Sustainable Street Patterns in the Suburbs

Anton Metalnikov

University of Manitoba

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Acknowledgments

I would like to formally acknowledge and thank all those who, in one way or another, contributed to this project.

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Executive Summary

Suburban development, and the curvilinear street pattern often used in it, are a common target for criticism within the planning community, yet they continue to represent a significant share of growth in many urban areas. This research set out to find out why the curvilinear street pattern is widespread in greenfield development, and whether its advantages can be accommodated in an altered street network design while mitigating its drawbacks. Suburban development expands the reach of cities and street network layout is a significant determinant in the character of those neighbourhoods. Different street patterns will have different effects on transportation characteristics of all modes, as well as different effects on the form and location of development. Street patterns are also permanent, and will maintain these same effects into the future.

To conduct this research, I performed spatial analysis on Winnipeg neighbourhoods to obtain a quantitative assessment of different street patterns. I also held interviews with representatives of eight different organizations involved in suburban development to learn directly their considerations in laying out street networks.

I found that while mature grid neighbourhoods on average score higher in measures of street network density and connectivity, there were many exceptions where more recent suburban developments with curvilinear street patterns scored just as high or higher than them. Through interviews, I found that efficiency was the most dominant consideration in street network design, as the curvilinear pattern allows for more land to be dedicated to housing rather than roads. Marketability, connectivity, and development regulations were important factors as well.

Based on these findings I recommend that specific problems and goals be the focuses of street pattern design, and not the choice of street pattern itself. Through collaboration between all stakeholders, street patterns can maximize and sustain key priorities in new neighbourhoods and expanding cities altogether.

Introduction

Suburban development on the fringes of urban areas has been a major focus, and concern, in urban planning for decades. It has been variably criticized as being monotonous, environmentally harmful, financially unsustainable, unsightly, and socially exclusionary, among other issues (Forsyth, 2012, p. 272). Specifically, these negative effects are seen as resulting from the disturbance of natural or agricultural land, the homogeneity of housing and commercial offerings, the low densities, and of the car-dependent designs involved in suburban development (Forsyth, 2012, pp. 272, 276, & 278). As one of the key considerations in contemporary urban planning thought, suburban expansion has been met with a variety of regulations and policies aiming to curb its ubiquity and negative externalities. Urban areas across North America have implemented tools such as urban growth boundaries, development charges, and tax incentives to lure development demand away from the urban fringe and towards infill and redevelopment in existing built-up areas.

While these tools have seen a varying degree of success in accomplishing this goal, suburban development remains a major source of growth in metropolitan. In Canada, 75% of population growth and 68% of dwelling unit growth occurs in the suburbs (Gordon, Hindrichs, & Willms, 2018, pp. 1-2). However, suburban development has not stayed stagnant in its design over this time either. Whether as a response to these regulations or to changing market context and demand, developers have begun to adjust their new neighbourhoods in a way that begins to address some of these criticisms. Housing types have begun to diversify, with duplexes, townhouses, and rental and condominium apartment buildings becoming more common options in new subdivisions (Brewer & Grant, 2015, p. 152). Even the traditional single-family home lots have become consistently narrower which – along with an increase in housing type diversity – has contributed to a greater overall neighbourhood density (Paulsen, 2012, p. 429). Active transportation paths have also become more common. Indeed, contemporary greenfield subdivisions have been evolving from their previous generations.

To have evolved, however, means that they have made changes from previous suburban incarnations. That is, the base structure of suburban developments has remained, and the multiple iterations of them retain strong similarities. As such, despite the changes that are being made in suburban design, and their general adherence to the evolution of conventional urban planning thought, suburban development and its form remains a frequent target of planning criticism.

One of these similarities – the hierarchical curvilinear street pattern – is the focus of this research project. Though suburban street patterns have doubtlessly seen changes from the first post-war developments in the 1950s, many of their specific attributes remain. Internally, bays and cul-de-sacs coming off of collector roads is a popular development pattern. Streets curve and turn in an organic, unprescribed fashion with no obvious overarching structure. Externally, these developments use a small number of deliberate connections between the neighbourhood's internal network and the broader city street system. Though variations exist, these aspects make up an identifiable typology for many North American suburban street patterns.

Street layout design – and by extension, its study – is important for a variety of reasons. Perhaps the most important of these is the structure that it sets for all development that follows. Street pattern determines the amount of development that can be accommodated, its form, its density, and its relationship to the street itself. This is made even more significant by the permanency of the streets. A neighbourhood may have its buildings redeveloped and it may have its streets and intersections widened or altered, but the base form of the road network cannot easily change (Rashid, 2018, p. 633). Existing development is fully oriented both to the street as well as to the services running underneath them. Barring full-scale clearing of the site, acquiring a sufficient number of properties to make significant alterations would not likely be economically viable or logistically feasible.

The street pattern also forms the foundation of the transportation system and affects all aspects of its function. It impacts the circulation of automotive traffic, its speed, and its congestion. It also provides the framework in which public transit must operate, the network that cyclists can navigate, and the connectivity that pedestrians experience. With all modes, the street network can affect the user's experience, the mode's potential utility, and the interactions between modes.

This study aims to uncover why the curvilinear layout has remained popular, and how it could be adjusted to address some of its criticisms as greenfield neighbourhoods continue to be developed. The premise of this research lies on the assumption that the contemporary pattern is used because it responds to certain goals that developers or government may hold. As such, this research aims to discover what these goals are and how they may be met while addressing the concerns surrounding the curvilinear street system. This is not to say that this project will conclude in a perfect street pattern that fulfills both the considerations of its current users and detractors. Rather, it will synthesize these interests and recommend actions that can be taken to move towards potential alternatives that may be acceptable to a greater variety of interests.

To get there, this report will outline the research methods used, provide a literature review of what existing research has found on this topic and its related issues, and describe the context within which this research took place and the resultant limitations and opportunities for generalizability. Following this, findings are presented that demonstrate that while grid neighbourhoods often have superior connectivity to curvilinear neighbourhoods, there are many exceptions to this. Furthermore, more recent suburban developments on average have improved connectivity compared to older subdivisions. Results are also introduced naming land use efficiency and marketability as the primary motivations behind street pattern design. These results are then analyzed with regards to their potential causes and what their broader implications for suburban neighbourhood design signify. Based on these results and their analysis, a set of recommendations on improving street patterns and ensuring they represent the broadest coalition of interests are made. A conclusion will then summarize the findings, their relevance, and their potential for applicability, as well as provide some final thoughts on suburban street network layout and how it might continue to evolve in the future.

Methods

Two distinct sets of methods were used in this research, both of which were concentrated on the City of Winnipeg in the Canadian province of Manitoba. Winnipeg was chosen primarily because it experiences a high proportion of its growth in greenfield suburban developments using the street patterns at the core of this research, with 77% of the Census Metropolitan Area population growth between 2006 and 2016 occurring in the suburbs (Gordon et al., 2018, Appendix B).

Mapping Analysis

The first method used was spatial analysis of Winnipeg neighbourhoods done through GIS. The goal was to discover the existing conditions of street patterns in different neighbourhoods and to assess them based on a range of measurement indicators uncovered from existing academic literature. These measures included street density, intersection density, the connectivity index, external access point density, and the average distance between external access points.This then allowed me to compare different neighbourhoods – and by extension, different eras of development – in order to be able to quantify the differences between them and use that for analysis, as opposed to personal perception. An auxiliary benefit of this method is that it provided a test of the differences between these different measurement indicators and provided insight into their potential as a regulatory tool.

The work was performed by separating the Winnipeg street network into its constituent neighbourhoods as defined by the municipal government and measuring the layouts based on five street pattern measures. Certain neighbourhoods with no or minimal street networks were not included, as analysis on them was not possible. Because these omitted neighbourhoods consist entirely of industrial, agricultural and open space, or currently developing neighbourhoods, I did not consider this to be a concern. All data was obtained through the City of Winnipeg's Open Data Portal. Streets were assessed on their centre-line lengths, and back lanes were not included in the analysis. Through GIS, points were placed at every intersection as well as at each cul-de-sac. This combination of street lengths, end-nodes, and intersections was then used in the analysis of each neighbourhood's street pattern as per the five identified measurements.

A selection of the connectivity measures identified in the literature were used to assess each neighbourhood of Winnipeg. The intent was to employ as many measures as possible, both to obtain the most comprehensive overview of each neighbourhood as well as to be able to assess the differences between each metric. Five measures were chosen for use: street density, intersection density, connectivity index, external access point density, and the average distance between external access points. As identified in the existing literature, this collection of measures covers the base considerations of street network analysis: the layout's density, the layout's internal connectivity, and the layout's external connectivity.

Notable street network metrics, namely walkshed and block-based measurements, were not used due to complications in their use. Walkshed analysis relies on the selection of locations on a street network and determining the area coverable within a certain distance. While this is a highly accurate tool in determining the accessibility of any one location in a neighbourhood, it does not lend itself to larger-scale comprehensive analysis of entire neighbourhoods. Conversely, the five metrics selected were possible to efficiently calculate for each neighbourhood through the use of GIS. Other measures, namely cul-de-sac density and the cul-de-sac to intersection ratio, were not used due to their exclusive focus on one measure of street network connectivity –

the cul-de-sac. I determined these measures to be of limited value, given that cul-de-sacs form only one of many street pattern components. It is possible for well-connected street patterns to include cul-de-sacs and poorly-connected street patterns to contain no cul-de-sacs at all, and for this reason more comprehensive metrics were chosen. I do not consider this a significant limitation in this research, given that many research articles use as few as one measure in their analysis, and that the five measures used here include the ones most commonly used in practice and in academia and possess a collective breadth in their assessment targets. While the use of any additional measures would have provided additional insight, in consideration of the scope of this project the five chosen metrics were deemed to be sufficient in providing relevance and validity to the research.

Based on the street network data obtained from the City of Winnipeg, intersections and cul-de-sac point shapes were added manually based on street segment intersections and line ends. Analysis for all five measurements was done using a combination of neighbourhood boundaries as defined by the City of Winnipeg, street centre-lines, intersections, and cul-de-sacs. Back lanes were not considered in the analysis.

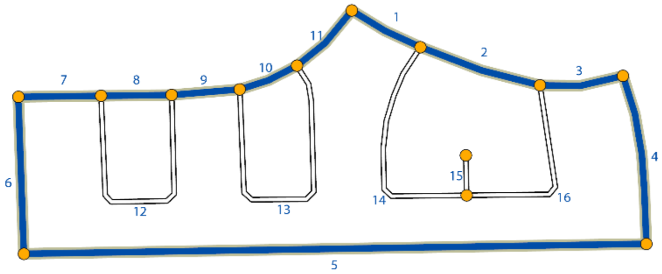


Figure 1 - Road links are separated into segments by intersections and end-nodes

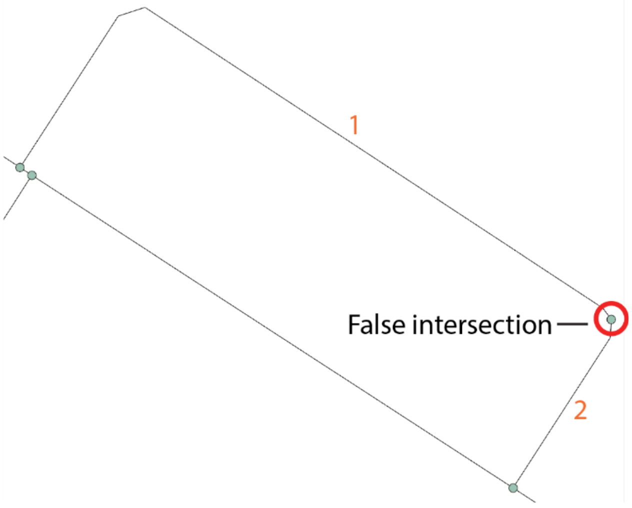


Figure 2 - A bay is incorrectly separated in an example of the occasional issues found in the GIS data used

Several issues and limitations arose over the course of this analysis. The first pertained to the quality of the data provided, as well as the availability of data overall. One constraint was the lack of a comprehensive active transportation layer available, which prevented the separate assessment of vehicular connectivity versus pedestrian and cyclist connectivity. While an active transportation shapefile is available on the Winnipeg Open Data Portal, there were many existing paths and trails that were not included in the file. As such, active transportation was not considered in this assessment as the data provided did not allow for its quality analysis. The other data quality issue related to the structure of the street shapefile. Street network data used had all roads separated into segments between intersecting points (Figure 1). Occasionally, this was done incorrectly as turns were perceived as intersections, which created excess street segments and intersections (Figure 2). This may skew results of neighbourhoods with larger numbers of bays. Finally, the inclusion of green space and water features in the total area of neighbourhoods may be a concern. While parks and retention ponds were deducted from neighbourhood areas, this was not possible with other features such as golf courses, which skews the result of some neighbourhoods. While comparisons between neighbourhoods remain largely accurate, certain such complications remain.

Another issue had to do with the placement of the neighbourhood boundaries. The neighbourhood boundaries as defined by the City of Winnipeg presented challenges, as these boundaries are often arbitrary while the shape of a neighbourhood can have a large impact on its ultimate measurements (Knight & Marshall, 2015). However, analysis proceeded using the City-defined neighbourhood boundaries as these boundaries reflect new suburban subdivision well, given that the development's boundaries coincide with the neighbourhood boundaries as the City defines them. Because these suburban developments are the primary focus of this study, I decided that selecting boundaries in this way was the most accurate way of assessing street patterns in post-war neighbourhood subdivisions, despite the issues this creates with primarily mature inner-city neighbourhoods. In other words, because any chosen boundary would have its own arbitrariness and effect on data, the use of City-defined neighbourhood boundaries was thought to have had the smallest effect on the primary target of the research.

Maneuvering around these issues presented its own set of challenges. In doing the analysis, I had to make several decisions on how to approach problems presented by the data. For example, neighbourhoods adjacent to a river would be at a significant disadvantage in calculating the number of access points leading out of the neighbourhood, as the river presents a hard boundary that severely limits the potential for road connections. While I included this distance to avoid disadvantaging neighbourhoods that do have bridge connections, both approaches created problems. In all, despite these challenges, I attempted to approach all cases with consistency. As such, the data provided for each neighbourhood is of sufficient quality to allow comparisons to be made between them. However, certain limitations were unavoidable, and care should be taken so as not to use the data provided beyond the scope of this research, whether to compare to neighbourhoods done in other studies or in basing recommendations off of them. With many neighbourhoods having unique intricacies, the precise methods used to address them can vary. Therefore, the utility of this data outside this research cannot be guaranteed.

Interviews

Interviews were chosen to obtain the most detailed possible information, as well as to respond to the Winnipeg context specifically. While a large amount of existing literature has covered the widespread use of the curvilinear street pattern and its effects, the collective literature has not approached the influences behind its widespread use directly and therefore has not sought to learn about the specific factors involved in the choices made in street network design. David Gray writes that interviews allow for responses that are more in-depth and are well-suited for "gathering information about a person's knowledge, values, preferences & attitudes" (2009, p. 370). As such, meeting in person with practitioners directly involved in subdivision development allowed me to probe for more detailed considerations involved in their decision-making and take advantage of the increased validity of primary data. Speaking with local practitioners working in Winnipeg also allowed me to contextualize the factors involved in street network layout to the specific opportunities and constraints in Winnipeg. While this research may be of use in large urban centres more broadly, being able to focus on Winnipeg specifically produces more detailed results that can then be considered when doing similar evaluations in other major cities.

At the outset of the project, I targeted nine different organizations for interviews. One participant invited abstained from participation. I selected organizations targeted for research participation based on their involvement in recent Winnipeg suburban developments. This involved searching through development websites looking for involved parties, searching through organizations' websites directly to see if they may have worked on suburban projects, or through referrals. This amounted to eight total interviews. Six of these interviews were conducted with an individual respondent, while two were held in joint interviews with two respondents each, leading to a total response of ten individuals from eight organizations. The roles of the respondents were as follows:

- **One engineer** (individual interview)
- **One City of Winnipeg planner** (individual interview)
- **One private planning consulting firm** (joint interview)
- **Five development companies** (four individual interviews, one joint interview)

All respondents were asked about their education and experience pertaining to neighbourhood development and design, and all respondents were deemed to be highly qualified and capable of providing informed insight for the purposes of this research. Of the six respondents representing development companies, five had professional degrees and experience in urban planning, and one had a background in engineering.

Interviews were done in a semi-structured fashion, with a set list of questions prepared for the interview, but with their specific wording and the order they were asked in changed as needed to fit the flow of the conversation. Additional follow-up questions were also added as was necessary. Semi-structured interviews were chosen due to their better suitability for qualitative analysis, where comparing different respondents' answers to each other was less important than obtaining the maximum amount of detail possible (Gray, 2009, p. 373). By allowing for probing and the adjustment of questions based on responses provided, the semi-structured interview format provided the opportunity for exploring unforeseen topics or themes (p. 373). This meant that I was not constrained by my existing understanding of the topic in conducting and steering the interviews.

Broad questions asked included the factors and goals that go into subdivision design and street pattern specifically, how the street patterns planners, developers, and engineers tend to use support these factors and goals, and how these neighbourhood designers are affected by existing policies and regulations. Additional probing questions were asked about how designers' neighbourhood layouts considered land use, transit, and its surroundings. I also asked questions on alternative street patterns, namely the fused grid.

Literature review

The existing literature regarding street network design can be separated into two main categories. One consists of the history of urban development, the factors that have contributed to the use of hierarchical curvilinear street patterns today, and the extent to which these factors remain relevant. The second consists of evaluation of the contemporary suburban street pattern and the effects that it has on a variety of issues. As such, this literature review will be split into the same two categories to provide context and background information for my research. A section on connectivity measures is also included to support my GIS analysis method, as well as to review the different methods of measuring and regulating street patterns overall.

Why curvilinear?

Michael Southworth has written most extensively about the changing nature of urban expansion, with the changing street pattern preferences identified as one of the key manifestations of these changes. In the 1993 article written with Peter Owens, four stages of growth are identified and assessed as representing distinct eras in American urban growth, three of which relate to street pattern. The first is the *gridiron*, which they argue provided the advantages of maximizing sellable street frontage and expediting the creation of lots, maximizing transportation accessibility, and being infinitely expandable. At a time of rapid development and speculation, these "were important attributes for a country preoccupied with growth and expansion." (Southworth & Owens, 1993, p. 274). The gridiron later evolved into the more internally-focused *interrupted parallels*, in which the grid was adjusted into longer blocks, and streets began to loop and curve back into the development rather than to connect into adjacent neighbourhoods. This allowed developers to reduce the total length of roadway they built, while also creating quieter communities (Southworth & Owens, 1993, p. 274). These goals were further enhanced in the *loops and lollipops* model which were designed to maximize the total number of lots in a given parcel and provided additional quiet and privacy (Southworth & Owens, 1993, p. 276). A more recent Canadian Mortgage and Housing Corporation (CMHC) report supports these claims, stating that curvilinear street patterns consume between sixteen and twenty-five percent less land for roads than the grid, thereby providing more land for developable lots (CMHC, n.d., p. 2). However, the report goes on to explain that these land savings are largely a result of long blocks, bays, and cul-de-sacs, and that the curvilinear design itself is primarily an aesthetic consideration (CMHC, n.d. p. 2). More generally, Southworth and Owens attribute this gradual transition to five key factors: a concern for personal and traffic safety and privacy, a desire for a more natural and less urban feel, changes in urban planning and engineering standards, a shift of responsibility for street layout from government to private developers, and the resultant increased importance given to lot yield and infrastructure efficiency and decreased concern towards inter-neighbourhood connectivity (Southworth & Owens, 1993, p. 281).

Southworth expanded on this transition in an article" written with Eran Ben-Joseph. They cite the 1936 bulletin *Planning Neighbourhoods for Small Houses* released by the largely real estate and banking representative-run United States Federal Housing Administration (FHA) which discouraged the gridiron plan (Figure 3). It discouraged and criticized the grid pattern for contributing a greater area devoted to streets than necessary, requiring all streets to be built to a relatively high standard given their more equitable share of traffic, and its visual dullness (Southworth & Ben-Joseph, 1995, p. 74). Instead, it promoted a hierarchical street layout that encouraged cul-de-sacs and discouraged through-traffic (Southworth & Ben-Joseph, 1995, p. 74). Because the FHA had mortgage insurance plans with over 70% of US commercial banks, it had significant leverage over development standards (Southworth & Ben-Joseph, 1995, p. 73). Wesley Marshall and Norman Garrick also attributed the shift to hierarchical and curvilinear street patterns to the Institute of Transportation Engineers (ITE) which published the report *Recommended Practice for Subdivision Streets* in 1965, which recommended curvilinear local streets with discontinuities to discourage through traffic, replacing four-way intersections with T-intersections where possible, and the use of cul-de-sacs (Marshall & Garrick, 2010a, p. 104).

