SHORTER ROADS GO A LONG WAY: THE RELATIONSHIP BETWEEN DENSITY AND ROAD LENGTH PER RESIDENT WITHIN AND BETWEEN CITIES.

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Résumé

Les routes forment un aspect important des gains d'efficacité de la densité de population : plus les gens sont nombreux le long d'un système routier, moins chaque individu doit payer pour le goudronnage, la maintenance, et le déneigement. Bien que la densité soit liée à la longueur de route par résident, les deux variables ne sont pas équivalentes. Deux zones urbaines peuvent avoir la même étendue spatiale et la même population, mais avoir des morphologies de réseau routier différentes, ce qui mènent à des données différentes pour la longueur de route par résident. La longueur de route par résident mesure directement une catégorie majeure de coûts, car une grande proportion de nombreux budgets municipaux est dédiée à la maintenance routière. Une meilleure compréhension de la longueur de route par résident peut donc promouvoir une politique prudente de développement urbain. L'objectif principal de cette recherche est donc d'investiguer comment la longueur de route par résident varie par rapport à la densité entre sous-catégories géographiques dans les villes. Neuf villes canadiennes ont été sélectionnées et la longueur de route par résident et la densité nette d'habitants selon les recensements urbains sont calculées. Les résultats présentent une association non-linéaire forte et consistante entre la densité de population et la longueur de route par résident. L'analyse est utile pour distinguer entre les banlieues de densité moyenne et basse. Les résultats suggèrent qu'un changement pourrait être nécessaire dans l'évaluation des coûts de la croissance à basse densité par les théoristes urbains.

Mots-clés:

Abstract

Roads are an important aspect of the efficiency gains that stem from population density: the more people live on a given road network, the less each person must pay for paving, maintenance, and snow clearing. While density is related to the road length per resident, the two variables are not synonymous. Two urban areas may have the same spatial extent and population, yet feature distinct road network morphologies, resulting in different values for road length per resident. Road length per resident measures a major category of costs directly, as a large proportion of many municipal budgets are dedicated to road maintenance. A better understanding of road length per resident can therefore support financially prudent urban development policy. The primary objective of this research is therefore to investigate how road length per resident varies with density between the sub-geographies of cities. Nine cities from across Canada were selected and the road length per resident and net density of their census tracts were calculated. The results present a strong and consistent non-linear associ-

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ation between population density and road length per resident. The present analysis is most valuable for distinguishing between medium-density and low-density suburbs. The results suggest that a shift may be necessary in how urban theorists communicate the costs of low-density growth.

Keywords: Road length per resident, population density, urban efficiency, smart growth.

INTRODUCTION

A central tenant of current urban planning practice is that increasing population density is associated with lower municipal infrastructure costs per person (Carruthers & Úlfarsson, 2008; Ewing & Hamidi, 2014; Hortas-Rico & Solé-Ollé, 2010; Slack, 2013). Roads are an exemplification of cost efficiency increases through density: the more people live on a given section of road network, the less the municipality pays for paving, maintenance, and snow clearing per person (Blais, 2011; Prieto et al., 2015). Road construction and maintenance is estimated to consume 6% of local government budgets in the US (US Bureau of the Census, 2015). Other municipal operating costs, moreover, tend to decrease with lower road length per person. For example, Mair et al. (2017) demonstrate a strong correlation between the total linear extent of a city's roads and its water and sewer network. Lin and Kao (2008) similarly identify the length of roads as a driving force behind garbage collection costs. When a greater proportion of a growing urban population is accommodated on existing roads, the total required infrastructure for the accommodation of that growth is reduced (McCahill & Garrick, 2012; Shin et al., 2009; Woudsma et al., 2006). Furthermore, reducing road length also decreases a city's impervious surface area per person, thereby reducing storm water costs (Litman, 2011; Jacob & Lopez, 2009; Arnold & Gibbins, 1996).

While population density is related to road length per resident, the two variables are not synonymous. Two urban areas of the same spatial extent and population can feature distinct road network morphologies, resulting in different values for road length per resident, and different consequent outcomes for cost efficiency. Several studies have analysed the effects

of population density on linear infrastructure costs per person (Arcaute, et al., 2014; Levinson, 2012; Müller, et al., 2013; Pauliuk, et al., 2013), with most studies comparing entire cities or large city areas. These studies suggest that the total length of roads and electricity cables increase sublinearly with population size — the length per person drops as population grows — by a power law with an exponent of roughly 0.85 (Bettencourt et al. 2007; Bettencourt, et al., 2013; Kühnert and West 2006, Lobo *et al.* 2013).

In contrast to the aforementioned studies calculating city-wide values, the present study contributes to the literature by analyzing the relationship between population density and road length per resident at the neighbourhood scale. Nine Canadian cities were selected for this neighbourhood-level analysis. Research at the neighbourhood scale better corresponds to the level at which municipal governments plan new subdivisions, offering greater opportunity to translate findings into practice. By comparing multiple cities, we explore the consistency with which road length per person varies with density.

METHODOLOGY

Study Locations

Seven medium-sized cities from across Canada were selected for comparison: Halifax, London, Oshawa, Saskatoon, Sherbrooke, Victoria and Windsor. Two larger cities, Calgary and Edmonton, were also selected as reference points to identify whether any detectable patterns were isolated to the medium size cities, or whether the results are generalizable to larger cities. The selected cities range in population from 170,000 (Oshawa) to 1.3 million

Shorter Roads go a Long Way

(Calgary). Cities were selected, in part, because they are not situated within a larger contiguous urban area, but are surrounded by rural countryside allowing an analysis of the full range of low-to-high population density.

