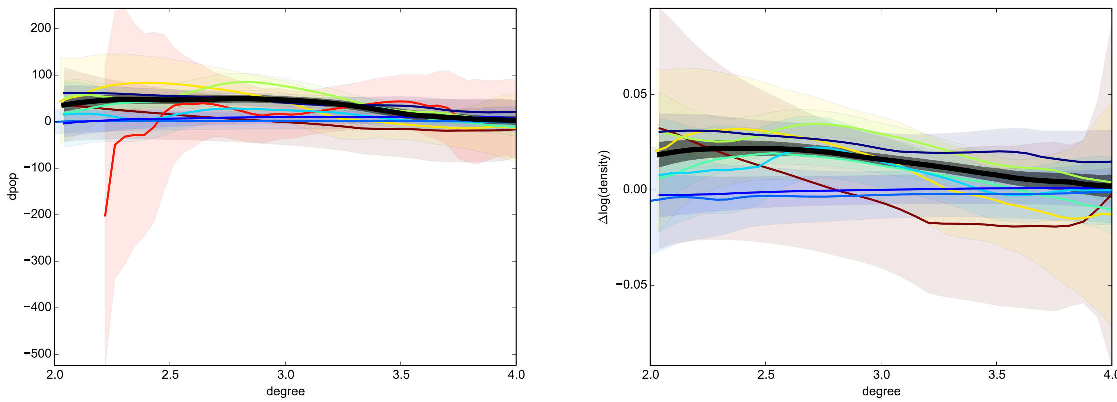

Figure 5.2: Population changes and population density changes, 2001–2006, by nodal degree. Shaded regions show 95% confidence intervals.

per room of an urban dwelling.[8] It appears, first of all, that price appreciation is not uniform, either across the country or even within certain Provinces such as Quebec and Nova Scotia. Secondly, it does still appear that during this period there is substantial appreciation in areas characterized by the extreme of "sprawl" road networks, with average degree near two. However, it appears that the market has above all favoured areas with high road connectivity, with over 60% rise in room value during this period of real estate boom.

6 Conclusion

We propose a new reason to consider policy aimed directly at urban form, in particular to influence the degree of connectivity of road networks in new developments on the edges of growing regions. Not only are the locations of such routes nearly permanent on century timescales whenever ownership of adjacent land parcels becomes decentralized, but theoretical considerations suggest that there could be further impacts on future neighbourhoods which magnify any negative or positive externalities.

Among the long-term externalized costs incurred by society as a result of low-connectivity road networks is the tendency towards a private motorized lifestyle not only for current decision makers but for residents of future nearby developments. The incentives of future developers and residents shift based on the existence of nearby connectivity and services, closing a positive feedback system.

In addition to health and congestion effects from increased private car com-

[8] Clearly, rooms are likely to be larger in lower-density areas, biasing our estimates away from our hypothesis, since high density is associated with high nodal degree.