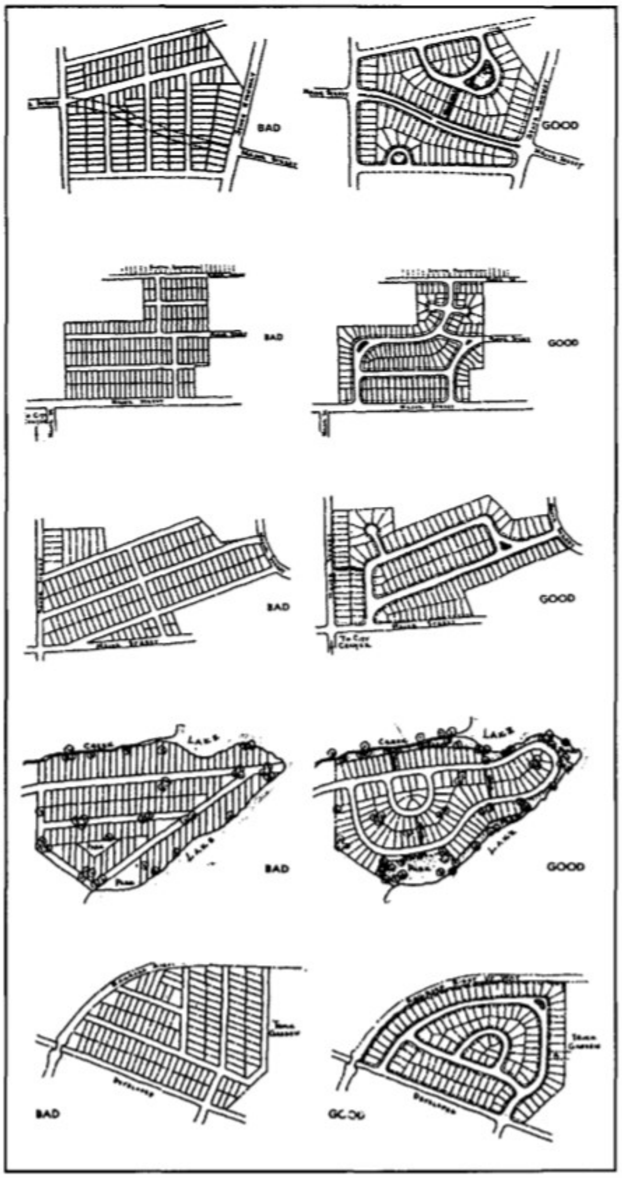


Figure 3 - Discouraged (left) and recommended (right) designs from the FHA (Southworth & Ben-Joseph, 1995, p. 75)

The effects of curvilinear street patterns today

Modal Split and Vehicle Travel

Given the influence that street network layout has on development and the transportation links within and between an area, a large body of research has emerged on the specific effects the curvilinear pattern has created.

One of the most common considerations was the effect of the curvilinear street pattern on mode share and vehicle use, with the results on whether non-automotive mode share increased or vehicle kilometres travelled (VKT) decreased being mixed, even within studies. One study analyzed twenty-four California cities and ran a statistical model with multiple controls on the relationship between community design and VKT. All else being equal, the study found that grid pattern neighbourhoods tended to result in lower VKT than in curvilinear neighbourhoods (Marshall & Garrick, 2012, p. 18). More specifically, however, it found that VKT decreased with an increase in intersection density and less road curvature, while also finding that VKT increased with an increased street connectivity and an increased number of intersections between major city-wide roads (Marshall & Garrick, 2012, p. 14). The authors explained this as increased street network having a synergistic effect by both “creating opportunities for active transportation and in making shorter and more efficient car trips possible” (Marshall & Garrick, 2012, p. 18).

This alludes to a key difference between mode share and VKT, in that a reduction in VKT is not equivalent to a reduction in automotive mode share. The authors state that areas with lower VKT were partially explained by an increase in transit use, walking, and cycling, but also by the greater proximity of destinations and directness of travel (Marshall & Garrick, 2012, p. 18). In other words, VKT can be reduced by people driving shorter distances while driving at the same rate. This phenomenon is addressed by Randall Crane from an economic perspective of induced demand, arguing that any “neighborhood configuration of land uses and street patterns improving local access will also increase trip frequencies,” which would be true for all modes (Crane, 1996, p. 59). In other words, even if a greater share of trips is taken by a mode other than the personal automobile, the increased total number of trips could maintain vehicle use at a similar, or increased, level (Crane, 1996, p. 59). While the street pattern contributes to the relative cost of each mode for any given trip, other factors altering these costs will also affect the overall mode share of a neighbourhood.

In their study on the difference in mode share between transit-oriented and auto-oriented neighbourhoods, Cervero and Gorham paired demographically-similar California neighbourhoods in the San Francisco Bay Area and in the Los Angeles region, with each pair having one transit-oriented and one auto-oriented neighbourhood based on indicators like street patterns, densities, and the built form. Controlling for income, they found that all transit neighbourhoods had higher pedestrian and cycling mode shares and trip generation rates, and lower drive-alone mode shares and trip generation rates (Cervero & Gorham, 1995, p. 217). All transit neighbourhoods except one also exhibited higher transit work mode share and trip generation rates as well (Cervero & Gorham, 1995, p. 217). However, two transit neighbourhoods had a lower overall transit mode share than its auto-oriented pair neighbourhood (Cervero & Gorham, 1995, p. 220). The effects of transit commuting overall were less clear. While in the Bay Area overall transit mode share was higher in all transit neighbourhoods except one, no significant difference was found in the Los Angeles region (Cervero & Gorham, 1995, p. 222). This was explained by the Los Angeles region's greater overall auto-orientation with its expansive area and freeway system, where while an origin may be located in a transit neighbourhood, the destination is more likely to be located in an auto neighbourhood.

A study looking at the differences between a conventional and a neo-traditional suburban neighbourhood in North Carolina's Research Triangle found that households in the neo-traditional neighbourhood generated 22.1% fewer auto trips and 23.4% fewer external trips, with a 305.5% increase in walking trips (Khattak & Rodriguez, 2005, p. 494). However, the conventional suburb had a greater pedestrian mode share for internal trips (84%) than the neo-traditional neighbourhood (63%) (Khattak & Rodriguez, 2005, p. 490). This was explained by the neo-traditional neighbourhood accommodating more utilitarian trips for shopping or services that are more likely to be made by vehicle, while walking trips in the conventional neighbourhood are made predominantly for recreation (Khattak & Rodriguez, 2005, p. 490). Furthermore, 78.4% of trips in the neo-traditional neighbourhood are made by vehicle, compared with 89.9% of trips in the conventional neighbourhood (Khattak & Rodriguez, 2005, p. 489). This difference is largely attributable to internal trip mode share, with 90% of external trips in both neighbourhoods being made by vehicle (Khattak & Rodriguez, 2005, p. 490). In addition to this, not accounting for work trips which may be biased to employment location proximity, households in the neo-traditional neighbourhood were found to travel 11.9 miles less per day (Khattak & Rodriguez, 2005, p. 495). Most interestingly, there was no statistically significant difference found in the total time spent travelling in either neighbourhood, signifying that neo-traditional households substituted faster travel modes for slower travel modes, but for shorter trips (Khattak & Rodriguez, 2005, p. 495).

In a similar experiment assessing two neighbourhoods close to each other in the San Francisco Bay Area, one old streetcar suburb and a post-war auto-oriented suburb, Robert Cervero and Carolyn Radisch found that residents of the streetcar suburb are five times as likely to make a non-work trip by walking or bicycle (Cervero & Radisch, 1996, p. 133). While this can be partially explained by its significantly shorter average non-work trip of 6.8 miles versus 11.2 miles, even trips of similar lengths had a lower auto mode share in the streetcar suburb than the auto-oriented neighbourhood (Cervero & Radisch, 1996, p. 134). Furthermore, the mean number of trips per day in each neighbourhood was very similar, and at the same number of cars per household, residents of the streetcar suburb "are about twice as likely to make a non-work trip by a non-auto mode" as the other neighbourhood (Cervero & Radisch, 1996, p. 136). The similar number of trips per day points to the increased mode share of walking and cycling replacing, rather than supplementing, vehicle trips (Cervero & Radisch, 1996, p. 137). Furthermore, "the relationship between vehicle ownership and non-work travel could very well be interrelated with neighborhood type," with neighbourhoods where it's easier to get around making it possible to have fewer cars (Cervero & Radisch, 1996, p. 140). With work trips, the streetcar suburb also exhibited a smaller single-car occupancy mode share, and had fewer trips to BART by vehicle, despite both neighbourhoods having an equal number of trips within a mile of the station (Cervero & Radisch, 1996, p. 137-138). In general, trips of the same length had vastly different modal splits (Cervero & Radisch, 1996, p. 140). By comparison, differences in transit modal share were minimal (Cervero & Radisch, 1996, p. 140).

A consistent difficulty in analyzing these studies is in separating the effects of street patterns from land use mix and self-selection into neighbourhoods that provide the opportunity to travel in the desired way. One study addressed this issue directly, by researching how travel behaviour changes when households change neighbourhoods. It found that when households move into more travel-accessible neighbourhoods, as defined by density, land-use mix, and street pattern, they tend to experience reductions in VKT and overall distance travelled (Krizek, 2003, p. 266). However, modal split does not significantly change, leading the author to conclude that household travel preferences remain fixed (Krizek, 2003, p. 277). A study by Randall Crane and Richard Crepeau concurs, finding "no evidence that the street network reduces either short or long non-work auto travel" (Crane & Crepeau, 1998, p. 226). The authors are also critical of the inaccurate methods used in other studies for studying street patterns in isolation without considering other design and travel characteristics such as street width, available infrastructure, density, or individual preference (Crane & Crepeau, 1998, p. 227).

With regards to mode share, walkability in particular receives significant attention in the study of suburban street patterns. In their analysis of specific connectivity measures, Wesley Marshall and Norman Garrick found that increased intersection density "was almost always associated with an increase in both of these nonmotorized mode shares" (Marshall & Garrick, 2010a, p. 109). Although increased intersection density has been cited as producing additional conflict points for pedestrians, Marshall and Garrick found that "the highest risk of fatal or severe road crashes occurs with a very low intersection density and safety outcomes improve as the intersection density increases" (Marshall & Garrick, 2010a, p. 114). Increased street density was also "generally associated with more walking and biking," and overall, a "dense, gridded street network with more urban street features is associated with much more walking and biking" (Marshall & Garrick, 2010a, p. 114). Focusing on the potential for walking rather than the mode split itself, a study in Calgary found that the "overall pattern of distribution of walkshed size corresponds closely to neighbourhood type, with the larger walksheds corresponding to the grid neighbourhoods, the mid-size walksheds corresponding to the warped grid, and the smallest walksheds corresponding to the curvilinear neighbourhoods" (Sandalack, Alanis Uribe, Eshghzadeh Zanjani, Shiell, McCormick, & Doyle-Baker, 2013, p. 252). A similar analysis of two Seattle neighbourhoods found that walking distances are approximately 40% longer in curvilinear layouts than in grid layouts (Randall & Baetz, 2001, p. 4). While actual pedestrian levels weren't studied, the other studies looked at point to this having an effect on travel behaviour**.** As the number of streets and intersections decreases, the length of routes between destinations increases, which reduces the size of a walkshed. And while many new suburban developments include a secondary trail system to provide more direct connections beyond the existing street network, the land use pattern often keeps destinations beyond walking distance (CMHC, n.d., p. 4). Considering the limited range the average person is willing to walk - seventy percent of Americans will walk 500 feet for daily errands, forty percent will walk a fifth of a mile, and only ten percent will walk half a mile – the accessibility of a mix of land uses is a critical second half to pedestrian route connectivity (Southworth, 1997, p. 38-39). The limitations of curvilinear street patterns in connectivity are its most commonly cited issue in the literature.

Findings relating to public transit are more complicated, as transit responds to road conditions in a similar way that personal automobiles do, while relying heavily on strong pedestrian connectivity to be accessible to its passengers. In their review of street connectivity measures, Marshall and Garrick found that increased intersection density was associated with increased transit use in cities with radial regional street systems and gridded neighbourhood street patterns, while having little or negative effects in all other street network types (Marshall & Garrick, 2010a, p. 109). A more comprehensive study focusing on transit mode share in work trips showed that warped parallel and mixed patterns are associated with an increase in transit ridership, while neither the curvilinear pattern nor the grid pattern showed any effect (Pasha, Rifaat, Tay, De Barros, 2016, p. 1020). The study also finds that increased length of high-speed roads is positively associated with increased transit ridership, while the length of arterials and local roads has no effect (Pasha et al., 2016, p. 1020). Similar to the results published by Marshall and Garrick, it finds no significant relationship between intersection density and transit mode share (Pasha et al., 2016, p. 1020).

Walkability was also commonly cited in research on the differences in the sense of community between neighbourhoods of different street types. For example, one study used a combination of GIS neighbourhood analysis and resident surveys to find that higher rates of walking for both transportation and recreation purposes was associated with an increased sense of community in Perth, Australia (French, Wood, Foster, Giles-Corti, Frank, & Learnihan, 2014, p. 682). A similar study done earlier found that every additional day of walking per week was associated with a 2.12% increase in sense of community (Wood, Frank, & Giles-Corti, 2010, p. 1384). The conditions that lead to more walking in the first place – directness of route to destinations, perceived street connectivity, infrastructure, and aesthetics – were all also independently linked with increased sense of community (French et al., 2014, p. 687; Wood et al., 2010, p. 1381). The discussion of the perception of connectivity in this article is important as it does not necessarily align with hard street network measurements. For example, if certain streets are considered difficult to cross, or certain paths are considered difficult to navigate, the perceived connectivity of a neighbourhood may be below the connectivity of a network as defined by the density and connectivity of streets and intersections. This is consistent with the finding that residents of quieter streets know more of their neighbourhoods than residents of busier streets, with the hypothesized explanation being that people reduce the amount of time they spend outside when a great amount of traffic and strangers is present (Wood et al., 2010, p. 1387). However, an acknowledged limitation of this research approach is the potential for reverse-causality with a greater sense of community encouraging neighbourhood residents to walk more (Wood et al., 2010, p. 1388). A similar survey-based study in Houston, Texas concurred with these broad results, finding that neighbourhoods that promoted walking and outdoor space were associated with more support given between neighbours, greater social ties, and a greater overall sense of neighbourhood attachment (Rogers & Sukolratanametee, 2009, p. 331). No significant differences were associated between the socio-demographic differences of the neighbourhoods assessed (Rogers & Sukolratanametee, 2009, p. 331). However, through its literature review, the study also noted the importance of spatial boundaries to creating a sense of community, writing that a well-defined boundary to a neighbourhood creates a stronger sense of place and resultant resident association with that place, and a stronger sense of community overall (Rogers & Sukolratanametee, 2009, p. 326). This runs somewhat in contrast to the writing of other authors on the segregation created by large arterial roads separating neighbourhoods, although there are other ways of establishing identifiable boundaries.

Safety

A large body of work has emerged in analyzing the traffic safety impacts of various street patterns. Assessing the severity of crashes between vehicles, it was found that "roads with less connectivity and frequent curves are marginally safer than traditional gridiron roads" and that, overall, the curvilinear design "decreases the injury risk of crashes involving two vehicles" compared to the grid pattern (Rifaat & Tay, 2009, pp. 64 & 66). Similarly, a separate study involving the same authors found that every street pattern other than the gridiron was associated with a reduction in the number of crashes (Rifaat, Tay, Perez, & De Barros, 2009, p. 248). However, the study had a significant, and acknowledged, limitation in that it did not consider crashes on several collector and arterial roads due to them often forming the boundaries between neighbourhoods (Rifaat et al., 2009, p. 251). Given that this class of road carries more traffic at higher speeds and with fewer intersections, its omission may skew the results of the study. A third study assessed the role of street patterns in determining pedestrian safety. It found that the curvilinear street pattern “increased the likelihood of injury and fatality” in vehicle-pedestrian crashes, while noting “no statistical difference between gridiron and warped parallel or between gridiron and mixed street patterns” (Rifaat, Tay, & de Barros, 2012, p. 348). This led the authors to conclude that the traditional grid is the preferred street pattern as it relates to reducing the severity of pedestrian injury in vehicle crashes (Rifaat et al., 2012, p. 349). The authors contrast this result to their own previous studies on the reduction of crash severity and frequency between vehicles in curvilinear street patterns. They explained this by noting that the increased number of intersections in grid patterns increase the potential for side impact crashes, which is a more vulnerable position for vehicle occupants. Conversely, for pedestrians, the curvilinear design reduces sight distance, which allows less time for drivers to slow down as well as for pedestrians to protect themselves (Rifaat et al., 2012, p. 350). All three articles used similar methods, analyzing all Calgary neighbourhoods using statistical models.

A study on twenty-four California cities divided into a safe and less safe category based on fatality rate in crashes found that street network density, as compared to connectivity, plays a bigger role in traffic safety (Marshall & Garrick, 2010b, p. 139). The study showed that while both the safe and less safe cities have similar connectivity indexes, total intersection density in less safe cities was thirty-eight percent lower than in the safer cities (Marshall & Garrick, 2010b, p. 139). Nonetheless, for both safe and less safe cities, rates of injuries, severe injuries, and fatalities all decrease as both the level of connectivity or network density increases (Marshall & Garrick, 2010b, p. 143). Another key difference noted between the two categories of cities related specifically to major road density, with less safe cities having lower figures. The authors hypothesized that with a fewer total number of roads, there might be a tendency to build much bigger roads to be able to accommodate the same amount of traffic volume (Marshall & Garrick, 2010b, p. 139). A follow-up article from the same authors added that based on a statistical model, “increasing intersection density from 144 to 225 intersections per square mile would result in a 15.6% reduction in total crashes, a 20.9% reduction in severe injury crashes, and a 42.5% reduction in fatal crashes” (Marshall & Garrick, 2011, p. 778). The additional decrease in prevalence of more severe injury types is hypothesized to be a result of lower average traffic speeds in networks with a greater number of intersections (Marshall & Garrick, 2011, p. 780). However, they also found that a higher connectivity index is associated with a higher risk of crashes of all severity levels, while a higher number of intersections between inter-neighbourhood citywide streets is also associated with more total crashes (Marshall & Garrick, 2011, p. 778). Increased VMT was associated with more total crashes but a similar number of fatal crashes, leading to the conclusion that "traffic volumes do not influence the expected number of fatal crashes as much as street network measures…or street design characteristics" do (Marshall & Garrick, 2011, p. 779). The authors also caution against interpreting their research as discrediting connected street patterns, adding that "highly connected street networks have the capacity to dissipate congestion from arterials, which allows cities to build arterials with fewer travel lanes and less travel on the citywide street network and be associated with lower crash rates," as is consistent with their findings on major road density (Marshall & Garrick, 2011, p. 780).

Street pattern measurements

A variety of different connectivity measures have been developed and used in studies done on neighbourhood street patterns. These include the total length of streets (Southworth, 1997), the number of blocks (Southworth, 1997), the number of access points (Southworth, 1997), the average distance between access points (Trudeau & Malloy, 2011), the number of loops and cul-de-sacs (Southworth, 1997), the number of intersections (Southworth, 1997; Marshall & Garrick, 2011; Trudeau & Malloy, 2011), a connectivity index measuring the ratio of street segments in between intersections and end-points to the total number of intersections and end-points (Kashef, 2011; Marshall & Garrick, 2011; Matthews & Turnbull, 2007), walkshed size (Ozbil, Peponis, & Stone, 2011), the number of dead-end intersections (Marshall & Garrick, 2011), among others. With each measure approaching street pattern assessment in different ways, no one measure can effectively sort different neighbourhoods into distinct street pattern typologies. Accordingly, the varied applicability of these measures and their ability to assess what they are intended to assess has been the subject of its own body of research.

One study stresses the need to separate these measures according to the specific aspect of street patterns they focus on. In particular, the authors lament the inability of other research to distinguish between measures of street density and street connectivity, or the interchangeable use of the terms (Marshall & Garrick, 2010a, p. 105). These indicators are not mutually dependent. A street network can be dense with a high road length per area with minimal connections between them, while a completely connected grid can have large distances between its streets. The authors tied street density to intersection density, as the more intersections exist in a given area, the more street length must ultimately be involved (Marshall & Garrick, 2010a, p. 105). However, this is an imperfect measurement given that it is technically possible to achieve a moderate street density with few intersections, such as through the use of a dense collection of parallel streets. They associated street connectivity to the connectivity index, which identifies a ratio between the number of street segments between intersections or endpoints to the number of intersections or endpoints (Marshall & Garrick, 2010a, p. 105). As referenced earlier, each of these measures has a different effect on the overall layout of a neighbourhood, as well as on the behaviour of its residents.

Intersection density has been referred to as the most used measure of street pattern analysis, due to the relative simplicity in its calculation as well as for its intuitive appeal (Stangl, 2015, p. 45). It is also the measure used by LEED for Neighbourhood Development (LEED-ND) which may further cement its popularity and ubiquity (Stangl & Guinn, 2011, p. 286). The connectivity index has also become popular in planning practice for similar reasons, as it is relatively simple to calculate and is effective at reducing the number of cul-de-sacs in a development, which provide an intuitive barrier to connectivity (Stangl, 2015, p. 45). This simplicity stands in contrast to the use of walksheds or route-directness tests. While this may be the most foolproof measure in explicitly outlining the accessibility of a given neighbourhood, it is severely hampered by the subjectivity and technical complexity involved in selecting points to calculate from and synthesizing the results (Stangl & Guinn, 2011, p. 288). The simplicity of measures like intersection density, however, leave them vulnerable to exploitation, with the study demonstrating multiple examples of visually disconnected street patterns that would pass or come close to passing intersection density requirements (Stnagl & Guinn, 2011, pp. 291-293).

Another study carried out similar tests with three of the most common street network measures – the connectivity index, intersection density, and street density – to demonstrate their limitations (Knight & Marshall, 2015, p. 257). The authors concluded that each "metric was shown to be a non-linear function of both area and geometry," with each one yielding different scores when the same street pattern was reduced or increased in size to fit a given area (Knight & Marshall, 2015, p. 257). In the study, multiple theoretical pure grid patterns were tested using these measures at multiple parcel sizes. Both intersection density and street density were found to have an inverse relationship with the area of the parcel (Knight & Marshall, 2015, p. 249).

That is, as area increased, grids of any size had reduced intersection density and street density measurements. The connectivity index has the opposite issue: as area was reduced, all tested grids provided scores below their intuitive assessment (Knight & Marshall, 2015, p. 249). For example, at a parcel area of 30 acres, a grid of 400x400 feet would receive a connectivity index of 1.4, which forms the threshold line between a 'rural' and 'suburban' street pattern as defined by the Virginia Department of Transportation (Knight & Marshall, 2015, pp. 241 & 251). While the authors concede the limitation in their study in that they did not assess any street patterns other than the pure grid, they argue that the inability of these common street network measures to accurately assess a grid pattern makes the study of their effects on more complex street patterns irrelevant (Knight & Marshall, 2015, p. 257). They conclude by cautioning that while it may be important to develop a strict regulatory mechanism that enforces neighbourhood connectivity, the use of metrics that do not accurately accomplish this may result in negative consequences and uncertainty both for neighbourhood developers as well as approving authorities (Knight & Marshall, 2015, p. 257).

Similar concerns have been raised about the use of block-based measurements of connectivity such as block area, block face length, block perimeter, and block density maximums or averages (Stangl, 2015, p. 45). The logic behind block-based measurements rests on the notion that a block is an impassable area. Therefore, as block size increases, it creates a greater barrier to movement (Stangl, 2015, p. 45). However, the measure chosen can lead to inconsistencies in enforcing a minimum standard of connectivity. For example, while block perimeter standards are intended to provide flexibility in the geometry of blocks created, this flexibility can result in severely impeded access through the use of long and narrow blocks (Stangl, 2015, p. 46). A similar problem occurs when block area is used, as a long and narrow block will result in a smaller area than one with more equal block face lengths, despite being arguably more obstructive (Stangl, 2015, p. 47). Though this may be mitigated through a combination of both block perimeter measures as well as block face lengths, this is complicated by the issues associated with block face lengths themselves (Stangl, 2015, p. 47). While block face measures are accurate in a pure grid, because they measure between through-streets given that bays and cul-de-sacs do not divide blocks, this approach cannot address the overall configuration of blocks in an area and can exaggerate the length of blocks in modified grids (Stangl, 2015, p. 47). Finally, block density is heavily skewed by the placement of neighbourhood boundaries because blocks cut by a boundary would not be counted (Stangl, 2015, p. 52). This would create inconsistencies between neighbourhoods delineated by railways or major arterials, which would likely have an intact internal block system, and neighbourhoods with more continuous block patterns, as in pre-war grid neighbourhoods, where less-distinct collector roads often form the boundaries between neighbourhoods (Stangl, 2015, p. 52). Furthermore, this would also skew the use of block density depending on the area studied, as larger neighbourhoods would have a fewer proportion of their blocks cut off than smaller neighbourhoods.

Overall, street network assessment metrics can be useful, but must be approached with caution. This applies both to the analysis of neighbourhoods as well as of the measures' effects on resident behaviour. These measures are not baseless, and can be part of a larger framework of neighbourhood street network evaluation. However, given their limitations and potential for inaccuracy, they should be used in combination with other methods, including more qualitative and experiential analysis. I approached this research project with this in mind, using street network measures to assess Winnipeg neighbourhoods at a base level, and conducting interviews partially to clarify and contextualize the resultant data and themes.

Context

Though this research is intended to be applicable to all urban areas experiencing peripheral growth, it is important to acknowledge the context of Winnipeg on which the research was focused. Winnipeg is a mid-sized Canadian city with a municipal population of 705,244 and a metropolitan population of 778,489 as of the 2016 census (Statistics Canada, 2016). Over the last few decades the population of Winnipeg has grown slowly or stayed stable, but more recently its growth has increased (City of Winnipeg, 2011a). From 2011 to 2016, the Winnipeg Census Metropolitan Area saw a growth rate of 6.6%, or an average of 1.32% per year (Statistics Canada, 2016).

As a Prairie city with no major natural boundaries, there are no notable impediments to its urban expansion. Surrounding non-urban land is predominantly agricultural in use, relatively inexpensive, and has limited topography. There are no urban growth boundaries. These factors make greenfield development an attractive form of growth in Winnipeg, as developers are able to purchase large tracts of land and develop them with far fewer hurdles than in urban infill.

Furthermore, it has a relatively small urban footprint, and the newest developments on its edge remain within a convenient commuting distance of the city centre. Given the lower property values in Winnipeg, the lower cost of denser forms of housing are not as influential for the market as in other cities, and there is high demand from homebuyers for new, large single-detached homes in new suburban neighbourhoods. Given the physical and market considerations, suburban expansion remains the dominant form of growth.

Several unique local circumstances can affect the specific shape that this suburban development takes. One is the radial arterial street system in the city, which expands outwards from the city centre with limited routes connecting them outside of the developed area. This means that suburban subdivisions must typically rely exclusively on these radial roads for access, and they are designed accordingly, with these roads often forming neighbourhood boundaries. The second is the seigneurial river lot system in Winnipeg, where many agricultural lots are shaped in long thin strips coming off a river. As with arterial roads, these lot lines can often form subdivision parcel boundaries, and neighbourhood design must conform to this. In addition to this, an extensive heavy railway system in the urban area also forms many neighbourhood boundaries. Third, given the flat topography of Winnipeg and the surrounding area, water retention ponds are required in any new suburban developments, which the internal street and lot configuration must respond to.

Altogether, this context within which Winnipeg is found impacts both the propensity for growth to be predominantly accommodated through suburban expansion, and the layout this development takes. However, with context also being changed by time, there remains substantial variation in street pattern layouts between different Winnipeg neighbourhoods.

It is difficult to track this variation over time as the slow growth in Winnipeg results in individual subdivisions taking upwards of a decade to build out fully. However, maps included in the City of Winnipeg's official development plan, *OurWinnipeg*, provide a general overview of its neighbourhoods and the era within which they were developed (City of Winnipeg, 2011b). Figure 4 divides the city into "mature communities," which are established older neighbourhoods, "recent communities" that begin with the first suburban subdivisions developed, and "new communities," which are undeveloped lands targeted as sites for future expansion. Figure 5 highlights the areas of the city developed between 1950 and 1976. This

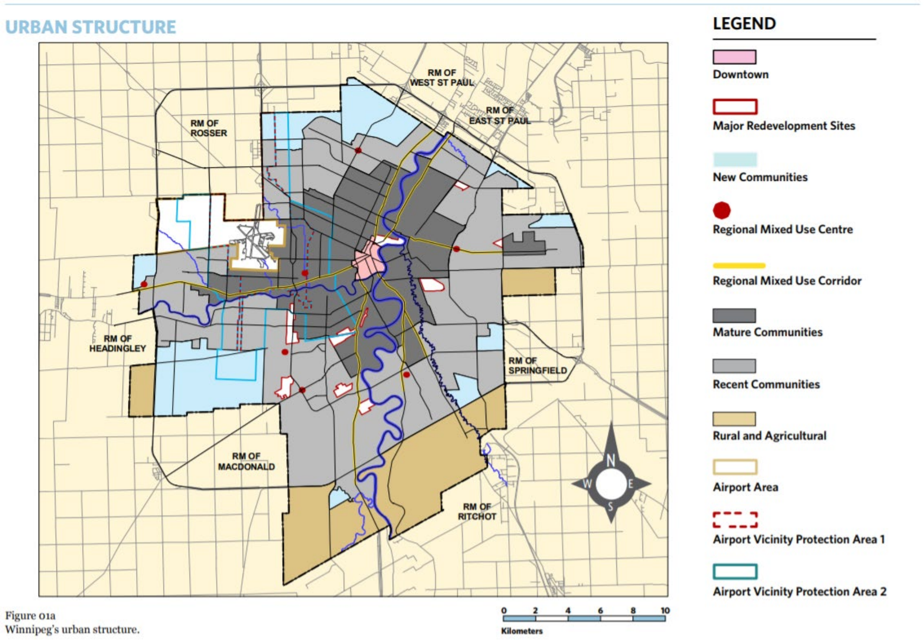


Figure 4 - Map illustrating the urban structure of Winnipeg.

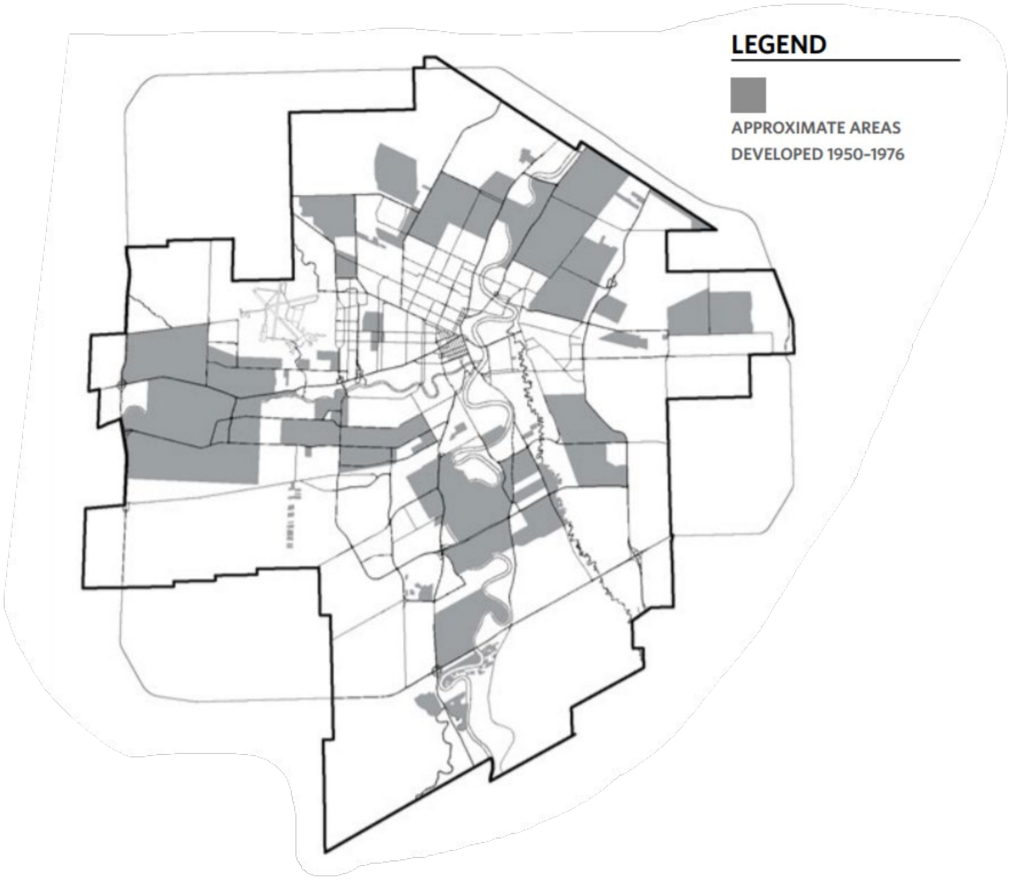


Figure 5 - Map illustrating the approximate areas developed in Winnipeg between 1950 and 1976.

provides additional context into the spatial analysis that follows, as it hints towards the broader street pattern differences between different development eras. However, even between the neighbourhoods shown, there can be substantial differences in street network layout.

Results

Mapping Analysis

As described in the "Methods" section, five street pattern measures were used to quantitatively assess different Winnipeg neighbourhoods and their street patterns, and make comparisons between them. Two measures – street density and intersection density – considered network density, one measure – the connectivity index – considered network connectivity, and two other measures – external connection density and average distance between external connections – considered connectivity outside the neighbourhood.

The street density map (Figure 6) employs one of the measures used in LEED-ND analysis (Knight & Marshall, 2015, p. 244). The rationale behind its use is simple: theoretically, the more total length of road there is in an area, the more opportunity there is for travel and connections. However, although this measure does not consider road width and therefore does not reflect the amount of land dedicated to roads accurately, an increase in the length of road in an area also corresponds with an increase in the total surface area given to roads rather than developable land, which is one of the key impacts developers seek to avoid (Southworth & Owens, 1993, p. 275). In addition to the construction costs and loss of sellable land, the "amount of land devoted to streets relates directly to infrastructure costs," which further increases the cost of a denser street network (p. 279). This is particularly true given that as the increased land that a greater length of streets takes up raises costs, at the same developable density it also splits those costs among a smaller number of homes. Similarly, once an area is developed, an increase in street length as well as underground infrastructure increases maintenance costs for government. In other words, an increased street density creates land and cost inefficiencies, while at the same time being an important indicator for accessibility, despite its imperfections as a measurement.

The street density map was created by taking the sum of the length of streets in each neighbourhood and dividing them by the total neighbourhood area. The data was then split into the five categories published using natural breaks as determined by the GIS. Certain neighbourhoods were not included because they have no road networks at all. Because these omitted neighbourhoods consist entirely of industrial, heavily agricultural, or currently

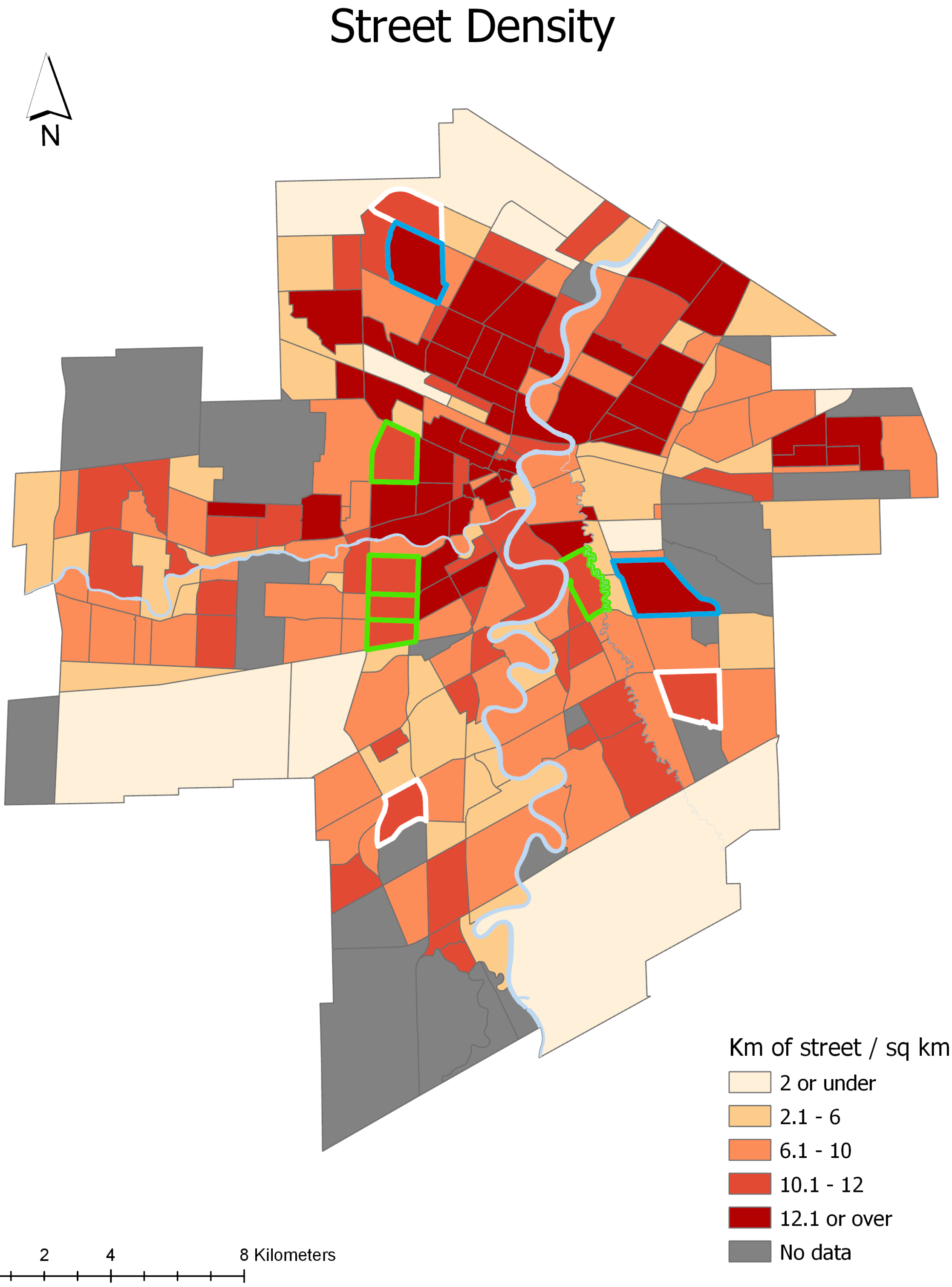


Figure 6 – Map illustrating the total length of streets per square kilometre in each City of Winnipeg-defined neighbourhood.

developing neighbourhoods, I did not consider this to be a concern. Another issue is to do with the inclusion of green space and water features in the total area of a neighbourhood. While parks and retention ponds were deducted from neighbourhood areas, this was not possible with other features such as golf courses, which skews the result of some neighbourhoods. While comparisons between neighbourhoods remain largely accurate, certain such complications remain.

Nonetheless, the street density map produces some interesting results. For one, many more recent neighbourhoods have similar street densities to older post-war neighbourhoods, and even some pre-war neighbourhoods. For example, neighbourhoods such as Bridgwater Forest, Amber Trails, and Island Lakes (in white on map) have street densities in the same range as Sargent Park, River Heights, and Glenwood (in green on map). A likely cause of this is the larger average lot size in older neighbourhoods. Nevertheless, older gridded neighbourhoods generally have the highest street densities in the city. This supports the broader claim that gridded neighbourhoods are more accessible, while also confirming that they are costlier to develop and maintain. However, even here there are some surprising results, in which 'model' traditional urban residential neighbourhoods fall into lower street density categories than some post-war subdivisions. For example, the mature grid neighbourhoods listed have a lower street density than Windsor Park and the Maples (in blue on map).

As with street density, intersection density is intended to serve as a measure of network density, rather than connectivity. However, it also addresses connectivity to a degree, given that the more intersections there are, the more opportunity there is to turn and the more likely it is for any given route to be more direct (Stangl, 2015, p. 45). It is calculated by dividing the number of intersections in a neighbourhood by the total area of the neighbourhood. Cul-de-sacs and intersections leading to cul-de-sacs only are not counted as intersections given that they do not contribute to the overall travel network or provide for multiple route options (Figure 7). Similarly to street density, an increase in intersection density may have the negative effect of reducing land and cost efficiency, as a greater number of intersections implies a greater number

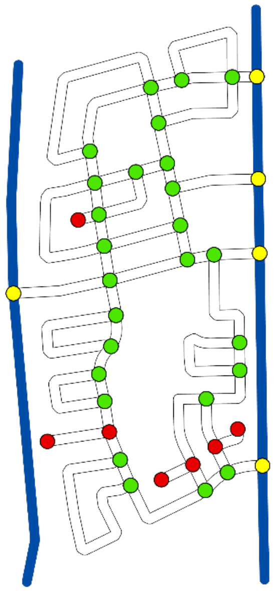


Figure 7 - Nodes in green are counted as intersections, while nodes in red (cul-de-sacs) and yellow (neighbourhood boundary) are not.