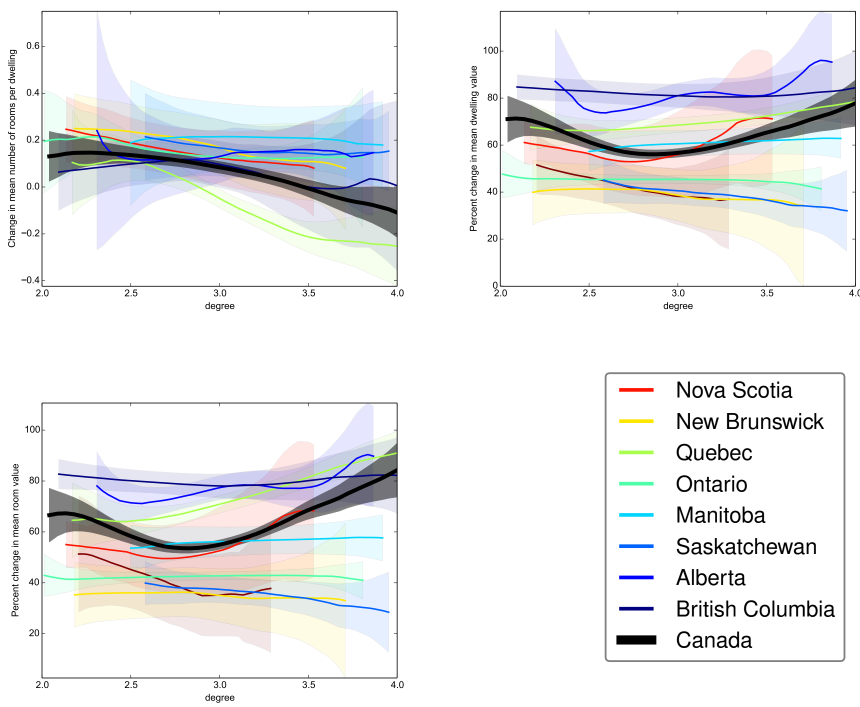

Figure 5.3: Change in mean number of rooms per dwelling, dwelling value, and room value, 2001–2006. Shaded regions show 95% confidence intervals.

mutes, we consider a problem with this self-propagation of urban sprawl to lie in the collective action problem surrounding private household capital. When roads enforce isolation on neighbours (in addition to affording isolation for oneself), households overinvest in and underuse private capital rather than participating in market services and shared resources. While we have not offered closed form propositions concerning the welfare effects of this externality, we propose that with low or "mid-range" fuel prices, these externalities are negative. In addition, they exacerbate the social costs from environmental pollution and above all greenhouse gas emissions associated with a car-oriented lifestyle.

The limited availability of data for Canada do not allow us to test these ideas in detail. However, there are already numerous reasons to favour policy targeting urban form in Canada; see for instance Thompson (2013). Our empirical contribution is to propose a method for large-scale quantification of development patterns that focuses on the core feature of the nearly immutable road network. As part of a broader ongoing effort, we have applied our algorithm to the Canadian road network in order to compare regional patterns and, crudely, recent changes.

Our main finding is that, in contrast to popular descriptions, the pattern of increasingly disconnected communities has reversed in Canada. New developments have, until very recently, still been decreasing the average connectivity across the entire road stock, but for two decades the new additions have been an improvement over what was built at the height of urban sprawl. This means that those municipalities still promoting or permitting construction of the archetypal cul-de-sac and degree-three developments may be missing what has been understood by others.

We present some tentative descriptive analysis to demonstrate the features of our dataset, suggesting that property values have increased most where road networks were originally highly connected. Future work will refine and leverage this new dataset for understanding Canadian policy and opportunities, as well as applying our method to road networks worldwide.

6.1 Lessons for Canada

We finish with an indication of the early policy implications from this work.

1. Planning policies must directly address the road network, in addition to other, more proximate (short-term) indicators of urban form. There is precedence for this; for instance, policies to discourage or prohibit cul-de-sacs and promote connected streets have been in place for over a decade in such places as Portland, OR, Austin, TX, Charlotte, NC and Cary, NC (Handy et al., 2003; Litman, 2014). These policies sometimes directly target the mean degree measure on which we have focused.

2. In places where low-connectivity roads are the dominant form of new construction, extra strong incentives, including regulation and charges targeting social costs, should be put in place to get over the path-dependent lock-in which is likely to influence subsequent construction.

3. As evidenced by the increase in average nodal degree of new development over the last 1–2 decades, construction trends in Canada are improving towards more densifiable road networks. As a result, strong government regulations imposed to promote this shift may be temporary.

4. Certain areas which, according to Table 3, are lagging in this transformation yet growing quickly, such as the suburbs of Vancouver, need special attention in order that they do not create and perpetuate a long-term, intractable handicap in their future efforts to curb greenhouse gas emissions and general material consumption levels.

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