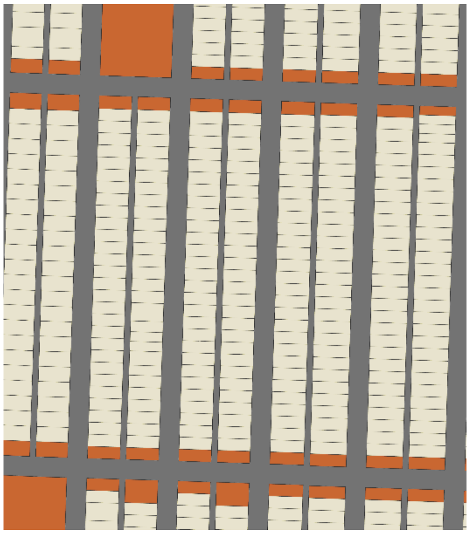
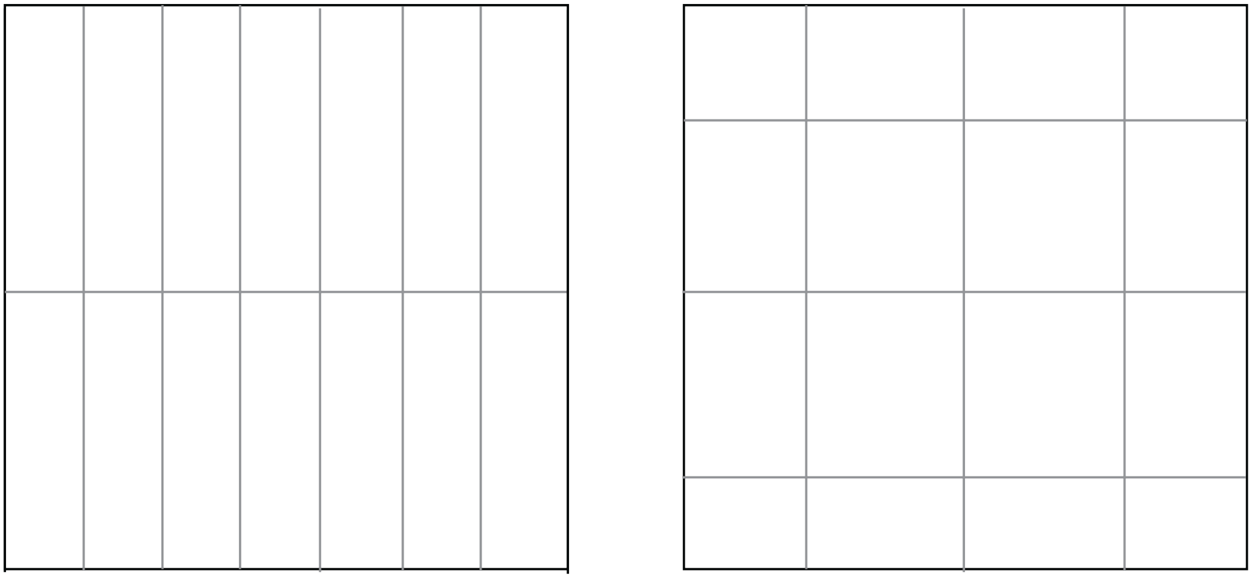


Figure 8 - One street-fronting lots in tan, with 'flanking' lots exposed to two streets in burnt orange.

of streets. More connections take up more land while also increasing flankage, wherein a lot may be flanked by a street on more than one side (Figure 8). If the purpose of a street is the creation of lots, connecting streets that do not enable additional lots of their own and run along the sides of lots already fronting onto another street are a pure construction and land expense. This reduces land efficiency and creates sections of road without direct revenue generation on them. However, while street density and intersection density are similar and can often be interrelated, this is not always the case. A street network can have a dense street layout and a sparse intersection density, or it could have a sparse street density and a dense collection of intersections (Figure 9).



Higher street density - lower intersection density

Lower street density - higher intersection density

Figure 9 - The street network on the left has a higher total length of street and lower number of intersections. The street network on the right has a lower total length of streets, but a higher number of intersections in the same area.

In all, the intersection density map (Figure 10) displays an initial similarity to the street density map, but with some key differences. While generally older and more central neighbourhoods had higher intersection densities, the effect was not as pronounced as it was with street density. In fact, an even greater number of more recent and less gridded neighbourhoods had higher scores than was found with street density. Once again, newer neighbourhoods such as

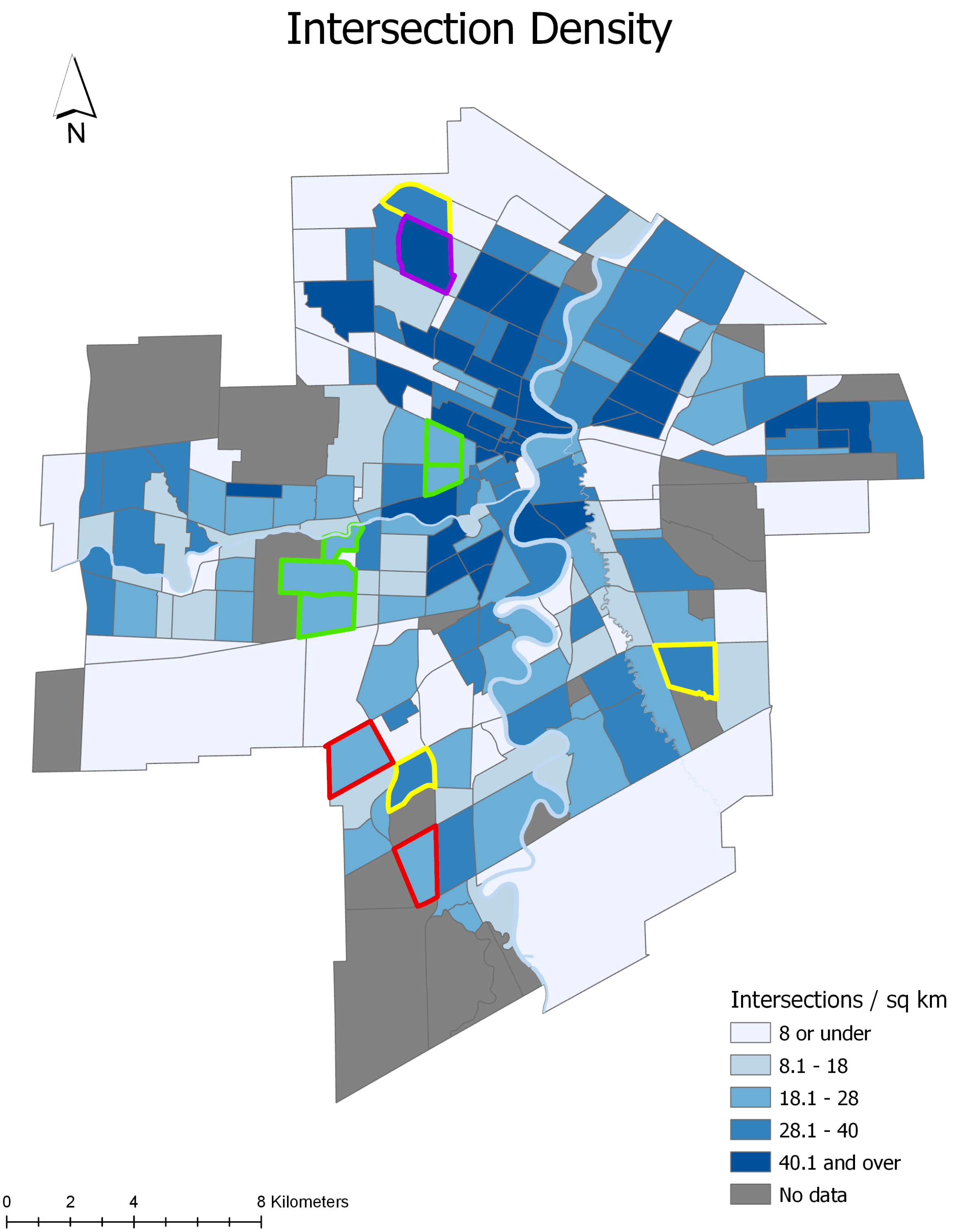


Figure 10 - Map illustrating the number of intersections per square kilometre in each City of Winnipeg-defined neighbourhood.

Whyte Ridge and South Pointe (red on map) had similar intersection densities to Daniel McIntyre, St. Matthews, and the Tuxedo neighbourhoods (green on map), while neighbourhoods such as Bridgwater Forest, Island Lakes, and Amber Trails (yellow on map) were even higher. Certain post-war neighbourhoods in particularly scored in the highest category, such as the Maples (purple on map).

There are several possible explanations for this. One is that high intersection density can be achieved with more mixed and curvilinear street patterns, and that the specific characteristics used in these patterns is more important than the general pattern type itself. For example, while Daniel McIntyre and St. Matthews are developed on a pure grid, their long blocks reduce the number of intersections by area. However, the specific parameters employed in intersection density calculations could also be a source of these somewhat unexpected results.

Most significantly, while cul-de-sacs and intersections leading exclusively to them are not counted as intersections, intersections leading to bays are. Though bays allow for multiple route options, they nonetheless do not contribute to broader travel accessibility within a neighbourhood and serve only their own residents. Their exclusion in intersection density calculations would therefore reduce the relative parity the map displays between mature central neighbourhoods and more recent suburban ones. In addition to this, some research makes a distinction between three-way and four-way intersections, with the logic being that a greater number of four-way intersections creates more opportunity for full movement between streets (Ozbil, Peponis, & Stone, 2011, p. 126). However, not only would performing separate intersection density calculations for bays, three-way, and four-way intersections create more complexity, it also assumes a hierarchy of intersections which may not exist in real-world contexts. More restrictive tool parameters may reward more truly accessible networks, but they may also lead to a definition of accessible as how closely a given street pattern resembles a grid rather than how generally navigable it is. While a grid does provide for "the shortest trip lengths and the largest number of route options," and a grid-based analysis may therefore be insightful in assessing the degree to which a street network resembles a grid, grid-based analysis would also mask the other differences between street patterns depending on the specific parameters used (Southworth & Owens, 1993, p. 279).

In contrast to street and intersection density, the connectivity index map is intended to measure the degree of connectivity between the streets that exist, rather than count how much total road there is (Figure 13). This means that a sparse grid network, for example, with long distances between intersections would still receive a high score (Figure 11). The connectivity index works by focusing on the ratio between 'links' and 'nodes.' Nodes include intersections, including intersections leading to cul-de-sacs, as well as cul-de-sacs themselves. Links are the individual street segments that are separated by nodes. Dividing the number of links by the number of nodes in an area provides the connectivity. The higher the score, the more connected an area is deemed to be. Links leading to an area boundary are counted, while the nodes that would be located on a boundary are not (Figure 12). This benefits areas with more external connections, rather than penalizing them with an equal number of nodes. Overall, the connectivity index works by the number of links rising by more than the number of nodes when new connections are added (Figure 14**)**. It also penalizes cul-de-sacs, which receive a ratio of one link to two nodes. As with street density and intersection density, the connectivity index has been criticized for inaccuracy in assessing the same grid street pattern at different scales (Knight & Marshall, 2015, p. 257). However, it has also been one of the most extensively used measures in both planning practice and research (Stangl, 2015, p. 45). It is typically evaluated dichotomously, with a score of 1.4 being considered as connected, and anything below it as disconnected (Marshall & Garrick, 2010a, p. 105; Matthews & Turnbull, 2007, p. 116).

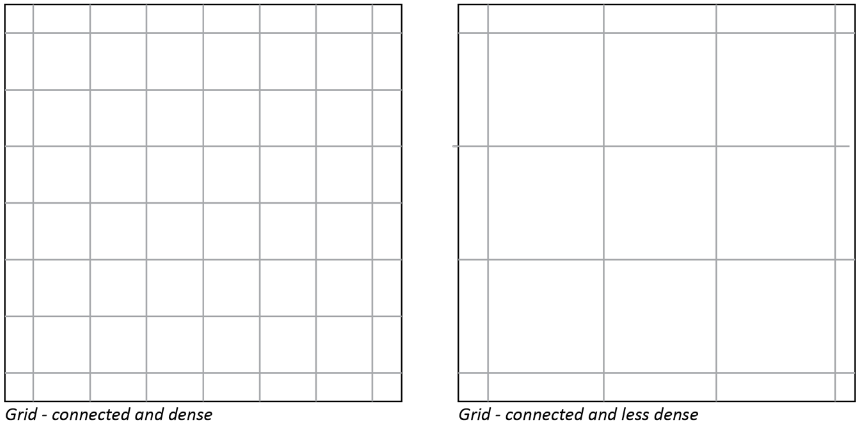


Figure 11 - At the same scale, the grid on the right would receive a high connectivity score, despite being more circuitous to navigate.

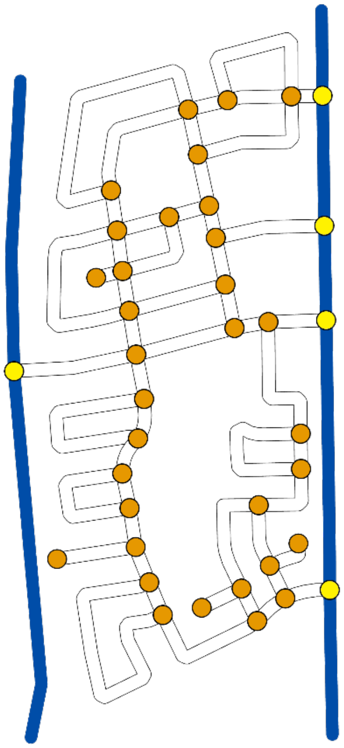


Figure 12 - Orange intersections and cul-de-sacs are counted, while yellow intersections with the neighbourhood boundary are not.

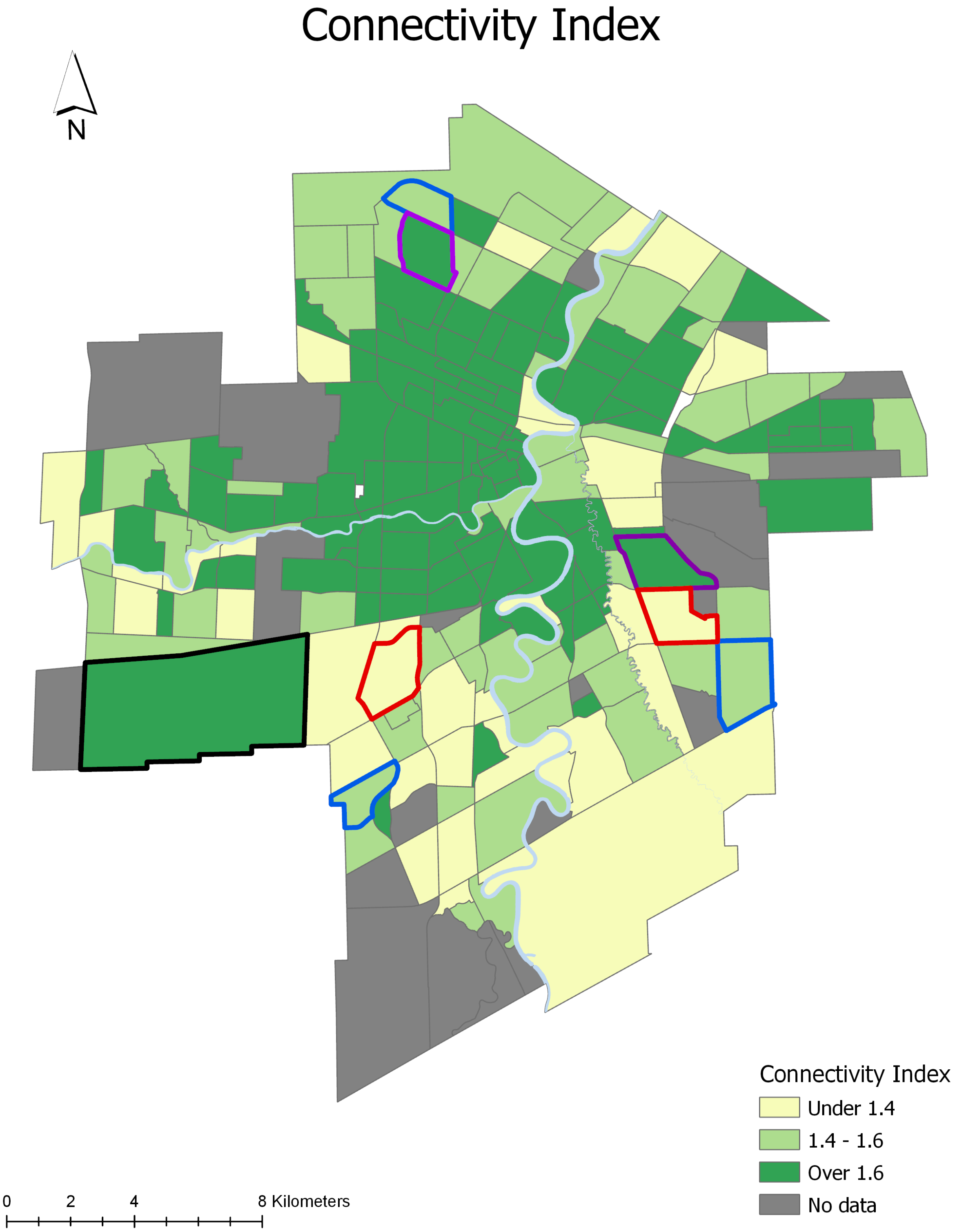


Figure 13 - Map illustrating the connectivity of each City of Winnipeg-defined neighbourhood as determined by dividing the number of road links by the number of intersections and cul-de-sacs in each.

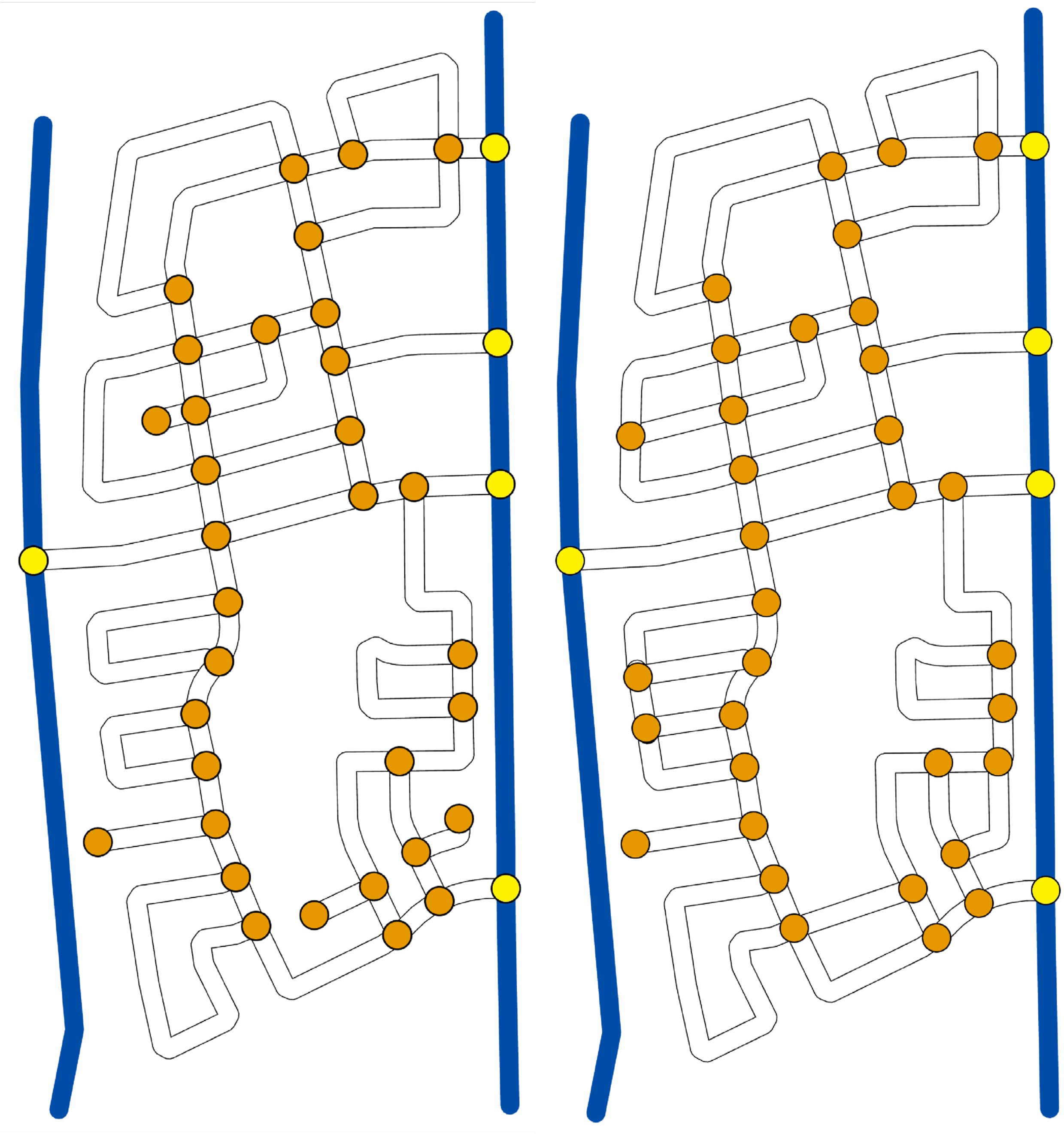


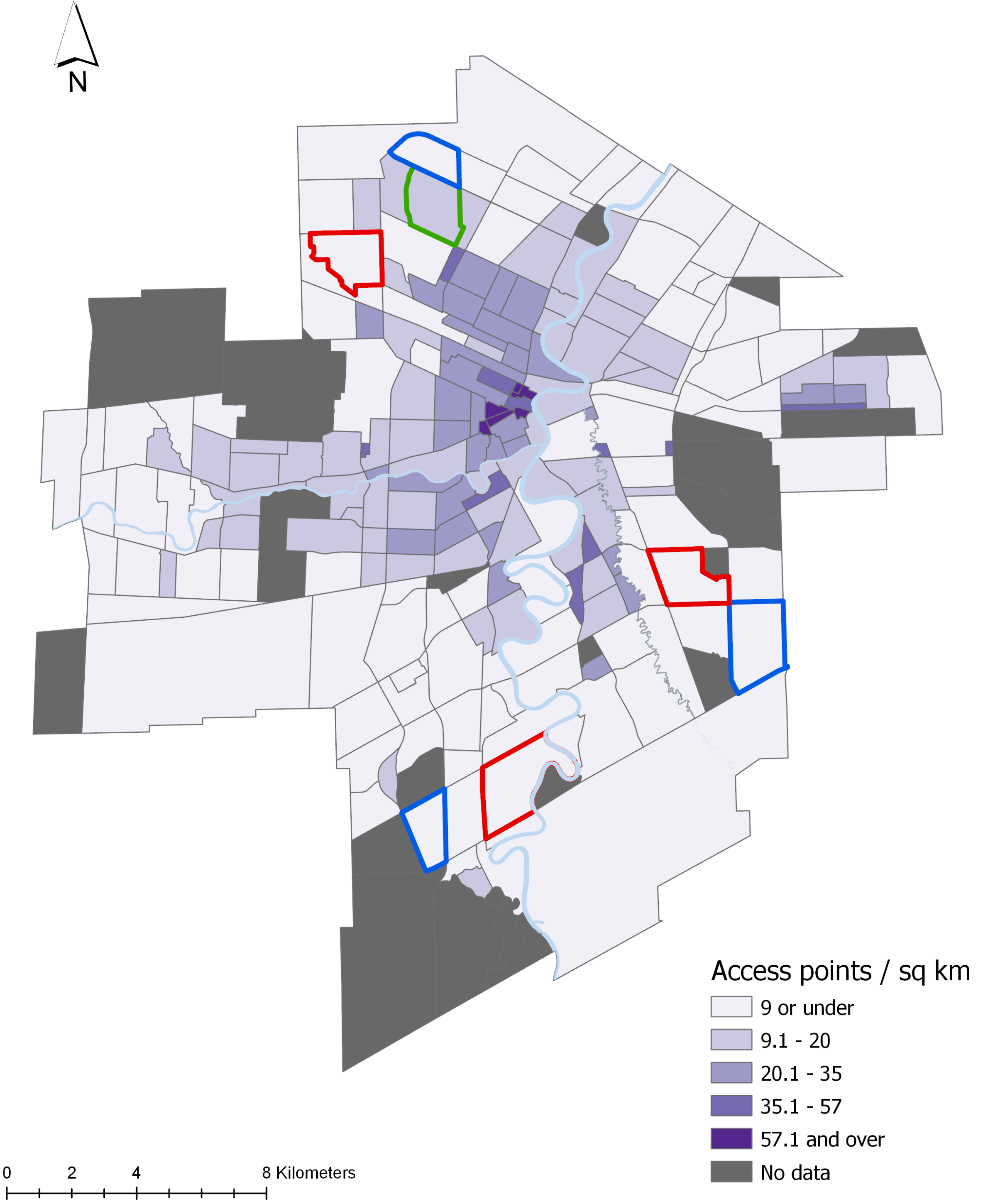
Figure 14 - The street pattern on the left has 51 links and 33 nodes, for a connectivity index of 1.55. The street pattern on the right bridges bays and extends cul-de-sacs into through-streets. It has 56 links and 34 nodes for a connectivity index of 1.65.

However, used as a regulatory mechanism, the Virginia Department of Transportation divides connectivity index scores into three (Knight & Marshall, 2015, p. 243):

- < 1.4 as rural
- ≥ 1.4 and ≤ 1.6 as suburban
- > 1.6 as compact

I chose to use this same scale given its conformity to the standard of use of 1.4 as a key indicator, but with additional detail to further distinguish between neighbourhoods. The connectivity index map showed a much clearer distinction between older inner-city neighbourhoods and more recent suburban subdivisions. The vast majority of mature neighbourhoods had scores above 1.6. Likewise, aside from exceptions including the Maples and Windsor Park (purple on map), few post-war neighbourhoods scored in the highest category. While this greater contrast may reflect the use of three categorizations rather than five, it nevertheless allows for meaningful comparisons between neighbourhoods. For instance, the connectivity index map supports the claim that the latest suburban developments have greater connectivity than older subdivisions. Though there are again exceptions, neighbourhoods including Bridgwater Lakes, Sage Creek and Amber Trails (blue on map) all had higher connectivity indexes than older subdivisions such as Linden Woods and Southdale (red on map). The connectivity index as a measure is beneficial in that it does not discriminate against the sizes of open spaces, for example, as it does not measure street density. However, it does penalize the location of open space, as open space located on the edge of a neighbourhood would not interfere with connections, while open space in the middle of a street network would. The map also shows the limitations of the connectivity index, with some largely rural areas receiving ‘compact’ scores (black on map).

The access point density map focuses on neighbourhoods’ external connectivity rather than their internal connectivity (Figure 15). It is measured by dividing the number of connection points to the boundary of the neighbourhood by the total area of the neighbourhood. The more external connection points there are, the more seamlessly the neighbourhood fits into its surroundings and the city overall. Conversely, fewer external access points make a neighbourhood more insulated. However, high external connectivity can also present issues for developers and neighbourhood residents. It can bring non-local traffic in the neighbourhood, depending on the internal street network. It may also contribute to an eroded neighbourhood



Access Point Density

Figure 15 - Map illustrating the number of access points per square kilometre in each City of Winnipeg-defined neighbourhood.

identity and sense of place as its borders become more passable (Rogers & Sukolratanametee, 2009, p. 326).

Calculating access point density presented a unique set of challenges. One example is where two internal streets intersect at the neighbourhood boundary. In this situation, I counted it based on the street network outside the neighbourhood. If the two internal streets led to only one accessible road, it was counted as one connection given that there was still only one point of entry. If, however, both internal streets extended beyond the neighbourhood boundary, they would be counted as two connections, as they allow access to two external connection options. Another example is the issue presented with hard boundaries such as railways and especially rivers, as they reduce the potential for external connections. In particular, this discriminates against neighbourhoods bounded by hard boundaries such as rivers or railways. In spite of these issues, a clear pattern between the city's neighbourhoods emerges. Gridded street patterns are the clearest benefactors of this measure, which is to be expected given that every street forms external connection points on each of its ends. The high scores of grid neighbourhoods also allude to the importance of street density in this measure. While theoretically streets connecting outside the neighbourhood can be largely independent of the internal network, in practice a greater internal street density has the potential to increase the external access point density, especially in grid pattern neighbourhoods. In contrast to the street network density and connectivity analyses done previously, there was little difference between older subdivisions and the most recent suburban developments. Both early post-war neighbourhoods, such as Windsor Park, Fort Richmond, and Tyndall Park (red on map), as well as more recent developments, such as Amber Trails, South Pointe, and Sage Creek (blue on map), fall into the lowest category for external connection density. This shows that while the most recent suburban developments have tended to incorporate denser and more connected street networks into their designs, the use of a limited number of external access points has persisted. It is possible that this is because external connectivity has been a less salient consideration over time, whether for developers, the market, or government, and therefore has not seen the same progression as other aspects of street network. This may also be due to the broader road structure in Winnipeg, in which suburban neighbourhoods are often bordered by large arterials that are more difficult to connect into. This is a likely explanation for exceptions, such as the Maples (purple on map) falling into a higher category as it lacks a major arterial on any of its sides, which facilitates a greater total number of external access points.

A similar pattern emerges in the map of the average distance between external connection points, although there is more variation between neighbourhoods of the same era (Figure 16). This external connectivity measurement also typically shows greater connectivity in grid pattern neighbourhoods. While the positive and negative effects of a more externally connected neighbourhood, as measured by a lower distance between external access points, are identical to those of high external connection point density, this measure focuses on external access points based on the perimeter rather than the area of a neighbourhood. If more external connections are added, the average distance between them is reduced.

The calculation of external connection distance involves a great set of challenges. While all the constraints around the counting of individual access points apply, determining the distance between them poses its own limitations. While determining the distance between adjacent or corner access points is fairly straight forward, calculating the distance between the furthest access points in a neighbourhood bordered by a hard boundary like a railway or a river is difficult in that each possible calculation option involves unique benefits and drawbacks. Counting along the boundary line has to been done manually and ignore the internal street network altogether. Counting along the connected face of the neighbourhood is the simplest, but is the least faithful to the true distance between connection points and disadvantages neighbourhoods with bridges. Counting along the outer internal collector street gave a more accurate distance but depended on the internal network structure and ignored streets between the collector and the barrier. Counting along the longest possible street length through the use of local streets would maximize the distance between the connection points, but this distance would also be longer than the distance along the boundary line and would create greater distortion based on the internal street networks. With these conflicts in consideration, I settled on counting the connecting distance via the outer internal collector street. While it does distort the true perimeter distance between connection points and variably affects specific street patterns, it most closely reflects the likely travel patterns of residents living further from the accessible neighbourhood boundary without artificially elongating travel routes through winding local streets. When this was not possible, due to a narrow neighbourhood not having an internal

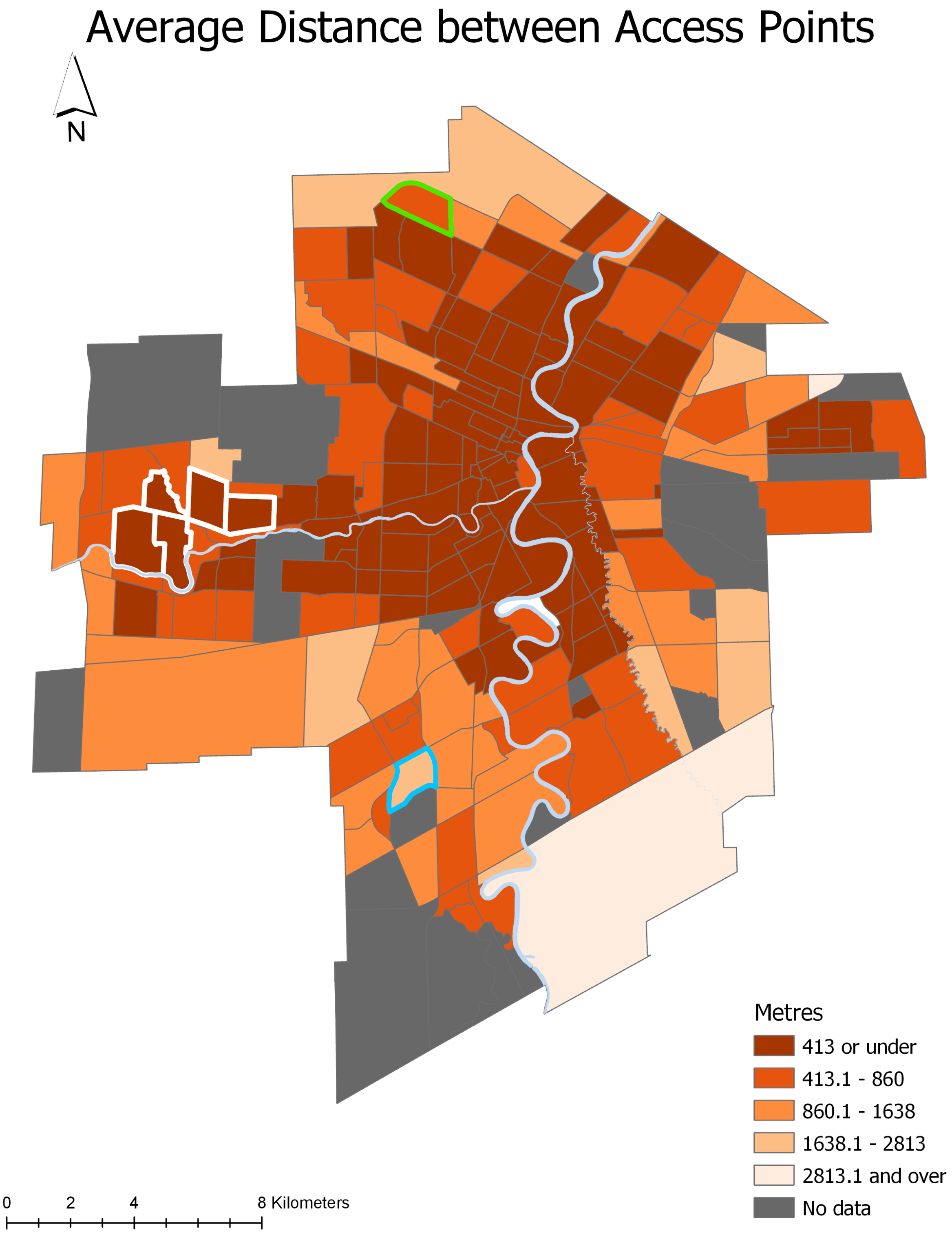


Figure 16 - Map illustrating the average distance between external connection points in each City of Winnipeg-defined neighbourhood

collector system of its own, the distance between the further external access point was counted along the road boundary, as the only solution remaining.

Overall, while this map also demonstrates higher external connectivity in older neighbourhoods, it shows more variation between newer neighbourhoods as well. However, there is not a strong a pattern in neighbourhood types or eras as there are in the street density or connectivity maps. In newer neighbourhoods, the differences appear predicated on what forms the boundaries of the neighbourhoods. Neighbourhoods adjacent to railways, rivers, and major arterials typically exhibit reduced external connectivity. However, this does not hold constant for Winnipeg's mature neighbourhoods. This suggests that, barriers aside, neighbourhoods have been able to compensate for being hemmed in on one side with a higher number of external connections overall. This is largely accomplished through the use of the grid pattern, though even neighbourhoods with other street patterns have been able to avoid it. This additional variation can be explained by the bordering road system. While Amber Trails (green on map) is surrounded by agricultural land on its west and north, it has minor arterials on both its south and its east, which allows it to incorporate a greater number of connections to them. Similarly, older subdivisions running West on Portage Avenue (white on map) may have been developed at a time where there were fewer restrictions on arterial road connections than there are now, which allowed for a greater number of external access points, and therefore a lower average distance between them. Conversely, Bridgwater Forest (blue on map) is surrounded by major arterials on three of its sides and by agricultural land, which severely limits its potential external connectivity and results in a higher average distance. However, there remains a fairly significant amount of variation between neighbourhoods with similar contexts, which may either reflect the preferences of the individual developers, or a flaw in the average distance between external connections measure or calculation.

Interviews

While the mapping analysis provided important context into the differences between street patterns in Winnipeg and the concrete way in which these differences are expressed in the varied measures used, they do not allow for much insight into the factors that have led to these differences. In other words, while GIS analysis shows how neighbourhood street patterns compare to one another, it does not provide much insight into the factors that lead to these differences, and to the layout of street networks in developments today.

Interviews with the people involved in suburban development fill this gap directly. In speaking to land developer staff (all but one of who had a professional degree and experience working in urban planning), private planning consultants, engineers, and city planners, I was able to receive direct input on what drives their neighbourhood planning and design process and the factors involved in the specific outcomes. For the sake of clarity, I will refer to all organizations represented as "respondents." For example, if in a joint interview two individuals made similar comments, they will be referred to as a single respondent.

Why curvilinear?

The primary question that I sought to answer was why neighbourhood street patterns in contemporary greenfield developments look the way they do. In developing an answer, I hoped to determine how alternative street patterns might be considered in this context. In considering how street pattern changes could address the negative externalities associated with contemporary patterns, what goals and interests they would need to accommodate, and how they would need to be implemented, it is possible to establish a more informed assessment of the potential for changes to our cities' growing street networks.

Efficiency

In asking about the primary factors and goals involved in street network design, a fairly diverse set of responses was collected, but one stood out as the most dominant: efficiency. Being raised by every respondent, and as the first consideration by almost all of them, this confirms what was found in existing literature (CMHC, n.d., p.2; Marshall & Garrick, 2010a, p. 104; Southworth & Owens, 1993, p. 276). Developer 5 argued that "the loop-and-lollipop [pattern] is the ultimate expression of efficiency." More specifically, efficiency referred to varied, but complementary, interests. The overarching factor was the efficient use of land, wherein the design of the street system would be done so as to minimize the total surface area spent on roadway and maximize the total land area available for development. The logic to this is simple: the more land that can be reserved for development, the more lots can be surveyed and sold, and the more total profit can be created through the development of a parcel. The measurement of this efficiency was universally spoken of in terms of lot frontage.

The developers surveyed measure this in different ways. Developer 4 described the process as a simple calculation of frontage density, or total length of frontage per area. Developer 1 spoke of a different formula which responds to the street network more directly. It takes the form of a street frontage ratio, in which efficiency is measured by dividing the total length of frontage by the total length of road. If the most efficient theoretical example, in which a single road of infinite length is fronted onto by lots on each side, the ratio would be 2/1, or 2. Conversely, a street that has less frontage, due to passing by a park or a lot's side, would receive a lower ratio. In all, the higher the frontage-street ratio is, the more efficient the layout is. In either case, the more frontage that can be extracted from a parcel, the more efficient the design of that parcel is.

This is manifested in street network design in several ways. One is the use of long blocks, which was emphasized by Developer 1. Every connection between parallel streets takes up land for the road, and also creates flankage, which reduces possible frontage and increases expenses**.** In figure 17, adding an additional street improves neighbourhood connectivity, but it also uses up land that could have been used for housing. For example, in the original illustration on the left, 321 lots are laid out, while the illustration on the right allows for 297 lots. The second is the use of the curvilinear street pattern, which can maximize frontage and minimize flankage by maintaining long blocks while allowing them to turn, as opposed to a grid pattern which requires corner lots to flank. This is because lots can be laid out coming off of bends rather than flank

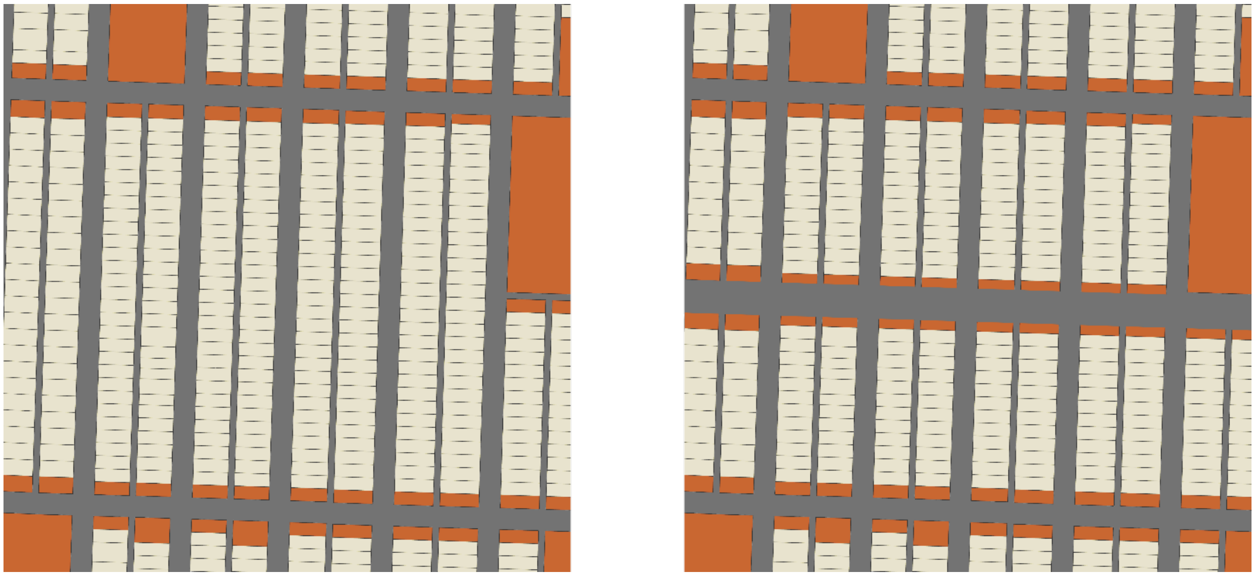


Figure 17 - Adding a road connection not only consumes developable space, but also reduces the number of single-fronting lots (yellow) and increasing the number of flanking lots (burnt orange).

onto corners. In Figure 18, the illustration on the left demonstrates how unconnected bays can maximize frontage through the use of lots coming off bends. Though the triangular lot shapes reduce the land available for other lots, connecting the bays as per the illustration on the right only creates one additional lot, while requiring a significant length of additional roadway to be built. The advantages of cul-de-sacs have the same principle, as further described by Developer 1. By allowing lots to encircle the street on its end, a frontage ratio higher than 2 can be achieved, while the cul-de-sac being extended into a connection through to the next street would eliminate that opportunity, bring the amount of frontage down, and introduce flankage (Figure 19).

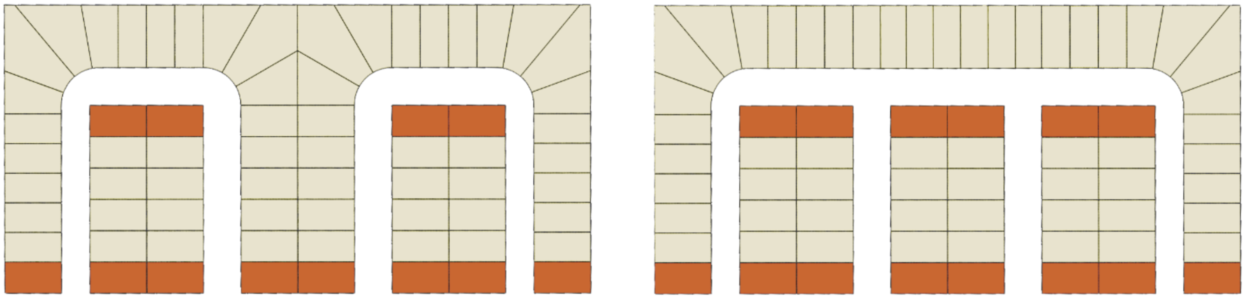


Figure 18 - The pattern on the right only includes one more lot than the one on the left, but requires a relatively large road and service extension, and creates flankage on two additional lots (burnt orange).

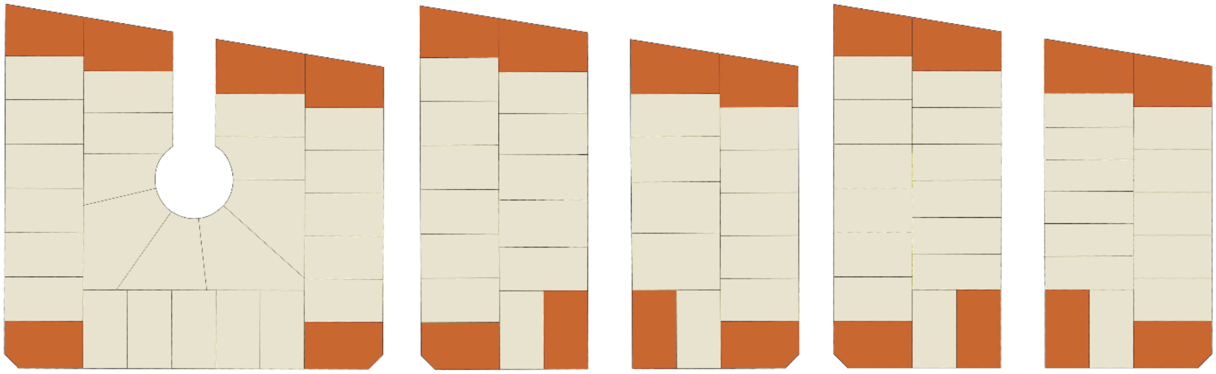


Figure 19 - By continuing the cul-de-sac through to the next street in the second pattern, one lot is lost and flankage is created for two (burnt). If lots are narrowed as in the third diagram, two extra lots are created as compared to the cul-de-sac pattern.

However, not all respondents agree with the use of these tools to maximize efficiency. Developer 4 spoke against the curvilinear pattern, and bays and cul-de-sacs specifically, in relation to its effect on efficiency. Engineer 1 voiced a similar assessment. Their argument is that the relationship between street network layout and efficiency depends heavily on the lot sizes being produced. With wider lots, curvilinear layouts allow for a greater total number of lots to be produced. Developer 1, who maintained general support for the curvilinear design and its efficiency, concurred with this development unprompted, explaining that “we’re going to see moving forward that lot sizes are getting smaller and smaller to the point that cul-de-sacs are probably going to be fewer and fewer.” However, there is a minimum width that a lot must have to functionally be able to be placed on a curve or cul-de-sac. All respondents noted the average width of lots having decreased significantly in recent years. This leaves developers with a choice between fronting fewer wide lots around a cul-de-sac, or fronting more narrow lots onto a straight street. For developers who prefer narrower lots, the latter alternative allows for a greater total number of lots to be created. In addition to this, the triangular lot shapes that arise from placement on curves or cul-de-sacs are larger than typical rectangular lots, which further reduces efficiency as more land is used by fewer lots.

Another important consideration in efficiency is not only the amount of developable land created, but the cost of the services associated with that land as well. Being able to reduce the amount of road needed allows for less money to be spent on the road construction and pavement itself. This is not only reflected in the road layout, but in its classification as well. Because collector roads accommodate a greater amount of traffic, they are mandated to be built wider by the City’s development standards, which makes them more expensive to build than local streets. In addition to this, because development standards do not permit private driveway access onto collector streets, houses that front onto them must either do so through a frontage road (sometimes referred to as a jug handle), or a back lane (Figure 20). This adds additional roadway and pavement to construction, and therefore to cost. Furthermore, because piped services such as water, waste, and storm drainage follow the road network to reach dwellings, having a shorter

Figure 9 - Frontage roads and back lanes used along collector roads in Bridgwater Forest.

length of roads also allows for a shorter, and therefore cheaper, length of piped services underground.

Developer 1 and Developer 4 both discussed this efficiency objective as a positive for the City as well, given that all infrastructure is transferred to its ownership upon completion of a project, with the exception of private condominium complexes. If the total amount of roadway and piped services in an area is reduced, there is less physical infrastructure for the City to maintain, as well as replace in the distant future. In addition to this, a greater number of lots per area contributes to a greater amount of total taxable property as well. Developer 1 and Developer 4 described the relationship as one where when they are efficient, the City can be efficient as well.

Marketability

Another key goal identified in neighbourhood development was marketability, or the ability to produce both individual lots as well as overall communities that homebuyers would want to purchase into. Developer 1 emphasized this as a process in which they do not create the market, but chase it. In other words, developers aim to create the housing product that consumers will be attracted to, rather than create the product they believe people should be living in. In fact, meeting this consumer demand was a source of fairly significant concern in the responses of all developers. Because the development process occurs over a long time period, developers are planning for housing stock that will not enter the market for years after. As such, they have to predict what homebuyers will want in the future. Providing the proportion of different lot sizes (small or large, rectangular or triangular), housing types (single-unit, duplex, townhouse, apartment), and locations (cul-de-sac, back lane, etc.) that allows for subdivisions to sell is a challenge developers attempt to meet with every new development. In particular, several respondents including City Planner 1, Developer 1 and Developer 4 noted that the housing market and consumer demand has been changing rapidly in approximately the last 5 years, which increases the difficulty of meeting it in designing new neighbourhoods.

Street pattern design is important for this process in a number of ways. One is product diversity, or having a sufficient assortment of different housing types that can accommodate multiple sources of demand. Developer 4 and Planning Consultant 1 used the same metaphor of the stock portfolio, in which a diversity of investments allows for the overall portfolio to remain healthy as stronger investments balance out the weaker ones. This relates directly to the curvilinear street patterns, although different developers had opposing views on this. Developer 1 and Developer 3 noted the importance of corner bay and cul-de-sac lots, as their larger size made them more attractive to a certain market segment. Developer 1 named the resultant pie-shaped lots as typically the first ones to sell. In this context, laying out streets that allow for a sufficient number of these lots to be created, such as bays and cul-de-sacs, becomes a specific goal in the overall design process. However, Developer 4 had an opposite perspective and experience, saying that they seek to avoid pie-shaped lots in their layouts. Not only was this due to the inefficiencies they create, where the extra yard space could have been made use of by being consolidated into more lots, but because of the difficulty they have in selling them as well. All respondents noted the decline in purchasing power and the rise in costs in real estate, which is the reason for lot widths having decreased over time. This makes larger pie-shaped lots a less accessible product. In fact, Developer 4 claimed that cul-de-sac lots are the last to sell in their developments.

More broadly, however, street network design can improve marketability at the neighbourhood scale. Multiple respondents discussed the importance of traffic calming, noise reduction, and a sense of privacy in their street layouts. While this is most directly achieved by the inclusion of bays and cul-de-sacs, the curvilinear design was credited as being able to accomplish these goals more generally. Twists and bends serve to reduce traffic speeds and noise, while a focus on incorporating more local streets maximizes privacy. Developer 3 emphasized this point in particular, arguing that homebuyers perceive winding roads as safer and more secure. They added that these curves work to reduce the visible length of the street and make it feel more private. Overall, there is a focus on reducing traffic on local streets, but also on reducing non-local traffic in general.

This has both a marketing as well as a practical side to it. From a marketing standpoint the minimization of traffic through a neighbourhood improves the sense of safety, quiet, and privacy for residents. More practically, additional traffic through a neighbourhood would require increased road construction costs. With all development plans having to undergo a transportation study in order to assess both the network's ability to accommodate projected traffic volumes as well as determine required road standards, street patterns that discourage external traffic are preferable to developers. Because roads with higher projected traffic counts have to be built wider based on the City's development standards, if a neighbourhood street becomes attractive to non-resident travelers it would have to be built to a higher standard, which would cost more. Overall, developers aim to develop street patterns that meet the traffic requirements of their neighbourhoods, without excess capacity for non-local traffic. Engineer 1 described this from a developer's perspective, asking why they should build their interior roads wider to accommodate an adjacent development when through-traffic should be concentrated on the arterial streets. They also stated that from a traffic perspective the aim of the street design is to direct neighbourhood residents to city-wide arterials "as fast and efficiently as you can."

Connectivity

Connectivity, overall, was highlighted as an important consideration in street network layout. By far the most dominant theme in connectivity raised was walkability. Planning Consultant 1 cited improved active transportation connectivity as one of the most significant distinctions between contemporary subdivisions and older greenfield developments. Developers and planners alike acknowledged the criticism of curvilinear street patterns as impeding walkability but spoke favourably of recent attempts to address this, most notably through a focus on pedestrian and cycling trails. These trails are credited with creating a much more connected pedestrian system, in which where vehicles may be routed circuitously, but pedestrians can travel directly. The trail systems were also credited for contributing towards external connectivity by providing connection points to the larger city-wide trail network, which was named by Planning Consultant 1 as something that receives much more attention than in the past. In addition to the trails, one developer emphasized their commitment to sidewalks, noting that they went above the necessary requirements to further improve pedestrian connectivity. Being able to walk to transit service was also frequently raised as an important connectivity component, with every respondent citing the City guideline of the majority of residences being with a 400-metre distance of a bus stop.

Engineer 1 explained that this was addressed through street network layout by designing the collector road to loop within the subdivision. Not only does this maximize the number of local streets while minimizing the travel distance to the arterial, it also typically brings the neighbourhood within 400 metres of transit service given that bus routes operate on collector streets. Connectivity for transit itself, however, was only brought up by one respondent, Developer 3. They recognized the difficulty in operating transit in an inward-facing curvilinear street pattern but noted the conflict between expediting transit operation and reducing non-local traffic cutting through the neighbourhood. They argued that if a more direct route for transit was provided through a neighbourhood it would also become a shortcut for non-local traffic, which would both increase traffic in the neighbourhood as well as contribute to the snowballing of rising construction costs as the road standard would rise. Inter-neighbourhood connectivity as a whole was referred to in a similar way by multiple respondents. While connections between neighbourhoods were deemed important, respondents tended to prefer for them to consist of shorter links rather than continuous routes. This is a result of both the desire to reduce through-traffic, as well as a practical response to the use of loops as the most common internal collector street structure.

Development guidelines and engineering requirements

City development guidelines and engineering requirements were implicated in both large-scale and small-scale street network configuration decisions. At the larger scale, park and stormwater retention pond requirements form the greatest constraint. For parks, multiple respondents noted that the City parks department strongly prefers the parks dedication requirement to be met through the use of fewer but larger parks, with a single expansive park possibly being the ideal. This relates to maintenance as, for example, it is easier to mow a neighbourhood's park system in one visit than it is to travel between several smaller parks. This also facilitates the creation of long continuous trail systems in neighbourhoods. However, Engineer 1 noted that in the past the parks department had an opposite stance in which it preferred multiple smaller parks to bring them closer to residents. This may partially explain the differences noted in the mapping analysis section between suburban neighbourhoods from different time periods. The preference for large parks affects the street network design as it creates an obstacle to street connections.

Retention ponds have a similar effect. In order to reduce costs, developers construct long and narrow ponds. This brings the most amount of residences to relatively proximity to them, which allows developers to build shorter, smaller, and therefore cheaper pipes between houses and ponds. An effort is also made for the ponds to form a close chain with each other. Because the ponds need to form an interconnected system, this allows for the use of shorter and smaller pipes between them as well. Along with parks, this contributes to a large area which is difficult to intersect with streets.

Engineering restrictions also inhibit the number of access points a neighbourhood may create with arterial roads. Given that arterial roads often create the boundaries between new subdivisions on all four sides, this severely limits their external connectivity. However, multiple respondents noted the traffic issues present with older arterial roads with a high number of connections, with St. Mary's Road being cited as an example by Engineer 1 and Planning Consultant 1. The high number of connections from local streets to St. Mary's Road creates more conflict points and slows traffic as vehicles turn, particularly when turning left. On a smaller scale, the restrictions on direct driveway access to collector streets force the use of frontage roads and back lanes, which add additional costs to developers. As such, these requirements may also contribute to the specific street network designs created.

More broadly, the City of Winnipeg Transportation Standards play an influential role in street pattern design. Roads that are anticipated to accommodate more traffic are required to be built to a higher standard, which namely affects the minimum intersection spacing and width of the road (City of Winnipeg, 2012, p. 22). Developer 4 noted that these expected traffic levels are determined based on a transportation study that is required in the development process of all new subdivisions, and includes street network assessment. These standards, along with a desire to reduce external traffic overall, may contribute both to an attempt to concentrate traffic on a limited number of roads and to reduce the attractiveness of those roads as connections within a neighbourhood. In other words, larger roads built within a neighbourhood are intended to accommodate virtually all internal traffic while serving as little external traffic as possible. Transportation standards are reflected in this in that if a road is more conducive to external traffic, it will be required to be built to a higher standard, which may then attract further traffic to it, resulting in a positive feedback loop. Developer 4 described this process in reference to the challenge in providing through-streets within a neighbourhood to improve its external connectivity:

> *Yeah I mean more connections are nice, but it's an operational thing for the adjacent roads.…we wouldn't probably want to build a residential collector that connects those two points directly because it will inevitably become a shortcut. And if we build a shortcut road, okay, but then it'll be a collector that no one wants to live on and we'll back homes onto it, and it's going to be busy so we're going to build a berm, so you know, no one's…this isn't going to be a pleasant street to be part of the neighbourhood. It's going to create a boundary within the neighbourhood. So if we connect those points by something like this, connected by another collector here, it's not an obvious shortcut, and it can be a smaller collector, it doesn't have to support as much of the regional traffic, which*

can stick on the bigger roads. We can put homes fronting onto it. We can treat it in a different way, and it can be part of the neighbourhood, rather than a 4-lane divided collector with wood fences and berms as far as you can see that's just cutting up the neighbourhood.

I think what we don't want to do is create…turn local collectors into alternatives for regional transportation. And a straight, short route does that. But if we do that, then we have to accept that the scale of those roads are going to increase. So if we can do this and show that it's not going attract many trips off the boundary roads, the scale of that road can be smaller. If we put a straight line through and model it, there's going to be a certain number of people that are trying to get from over here to here, that's now going to be a shorter route that'll be quicker. The traffic volume's going to go up, the scale of the road's going to get bigger, the size of the intersection's going to get bigger.

Design

The final major goal in street pattern layout identified was creating an aesthetic appeal to the neighbourhood. Several respondents concurred with literature that described the grid as boring and monotonous, and spoke of curvilinear street patterns as bringing visual interest into a neighbourhood. Neighbourhoods such as Bridgwater Lakes were identified specifically as ones where the street pattern contributes a design element that creates a sense of place. More generally, the potential for the use of deliberate curves to highlight specific features and sightlines was identified as an advantage of the curvilinear pattern.

Overall, developers appeared interested in both the economic case that their street patterns contribute to as well as in the adherence to sustainability, design, urban planning principles, and general livability. While some developers did note that there can be conflict between economically-oriented and design-oriented street pattern layouts, and that different developers found themselves at different points on the spectrum between them, respondents also all voiced their general satisfaction with the quality of their suburban developments. The private planning consultants expressed a similar view. Overall, street layout was identified as a key consideration in neighbourhood development by all respondents.

How the curvilinear street pattern reacts to specific issues

Transit

Respondents were then prompted to elaborate on specific considerations involved in street network layout. The first was transit. There was little additional discussion on transit aside from the 400-metre walksheds identified earlier. Developer 4 went as far as to say that they "don't really think a ton about transit because it's never been an issue." Nonetheless, multiple respondents noted that Winnipeg Transit provides their input on subdivision plans as they are processed for approval, though Planning Consultant 1 stated that they "don't think there's a great deal of emphasis on transit dictating how the road network works."

Several respondents also discussed their integration of denser residential uses along transit routes as a form of transit service support. City Planner 1 affirmed the importance of higher density in proximity to transit and identified it as one of the City's priorities in subdivision evaluation as a way of supporting transit. In a broader sense, Planning Consultant 1 noted that if transit connectivity is a goal, it can be best accommodated through the City's precinct planning process. This is a policy framework in which expansive greenfield areas that will be accommodating multiple individual subdivisions are comprehensively planned between all relevant stakeholders to create a more cohesive final collection of neighbourhoods. This would allow the City as well as the various developers with landholdings in an area to identify the specific connections that would need to be serviced along with a network configuration that would achieve it. However, Developer 4 commented that the precinct plan may not be sufficiently large-scale or definitive, and voiced their support for the development of a city-wide transit master plan that lays out the goals and expectations of transit service and its accommodation in greenfield development.

Land use

The concentration of density on transit routes, which operate on collector road systems in subdivisions, was also noted as one of the explicit ways in which street layout and land use intersect. This occurs due to the complementary relationship between transit and density, but also simply because the larger roads are better capable of handling the additional traffic generated by denser land uses. Furthermore, it eliminates the need for a frontage road or back lane to be constructed. For the most part, however, respondents stated that land use generally follows the road network. Planning Consultant 1 elaborated by saying that a neighbourhood designer "might have an overall goal in terms of land use that [they] might want to achieve, but how it's actually laid out within [their] site would be driven by roads or providing more roads to achieve those goals". However, there can be exceptions in circumstances where a specific land use outcome needs to be accommodated, such as in an industrial area where buildings need to be of a certain size and where the road network needs to be able to accommodate a high level of traffic. Speaking about the distribution of land uses, Developer 4 believed that a grid pattern was more conducive to a deliberate transition of uses and density. For instance, one block could be high density, the next could be medium density, and the one behind it low density, which achieves a stepping-down effect.

Future neighbourhood evolution

When asked if the long-term future evolution of the neighbourhood regarding its potential for intensification or land use changes was considered in the street network design process, all respondents answered by saying that it is not. Numerous reasons were given for this. The dominant one was that upon development completion developers are typically left with no remaining land ownership in the neighbourhood. This inherently reduces their interest in the way a neighbourhood may change in the future given that they are likely to not be involved in that process. Furthermore, to be prepared for potential intensification or land use changes the infrastructure would likely have to be built to a higher initial standard, which would increase developers' costs but benefit outside parties. Additionally, two developers noted that it is simply too difficult to predict how a neighbourhood may change or what the development and market contexts will be to be able to account for that change at the initial design stage. Finally, Planning Consultant 1 added that the political difficulty of adding density or land use mix in established neighbourhoods makes it unlikely for significant change to be a salient future consideration. Developer 3 echoed this, saying that while the neighbourhoods may not be able to handle large-scale redevelopment, gentler densification such as the introduction of secondary suites would be able to be accommodated by the road and pipe infrastructure.

One large-scale opportunity for redevelopment was consistently raised however: commercial centres. They were highlighted for hosting buildings of cheap construction and relatively short lifespans as well as for consisting largely of underutilized surface parking. As retail trends change and the need for infill grows, older strip malls and similar developments were identified as prime opportunities for accommodating growth in mature neighbourhoods. Developer 4 and Developer 5 argued that if future densification and infill was a priority, however, that a grid street pattern would best accommodate it. This is because the grid provides for more redevelopment opportunities, given that its lack of curves and cul-de-sacs accommodate multiple-unit buildings more easily. Developer 5 admitted that they believe that aesthetically higher density simply fits in better on a grid. However, other respondents voiced the opposite opinion, stating that no individual street network configuration, including the curvilinear pattern, necessarily precludes higher-density development from being accommodated.

Regulations

When asked if there were existing City regulatory constraints that prevented neighbourhood designers from creating the street patterns they truly wanted to, a wide variety of individual policy inconveniences were identified, but all respondents named them as being minor and as not affecting their overall street network layouts. City Planner 1 agreed, stating that they believed that developers have significant freedom in creating the street patterns they want. Nonetheless, some more influential constraints were named, such as the preference for larger parks and engineering requirements, specifically the inability to front directly onto collector streets and the inability to include more connections to arterial streets. However, it was unclear as to whether the loosening of these restrictions would change street pattern preferences in any meaningful way, as other considerations such as the desire to reduce external traffic in a neighbourhood can coincide with them. Developer 4 also expressed an interest in more detailed City-led master plans regarding considerations such as parks, active transportation, infrastructure, and transit. They believed that there is a great deal of uncertainty in what is specifically required of them in any given greenfield parcel, and that being able to refer to a greater structure that represents the City's goals would allow them to more effectively plan their neighbourhoods around them. More broadly, Developer 4 spoke of the need for greater communication between different City departments, as there can sometimes be conflicting requests or assessments of neighbourhood development proposals.

Finally, all respondents were asked their thoughts on the fused grid pattern developed by Fanis Grammenos of the CMHC (CMHC, 2007; Figures 21 & 22). The intent of the fused grid is to accommodate the advantages of both the grid and curvilinear designs, through a larger gridded arterial and collector street system that hosts bay and cul-de-sac-based neighbourhoods within it. I introduced it in interviews as a possible example of a street pattern that might address the goals of developers while also addressing the issues associated with the curvilinear layouts. Every

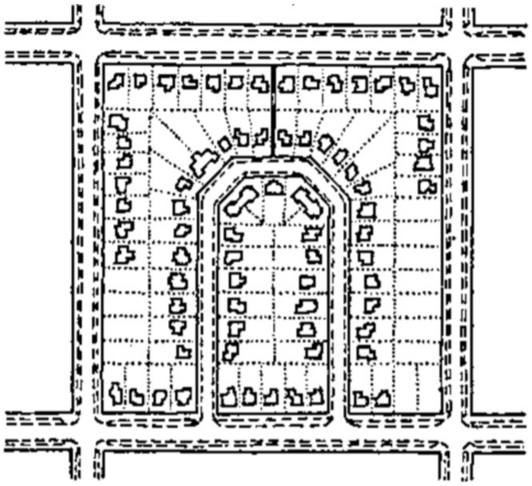


Figure 21 – Fused grid-like design (Southworth & Ben-Joseph, 1995, p. 74)

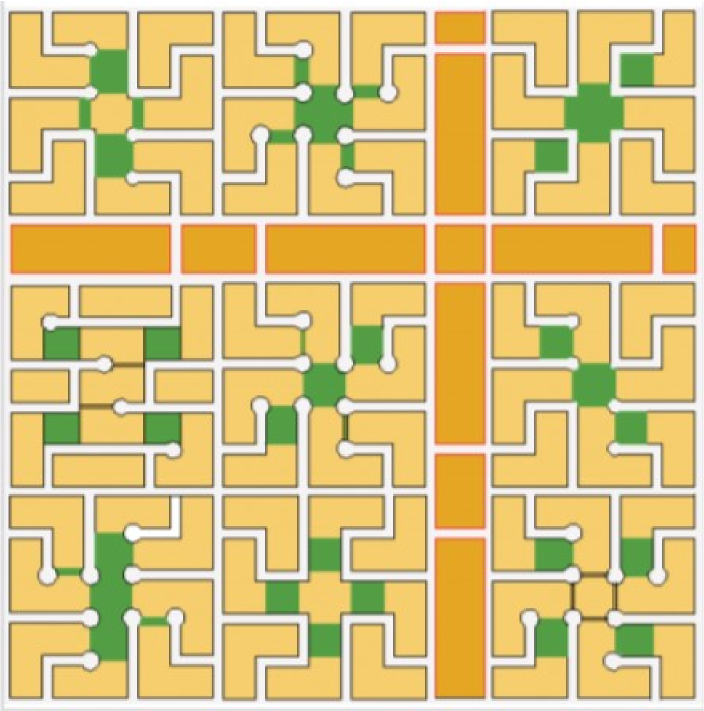


Figure 22 - Fused grid pattern as designed by Fanis Grammenos (CMHC, 2008, p. 2).

respondent expressed a prior awareness of the fused grid concept. The overall response was mixed. Its advantages named included its greater dispersion of traffic and route choices, piped services provision efficiency, land use efficiency, transit service accommodation, and flexibility. Developer 1 noted it would be highly marketable as well, as it combines the quiet of bays and cul-de-sacs with close proximity to direct commuter routes. However, a number of issues were identified as well. In general, there were concerns about the larger number of busier streets affecting the neighbourhood character, the likely increase in collector street-fronting lots, the questionable necessity of such a large number of collector streets, and its hindering of extensive park and trail systems. Specific to the Winnipeg context, issues were raised about the fused grid's ability to incorporate water retention ponds and the difficulty of imposing a grid on a city with a largely radial arterial street system and river lot agricultural pattern. Developer 1 clarified that even in greenfield areas, because large arterial roads are often built out beyond the existing developed area and individual lots determine the overall developments typically being based on "fairly odd shaped segments." Overall, while curiosity towards the concept was expressed and there were no cases of immediate aversion, there was little excitement for it either. In all, though all respondents – including developers and planners – had insights on improvements that could be made to street patterns into the future, they all generally expressed a general contentedness with street pattern design as it is currently developed.

Discussion

Neighbourhood street pattern typology

The results of the mapping analysis ultimately address two questions: how neighbourhoods of different eras and street patterns compare to each other, and how effective the different street pattern measures are. These findings will be discussed in turn.

The five maps analyzed concurrently do well to sort the different neighbourhoods into a typology that reflects the core distinctions between them. I have classified this typology into four categories:

1. *Grid neighbourhoods*

Grid neighbourhoods are predominantly pre-war communities that developed rapidly in the early growth of Winnipeg. They are characterized by rectangular blocks of nearly equal length and frequent connections outside the neighbourhood (Figure 23). They are typically measured at a high street density, high intersection density and a high connectivity index. Examples include Daniel McIntyre, Jefferson, Victoria West, Glenwood, and the River Heights neighbourhoods.

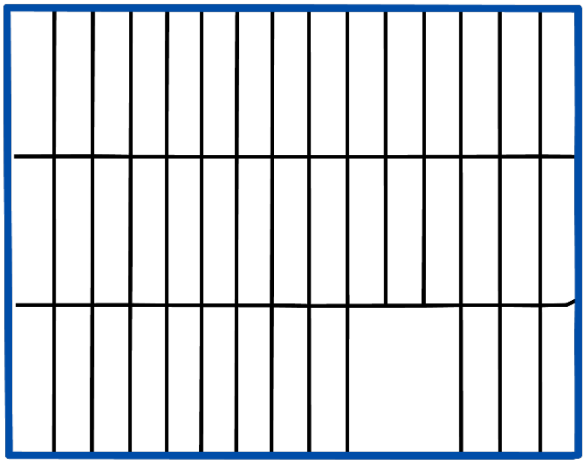


Figure 23 - Figure-ground map of a typical grid neighbourhood street pattern, featuring parallel blocks of equal length.

2. *Post-grid neighbourhoods*

Post-grid neighbourhoods were typically the first post-war neighbourhoods to be developed. They are characterized by a collector street system that approximates a grid but with a more fragmented local street system relying largely on bays (Figure 24). They are typically measured at a comparatively lower street density, a lower intersection density, and fewer external access points, but with a similar connectivity index. Examples include Windsor Park, Fort Richmond, Crestview, and the Maples.

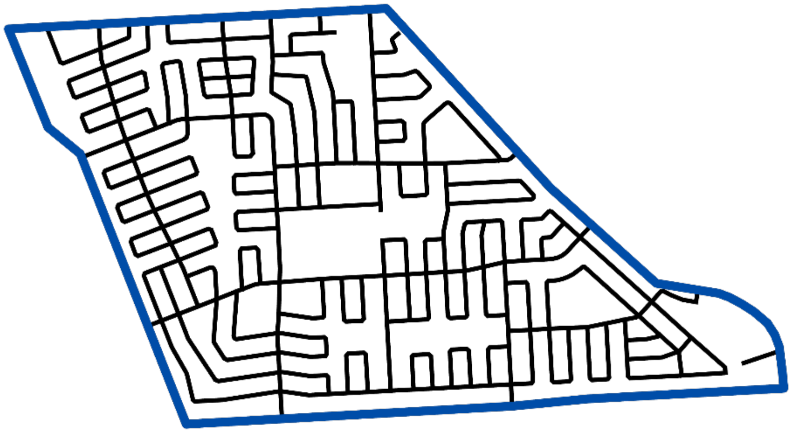


Figure 24 - Figure-ground map of a typical post-grid neighbourhood, with bayed local streets and a grid-like collector street system.

3. *Classic curvilinear neighbourhoods*

Classic curvilinear neighbourhoods followed the post-grid development era but continue to be developed today. They are characterized by large looping collector street networks, a heavy reliance on bays and cul-de-sacs, limited access points outside the neighbourhood, and the introduction of retention ponds (Figure 25). They are typically measured at the lowest intersection density and connectivity index. Examples include Linden Woods, Island Lakes, and Whyte Ridge.

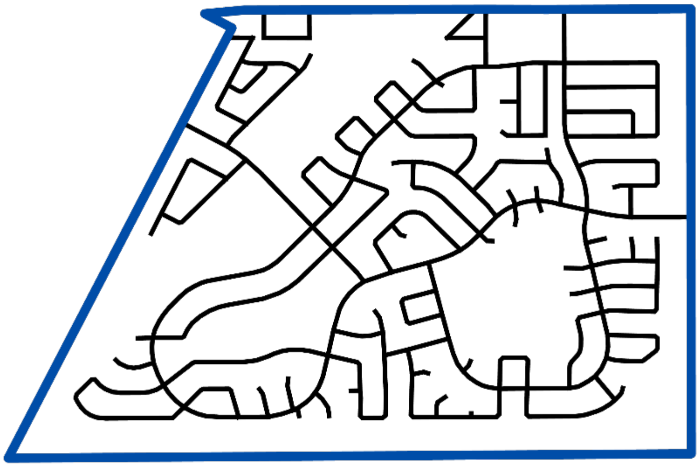


Figure 25 - Figure-ground map of a typical classic curvilinear neighbourhood, featuring a looping collector system and bay and cul-de-sac local streets.

4. *Contemporary curvilinear neighbourhoods*

Contemporary curvilinear neighbourhoods include the most recently developed greenfield neighbourhoods in Winnipeg. They are characterized by the same looping collector streets and limited external access points but rely much more on long grid-like local street bays than on cul-de-sacs (Figure 26). Compared to classic curvilinear developments they are typically measured at a similar or slightly higher intersection density and a higher connectivity index. Examples include Bridgwater Forest and Sage Creek.

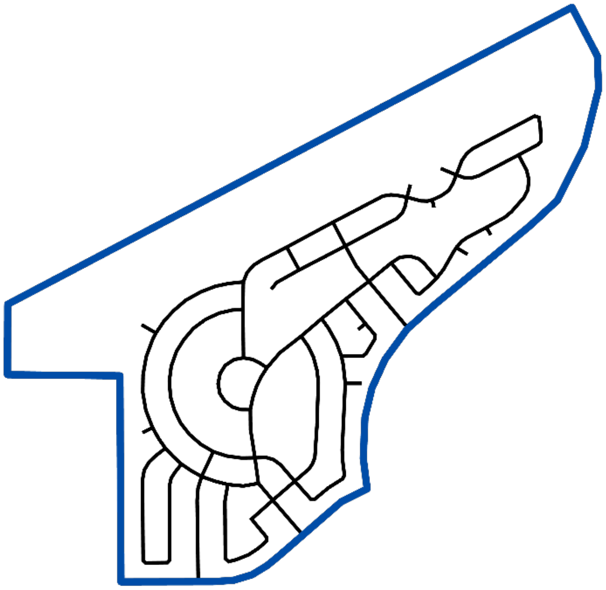


Figure 26 - Figure-ground map of a typical contemporary curvilinear neighbourhood. Though it appears similar to classic curvilinear patterns, it relies more on longer blocks and parallel bays and less on cul-de-sacs.

The more detailed street network characteristics of this typology are found in Table 1. This table shows that while there are tangible distinctions between different neighbourhood layouts, it also shows that there is significant overlap between them. This further exemplifies how street network measures are not definitive analysis tools, as most values of each measure can be achieved with any street pattern.

Table 1 - Typical street network measurement ranges

Typology Chart	**Grid**	**Post-grid**	**Classic Curvilinear**	**Contemporary Curvilinear**
Street density (m/km^2)	10.1 and over	6.1 and over	2.1 – 12	6.1 - 12
Intersection density (intersections/km^2)	8.1 and over	8.1 and over	8.1 – 40	8.1 - 40
Connectivity Index	1.4 and over	1.4 and over	0 – 1.6	0 and over
Access Point Density (Access points/km^2)	9.1 and over	0 – 35	0 – 9	0 – 9
Average Distance between Access Points (m)	0 – 860	0 - 860	413 - 1638	860 and over

The mapping results and the resulting typology provide a more quantitative base that supports many perspective-based arguments. For example, the differences in the intersection density and connectivity index between classic and contemporary curvilinear neighbourhoods supports the assertion made by many interview subjects that more recent developments are better-connected than those of the prior era. Though incorporating trail systems was not possible in this analysis, if it was, it is likely that pedestrian connectivity would be found to have increased substantially in the most recent developments and presented a more recognizable difference between classic and contemporary curvilinear patterns. Alternatively, the mapping demonstrated results that may run counter to conventional assumptions, such as to the connectivity of grid street patterns. For example, the River Heights neighbourhoods and Lord Roberts were shown to have similar intersection densities to classic and contemporary curvilinear neighbourhoods such as Linden Woods, South Pointe, and Sage Creek. Similarly, though they had a higher intersection density, Daniel McIntyre, Riverview, and Central St. Boniface all had similar intersection densities to Whyte Ridge, Bridgwater Trails, and South Pointe. This can be interpreted in two ways. One is that a neighbourhood does not necessarily have to be laid out in a grid pattern to achieve higher street density. The second is that deviating from the grid towards a more mixed or curvilinear pattern does not necessarily save on infrastructure costs. These examples illustrate how broad street pattern types alone do not inherently lead to a specific connectivity outcome, and that the finer-grained configuration of these street patterns has a significant effect. As in this example, grid patterns with long blocks will have fewer intersections and, by extension, less connectivity. Additional detail into the comparisons between different neighbourhood types and their street network measure results are found in Table 2, with illustrations in Figure 27.

The mapping analysis also showcased the limitations of these connectivity measures beyond their initial accuracy. They cannot be relied on in isolation to determine the connectivity of a given street pattern and must be used in combination with each other, along with qualitative analysis. While existing research discusses the need for assessment of both street network density as well as connectivity, even within these categories the use of one individual measure is insufficient (Marshall & Garrick, 2010a, p. 104). For example, while the River Heights neighbourhoods have very high street density, their intersection density is low. External connectivity provides another example. While there are no good cases of this in any current

Table 2 – Neighbourhood Layout Measurement Comparisons

Neighbourhood	Type	Street Density (m/km^2)	Intersection Density (intersections/km^2)	Connectivity Index	Access Point Density (access points/km^2)	Average Distance between Access Points
North River Heights	Grid	10.9	16.5	2.5	17.6	181.4
Daniel McIntyre	Grid	13.0	26.2	2.2	21.5	163.1
Windsor Park	Post-grid	12.7	36.1	1.7	5.2	533.6
The Maples	Post-grid	12.3	41.9	1.6	10	243.5
Linden Woods	Classic curvilinear	9.4	21.9	1.3	2.2	1089.1
Island Lakes	Classic curvilinear	11.2	28.1	1.4	2.9	908.2
Bridgwater Forest	Contemporary curvilinear	10.4	33.1	1.4	2.3	1886.4
Sage Creek	Contemporary curvilinear	6.0	16.9	1.4	0.5	2338.3

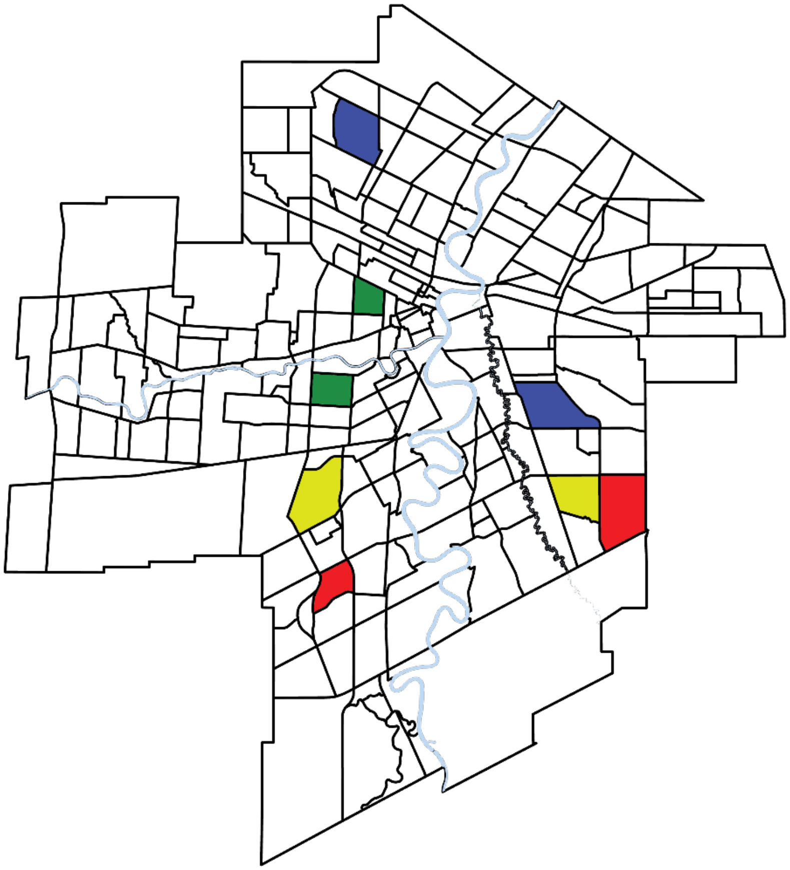


Figure 27 - Map of Winnipeg neighbourhoods exemplifying each of the four neighbourhood layout types.

Winnipeg neighbourhoods, it would be possible for a development to have a high number of external connections while remaining difficult to pass through and a barrier to citywide travel. For instance, if the loop remains as the primary collector network, additional connections along its perimeter do not necessarily enable increased connectivity through the neighbourhood. This can be interpreted in two ways. On one hand, this could increase external connectivity while keeping traffic levels in the neighbourhood low. On the other hand, this illustrates that if an increased level of through-travel capability is desired, to support inter-neighbourhood transit connectivity for example, additional external access points are not sufficient. A denser street network between them within the neighbourhood is also necessary. While this relationship may be obvious, it is not accounted for in any combination of street network measures.

With respect to City regulations, the mapping analysis raises the question of the total impacts of park configuration expectations and traffic engineering requirements. The large interconnected central parks that have come to distinguish Winnipeg's curvilinear neighbourhoods may be a contributing factor in the generally lower street network density and connectivity, compared even to post-grid neighbourhoods. This, however, is not to say that existing park configuration requirements must be altered, or even that they, in fact, are necessarily responsible for these differences. Other considerations including the efficiency of the curvilinear layout, the necessity for retention ponds, or the potential for market-driven demand for extensive trail systems could all be independently contributing to the statistical differences between neighbourhood types. But with park size and retention ponds being the key non-street differences between older and more recent neighbourhoods, their direct influence on street pattern would be worthy of examination.

External connectivity has a similar relationship with different neighbourhood types and engineering standards. The restrictions on the permitted number of connections to the arterial roads that typically frame recent greenfield developments were often cited in interviews as contributing to reduced connectivity between neighbourhoods, with older arterial and collector streets such as St. Mary's Road, Grant Avenue, and Corydon Avenue cited as examples of streets that would not be allowed to be built today. However, as with parks, neighbourhood design decisions can be made independently of engineering requirements. Though multiple respondents noted that streets like St. Mary's Road would no longer be permitted, none expressed any desire for that to change, and the general goal of reducing non-local traffic in neighbourhoods is also consistent with fewer external access points. Furthermore, as previously discussed, even a greater number of access points does not automatically imply greater inter-neighbourhood connectivity if access points in different neighbourhoods do not line up with each other or if the connecting roads themselves are short and lead to circuitous collector street systems. Overall, while certain City regulations may prohibit design treatments that would increase street network density or connectivity, it is likely that they coincide with the neighbourhood design preferences of developers anyway.

Where this may not be true is with the strict road hierarchy and the street treatments it mandates outside of external connectivity. When asked about why the hierarchical and curvilinear street system is most popular in contemporary neighbourhoods, Developer 3 responded that the hierarchy is an engineering standard-imposed attribute and not one that necessarily correlates with the curvilinear street pattern. This hierarchy, or rather the conditions that it imposes on its roads, carries significant impact on the aesthetic and community characteristics of Winnipeg neighbourhoods. For example, at a small scale like the collector street, the design speed and direct access restrictions may lead to developers backing lots onto them, rather than fronting onto them, which deadens the street and establishes it as a corridor intended for travel alone. This stands in contrast to the arterial/collector streets in grid neighbourhoods which, frequency of connections aside, used the street as the focus of commercial activity and residential density. Post-grid and classic curvilinear developments, and to a lesser degree contemporary curvilinear neighbourhoods, tend to focus these uses at gateways into the community first, most often at the intersection of a major arterial and the internal collector street. Because major arterials are by definition limitedly accessible, this removes the opportunity for street activation and the synergy between land use intensity and transportation corridors. As a result, commercial centres become amenity destinations rather than broader activity cores. At a larger citywide scale, the high density of arterial streets intensifies this effect. For example, more recently developed sections along the south ends of Kenaston Boulevard, Waverley Street, St. Mary’s Road, St. Anne’s Road all have development backing onto them which relegates them to conduits for traffic exclusively. For transit, this creates a structure in which the most direct roads allow for the provision of service to the backs and boundaries of neighbourhoods, and in which transit-favourable road geometry and transit-favourable land use are separated.

None of this is to say that there is no need for large arterials or large commercial centres, and none of this is intended to exclusively criticize developers' responses to these realities. It is obvious that when presented with a large arterial on a parcel's boundary the most viable response is to back onto it to minimize noise and focus development inwards into a neighbourhood and its street system. It is also obvious that given that driving remains the dominant form of transportation in Winnipeg it must be effectively accommodated by not only the road network but also by parking supply. It is also possible that large retail plazas centred on major intersections are a response to market demand, in which people are happy to be able to access all their amenities at once. When driving, the distance to the nearest commercial centre is often minimal. Furthermore, even slightly greater dispersal of commercial amenities in a neighbourhood could complicate road and pipe infrastructure configuration for developers, mandate wider roads, and disperse traffic away from the busiest and largest roads. Planning Consultant 1 argued that we should not be basing our planning goals on the past. Conditions, whether dominant travel mode, residential development processes, or corporate retail trends, change, and this change is reflected in the built forms of the different eras of our cities. Therefore, functionally, our neighbourhoods as they are currently designed work. City residents can live on a quiet street with an extensive parks and trails system, access an expressway by vehicle quickly and travel a relatively unimpeded route to work, and stop by a grocery store with ample parking on the way home. For many people, this works.

However, there are issues involved in this arrangement as well. While vehicular traffic is accommodated efficiently, other modes can be hampered by both the neighbourhood-level and citywide street network. Transit is made to maneuver through inward-facing and looping neighbourhoods with limited connections between them. Pedestrians, while being provided increasingly extensive and interconnected trail systems, must often travel long distances to reach neighbourhood-scale amenities. Where private space, whether a home or a restaurant, is primarily responsible for accommodating social activity, public space can become merely a venue for travelling between them. The current approach to street network planning is one in which a select few expressways and arterial roads are tasked with accommodating as much traffic as possible in order for collector roads, and especially local roads, to be as quiet as possible. While this might accomplish he goal of making residential streets quieter, safer, and more private, it also results in a structure in which "travel roads" are so busy that they cannot directly accommodate development, and residential streets are so quiet that they cannot accommodate commercial or higher-density residential uses. Though there is undoubtedly synergy in locating higher-intensity land uses at the convergences of large traffic-heavy roads, this also has negative effects in that it concentrates activity in neighbourhood areas that can be difficult to access from within the neighbourhood itself, especially if not driving, although recent developments have worked on mitigating this. Not only does this broad neighbourhood design structure not conform to general urban planning principles, but it is also vulnerable to future changes, much in the same way that interview subjects criticize grid neighbourhoods for their inability to effectively accommodate vehicular traffic today. In order to be resilient, our neighbourhoods must offer choice. Engineering requirements and developers' responses to them can inhibit the degree of such choice that is provided in cities' newest neighbourhoods.

Context and priorities in street network design

The changes in context that lead to changes in neighbourhood design are already evident, as raised by interviewees. Developer 4's interest in grids is a relatively small but recent example of this. As land acquisition and development costs have risen, new residential lots have become narrower as developers seek to maintain accessible final product costs. These narrow lots have made flankage less of an issue as a grid allows for a greater number of narrow lots to ultimately be laid out along a street while having a lesser share of lots flanking onto two streets. To be clear, Developer 4 remained as driven by efficiency as the others. But for them, the most efficient street pattern changed due to their lot size distribution. This network manifestation of efficiency is like one of the key reasons for the differences between classic and contemporary curvilinear neighbourhoods. As lot sizes narrow, the use of long bays allows for a greater number of lots to be developed than through the use of cul-de-sacs, while maintaining a minimal amount of flankage. This has returned somewhat of a grid-like structure to new subdivisions, wherein parallel bays radiate out from the collector street system parallel, but simply do not connect with each other. This shift in design efficiency illustrates how street patterns are simply a means to an end, and even if that end stays the same, the means to achieving it may change as context changes too.

These changing circumstances can provide opportunity in other ways as well. As multiple respondents noted, a diversity of housing stock being produced is important as more people become interested in housing options other than single-family houses. Though contemporary curvilinear street patterns retain strong commonalities with classic curvilinear patterns, this diversifying of housing stock can amplify this change. It can provide more room for creativity as different housing types, distributions, and complementary street configurations can be explored, and ultimately that potential and opportunity for diversity is essential to broader considerations of what our neighbourhoods may look like. And though multiple developers interviewed described themselves as intensely risk-averse, they also expressed a general willingness to experiment. This was not stated explicitly, but comments describing unique attempts at providing a different housing product or street treatment and the results thereof were made by multiple developers. In general, there was an enthusiasm displayed on behalf of those interviewed for creating distinctive and interesting neighbourhoods. Developers do not want to design "cookie-cutter" suburbs, both due to marketability considerations as well as out of a general interest in urban planning principles and a commitment to their city. This creativity and experimentation need to be supported. City Planner 1 expressed a similar view in saying that they are conscious of the potential for stifling this creativity through policies or regulations that are overly prescriptive. Instead, they suggested that the City can establish a set of considerations or issues that must be addressed but provide the freedom for the developer to generate the resolutions to them themselves. This problem and goal-oriented approach can maintain the flexibility needed to accommodate unforeseen circumstances that developers want, while securing the City's broader interests.

Overall, what the interviews with a diverse group of interests and stakeholders in neighbourhood development uncovered is that the designs chosen for new neighbourhoods reflect the priorities at the time of development. Although innovative street networks, such as the Radburn model for example, have been used in the past, this has generally been true (Southworth & Owens, 1993, pp. 273-274). The grid pattern employed in the early days of North American urban area settlement and expansion was not used because developers and governments held a strong devotion to urbanist ideals, but because it allowed for lots to be created quickly and as needed at a time when expansion was rapid and land costs were low (Southworth & Owens, 1993, p. 274). Since then, land and infrastructure efficiency has been the dominant priority for developers, and this is unlikely to change as land costs continue to increase. However, the priorities beneath efficiency also affect final street pattern outcomes. For example, right now having a large cohesive parks and trails system is a priority both for the market as well as for the City due to maintenance considerations, and neighbourhood design has responded accordingly. Developer 1 said they avoid intersecting the parks and trails with roads and when they do, it is only with collectors – never with local streets. However, if the provision of parks and trails was less of a priority to the market or the City's maintenance concerns compared to opportunities for additional density or internal transit connectivity and efficiency, for example, street patterns would likewise adjust.

All of these factors, and all others involved in neighbourhood design as well, are worthy of consideration, but it is their prioritization that leads street patterns to be designed they way they are. As such, it is possible that the contemporary curvilinear street pattern continues to be in the process of evolution away from the classic curvilinear design and will differentiate itself more strongly with time.

A new street pattern standard?

Though the fused grid was identified early on in the literature review as a potential improvement to current practices that could combine the quiet and safety of curvilinear patterns with the connectivity of the grid, it should not be considered for widespread indiscriminate implementation. While it does have distinct advantages and can be drawn from in the street network design process, and at times perhaps even faithfully implemented, based on the reservations that multiple respondents expressed with it, it cannot be declared a comprehensive or flawless replacement to the issues referred to in curvilinear street patterns in the literature. Street patterns should respond to their context rather be imposed on them, and likewise, street patterns should respond to issues or goals rather than shape them. If specific problems are identified with contemporary curvilinear street patterns, they should be met with deliberate action that accounts for other interests as well. While these solutions could incorporate ideas from or fully use the fused grid or any other street pattern, it is important for neighbourhood designers to leave themselves the flexibility to respond to unique contexts and challenges as they arise.

Multiple respondents noted that this was an interesting time to be assessing street network layout given the rapidly changing development trends. However, they largely referred to reduced lot sizes and increased assortment of housing types and densities. To a lesser extent, they also referred to the increased focus on active transportation both within neighbourhoods and between them. But, aside from Developer 4 and their interest in grids, there were no significant trends noted with street patterns themselves. In fact, Developer 5 observed that street pattern preferences have generally been slow to change which they attributed to simple momentum. When neighbourhood designers are accustomed to producing curvilinear street patterned neighbourhoods, when city planners are used to reviewing them, and when homebuyers continue to purchase in them, it can be difficult for developers and consultants to try something new. Whether, and how, changing housing stock preferences and production will begin to affect the street patterns themselves will be important to keep track of. Already, the growing popularity of townhouses has resulted in greater area in developments being reserved for townhouse complexes with private internal roads, as well as to large apartment complexes encircling surface parking lots. How the continued need to accommodate these complexes will affect broader neighbourhood street patterns, and how large blocks will affect connectivity, will be important to assess moving forward. Specifically, as housing stock and street network layout progress, continued communication between the development industry and the City will be necessary to maintain a common understanding of the issues and potential responses as they become apparent.

More broadly, consistent dialogue and collaboration between developers, the City, engineers, and all other stakeholders involved in greenfield development and city-building overall is necessary not only to assess and respond to changing trends, but also to assess existing goals and regulations. Though this already occurs within the precinct planning process, an expansion of this relationship to address greenfield development more broadly can contribute to a more deliberate collective consideration of street pattern characteristics and the individual priorities and goals that are sought. Ensuring that the objectives currently advocated for remain relevant and their enforcement mechanisms remain functional is imperative to ensuring that future neighbourhood developments continue to meet the latest circumstances and priorities. Such dialogue is also important in maintaining certainty and mutual understanding between developers and different City departments in order to ensure that the collective vision for development requirements is coherent and mutually reinforcing.

This dialogue is important because while the goals that developers hold drive much of street pattern design in new neighbourhoods, public policy does as well. Developers interviewed gave many examples where policy and preferences of the City – whether they be road standards or park distribution – affect the ultimate layout of a community. Public policy ultimately sets the context within which development occurs, and is the space within which municipalities can enforce their own priorities. However, to do so unilaterally may have inadvertent effects for developers or conflict with other policies. For example, if the City of Winnipeg was to mandate improved inter-neighbourhood connectivity through more direct road connections within neighbourhoods, this may impose additional costs on the developer who would then be required to construct that road to a higher standard if it was to accommodate greater traffic. In this case, the engineering standards of the City itself would be a hindrance to this policy change. As such, these goals and the role of public policy within them are best considered in a broader discussion where their interconnected nature can be more thoroughly considered and reorganized as necessary.

Recommendations

Though my research focused on the case of suburban development in Winnipeg, the broader findings contain a variety of implications applicable to many urban areas experiencing peripheral growth. These include the potential use of street network measures as regulatory tools, the benefits of periodic regulation evaluation, focusing on neighbourhood goals rather than street pattern types, incorporating ongoing collaboration, and creating long-range plans for greenfield areas.

Though street network measures can be useful tools in evaluating and comparing neighbourhood layouts – and by extension, proposals for them – they should not be implemented as a standalone regulatory requirement or metric. If a certain level of street density or connectivity is a goal in neighbourhood design, the measures used in this research are not sufficiently accurate so as to be relied on exclusively, as demonstrated in the literature. And if more specific goals are sought, such as a minimum level of through-access in a neighbourhood, these measures would be incapable of assessing them. In consideration of these limitations, a development's street pattern assessment process would be more effective as a more comprehensive overview of the network, its characteristics, and the effects it could have. The use of specific street pattern measures can be a part of this, but the necessity for a more qualitative assessment cannot be discounted. Given the various perspectives that arose through interviews with developers over perceived overregulation in some areas and a lack of direction in others, any attempt to introduce these metrics into the approval process must be approached with interstakeholder collaboration and only be implemented in the case of a pressing need or mutual benefit.

Similarly, it is worthwhile to consider and evaluate existing regulations and assess whether they continue to support the interests they are intended to, whether they continue to be beneficial in the current context, and whether their enforcement continues to support local planning priorities as they stand. For example, the City of Winnipeg preference for fewer but larger parks in new neighbourhoods reflects a priority on minimizing maintenance costs, while City engineering standards incorporate a set of road design requirements that aim to avoid traffic congestion. Upon review, however, it could be found that the most easily maintained park configuration has changed, or if transit operational efficiency becomes a concern, that road engineering standards contribute to this and may need to be reconfigured. This is similar to how more grid-like neighbourhoods are becoming more efficient than cul-de-sac-based street patterns due to the narrowing of lots. As circumstances and goals change, regulations need to change with them in order to ensure that outcomes reflect the most recent preferences.

The importance of focusing on the specific goals desired from street patterns is a key lesson itself. Rather than advocating for a certain type of street pattern, it is more beneficial to be concerned with the interests it can accommodate. For example, while a grid may have certain benefits for transit, imposing its use would reflect an interest in the pattern itself rather than its effects. Instead, if transit connectivity is a goal, its accommodation can be explicitly considered in the street network design process without immediately responding with a specific street pattern. While this is likely to involve trade-offs, in such a process trade-offs are more likely to be directly considered and weighed than when a certain street layout is the goal itself.

Though street network design goals or priorities may conflict, they do not have to. For example, while curvilinear street patterns may reduce pedestrian connectivity, the introduction of active transportation trails in newer neighbourhoods mitigates this and creates a much more direct pedestrian and cycling network within a community while retaining the curvilinear street pattern that may address the goals of efficient land use and large park accommodation. Given the large number of goals that may be considered in the course of the design of a neighbourhood, some trade-offs are likely to be inevitable, but with the equally large number of individual street pattern characteristics that can be altered, any individual neighbourhood can faithfully reflect the priorities of those that designed it.

Evaluating goals for new neighbourhoods and considering the street network designs that can accommodate them requires extensive collaboration between a diverse set of stakeholders. Planners, developers, and engineers must all be involved in the early discussion of goals for suburban development to ensure that the greatest number of interests are reflected, that they are accommodated through compromise rather than conflict, and that all stakeholders are equally informed on both development goals and the process that was used to develop them.

This collaboration would be particularly effective if done as part of a large-scale greenfield development strategy. While individual areas of a city may have particular considerations that may need to be considered, establishing a base set of goals and plans for suburban development overall would provide stability and certainty for developers, who would better understand what is asked of their developments, and for government, which would be able to lay out its requirements in a more organized fashion and feel confident they were understood. While, as with any plan, the goals decided on would change over time, regular updates and evaluation of strategies in place, as recommended above, would ensure that the plan and its goals would remain current and agreeable to all suburban development stakeholders.

Conclusion

The questions posed at the outset of this research sought to uncover the factors and goals involved in the curvilinear street pattern designs of recent greenfield subdivisions and consider how these may be addressed while simultaneously resolving the criticisms of curvilinear layouts as well. Maximizing the number of lots created in a piece of land while minimizing the infrastructure costs needed to service them was the dominant answer, being cited both explicitly, and often first, and being implicated in a variety of other considerations by all developers. Marketability was also a strong factor, with curvilinear street patterns maximizing the number of calm and quiet streets that homebuyers are drawn to. If a simple answer to the question of what interests are involved in the use of curvilinear street network layouts is needed, it is land and infrastructure efficiency, and marketability.

The mapping analysis confirmed this in its overview of different neighbourhood eras and their street patterns, and how they are distinguished by their data. Older grid neighbourhoods do, in fact, tend to have a higher total length of street per area than more recent curvilinear communities. Therefore, on average, grid neighbourhoods will devote more surface area of land in a neighbourhood to roads than to lots. The curvilinear design avoids this. However, a lower street density is also associated with reduced connectivity as described in the existing literature, which the mapping analysis also concurred with. In addition to lower street density, curvilinear neighbourhoods consistently exhibited lower intersection densities and connectivity indexes as well. Overall, this research demonstrated that curvilinear street patterns do have concrete advantages over other designs, but their disadvantages in connectivity are evident as well. Whether efficiency and connectivity are mutually exclusive, however, is uncertain, particularly as the manifestation of efficient street patterns change as residential lot sizes and housing types change as well.

If this change is to be effectively managed, it is important to remain cognizant of the common goals all those involved in greenfield development are striving for. City planners are likely to keep a big picture of how a neighbourhood fits into the larger city in mind along with more specific urban planning priorities, but developers are interested in this too. They want to create desirable neighbourhoods with good reputations, enable themselves to continue developing in the city, and are generally interested in contributing to quality urban planning in the city. Similarly, developers are focused on the efficiency of land use and infrastructure, but this efficiency benefits the City as well.

Currently, both developers and City planners referred to a negotiation-style dialogue being present between them, although respondents from both also admitted that this dialogue could be strengthened. Developers may see certain City requirements as unnecessary or overly restrictive, while the City may find that developers’ focus on efficiency refers to different priorities. For example, while reduced street length may reduce the amount of infrastructure to maintain, it may also increase the operating cost of transit as it meanders through a neighbourhood’s indirect street network. Furthermore, even within the City, there can be disagreements between various departments, each with their own perspectives and priorities. Collaboration may not necessarily be simple, but it is necessary to allow for both common and divergent interests to be worked through.

As such, to the question of how the factors and goals behind curvilinear street patterns can be accommodated while also addressing their associated concerns, no specific street pattern is recommended. To do so is both impossible and unnecessary. It is impossible because street patterns are not as distinct as they can sometimes be described. Within this research I often contrasted grid and curvilinear street patterns, but there is tremendous variation within each of those broad categories. For example, grids can be composed of short or long blocks and can be fragmented with parks, buildings, and cul-de-sacs as well. Curvilinear patterns can incorporate a single collector street loop, or they can use more linear collector systems. They can rely more on bays or on cul-de-sacs, and can also be composed of shorter or longer blocks. It is unnecessary because no one street pattern can respond to the individual circumstances of each site or time period.

Therefore, it is more valuable for problems and goals to be focused on in new developments, and not individual street patterns. If street patterns are merely a means to an end, determining what the end ought to be first will lead to an ultimately more effective street pattern design. With all those involved in neighbourhood design collaborating on identifying what the problems and goals are and how best they can be addressed, whether with individual projects or in broader citywide plans, future developments can continue to improve on those before them. Negotiating priorities and finding common ground on how street patterns will be implicated and improved is complicated but necessary and, though they may feel obvious to some, it is hoped that this project contributes to this potential for progress by expressly laying out the factors and conditions that affect street network layout, the trade-offs between them, and their implications for those who create new neighbourhoods, those that live in them, and for the city as a whole.

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