Measures of Density

The simplest definition of density — population divided by area— is called “gross density,” and it has certain shortcomings for comparing areas within cities. This type of measure, which we will refer to as ‘gross density’, is not sensitive to whether differences in density are caused by low density settlement, or by intentional interruption of urban continuity (e.g. by large parks or floodplains). If two neighbourhoods are separated by uninhabited open space, their gross density differs substantially depending on how much of that open area falls inside the boundary of one neighbourhood (e.g. census tract) or the other. Gross density also exaggerates the difference between compact urban neighbourhoods (where built form covers all available land), and exurban neighbourhoods (where large undeveloped gaps exist between homes). These gaps push the density of many census tracts to nearly zero, making it difficult to analyze differences between various forms of built environment.

An alternative to gross density is to measure net density: population divided by built area. In contrast to conventional calculations of a population’s gross density, we do not divide population numbers by the overall surface area of a neighbourhood. Instead, we divide the population counts by the surface area of land cover identified as urbanized.

To identify urban land cover we use ‘Built-up area files for the census metropolitan areas (CMA) and CMA-ecosystems’, produced by Statistics Canada and distributed in the shapefile GIS format. The Built-up area data are created through the processing of remote sensing imagery to delineate patches of land “characterized by a high percentage of impervious surfaces including roadways, parking lots and roof tops” (Statistics Canada, 2016, p.3). These data provide an opportunity to investigate cross-country comparisons of population density

based on “a consistent methodology to compare urban development trends across the country” (Statistics Canada, 2016, p.2).

Unit of Analysis

Population data is provided by Statistics Canada on a wide range of geographic scales, from national to street block level. Census tract geography is chosen as the spatial unit of analysis for several reasons. First, census tracts are typically employed in urban research studies to represent neighbourhoods, or an area within which residents perceive a common set of socioeconomic effects and a similarity of service experiences (Goodman, 1977). Second, larger census divisions are not sufficiently responsive to changes in morphology, and smaller units (e.g. dissemination areas) usually represent only a few streets, insufficient to express urban settlement patterns.

For any scale of aggregation, there is risk that the modifiable areal unit problem will introduce systematic bias (Horner & Murray, 2002; Parenteau & Sawada, 2011; Prouse et al., 2014). In this analysis, the risk is relatively low since it employs only aggregates of population counts, rather than population characteristics. The risk is further reduced by excluding unpopulated areas which could otherwise distort density estimates depending on which census tracts are drawn to include them, and which are not.

We utilize population counts based on 2011 census tracts boundaries (Statistics Canada, 2011a) in order to align the most recent data on built-up areas, which are only produced every ten years (2001, 2011, etc.). All census tracts within the census metropolitan areas (Statistics Canada, 2011b) of the nine cities – equalling 1023 census tracts – have been analyzed and incorporated into the calculations.

Roads

We seek to analyze roads that serve the basic functions of the city, with a focus on those that create road frontage for homes or businesses. We therefore exclude roads that are not open to the public (e.g., military bases, industrial, institutional or education-

Shorter Roads go a Long Way

al facilities) or have a primarily recreational character (e.g., unpaved trails). We also exclude highways since, unlike local residential streets, most highways serve long-distance transportation and exist whether or not they were bordered by a particular neighbourhood. All the above roads were consistently removed from the country-wide dataset before the data was further processed.

We relied on the 2011 Census Road Network File supplied by Statistics Canada (2011c) to ensure a consistent method for sourcing and treating road data for cities across the country. The centre line dataset “is comprised of street arcs depicting the national road network and includes attribute information such as street arc unique identifier, name, type, direction, address range, rank and class” (Statistics Canada, 2011c, p.8). This consistent, nation-wide categorization of street types was instrumental to our selection of roads prior to the geospatial analysis. Based on the attribute table of the Census Road Network File, we removed all roads that had a ‘NULL’ value in the ‘TYPE’ column (i.e. roads without a civic address/road name), a value of ‘1’ or ‘2’ in the ‘RANK’ column (i.e. National Highway System) or a value of ‘25’ through ‘29’ in the ‘CLASS’ column (i.e. connectors/ramps, trails, rapid transit, planned roads, strata).

The availability of a national dataset which allowed for a consistent method of street selection across the country was the primary reason for choosing street kilometres as a road length measurement rather than lane kilometres. Datasets similar to the Census Road Network File are not available per traffic lanes, and would need to be merged from various sources across cities without uniform road classifications. However, there are further reasons why we were able to neglect a differentiation between road kilometres and lane kilometres for the purposes of this research:

First, the demand for road capacity is not primarily driven by the adjacent residential population. The median commute distance to work in Canada is 7.7 km, which means that the typical worker commutes substantially beyond their own census tract (Statistics Canada, 2017). The focus of this study is

the length of road necessary to provide access to all homes within an area, and not the capacity of road necessary to meet travel demand.

Second, demand for road capacity tends to be highest in areas with a higher proportion of shopping and work destinations, such as downtowns, which attract drivers both from the local area and the urban region as a whole (Kuzmyak 2012). Downtown residents are often those who drive the least, and so it would be misleading to link road-capacity requirements with local homes (Ewing and Cervero 2001).

Third, the lane-length per resident value is not useful for public right-of-ways which may have been pedestrianized or converted to shared pedestrian/vehicular road spaces without traffic lanes. While the number of such streets is still limited in Canada, calculations based on lane lengths would introduce significant errors on blocks abutting pedestrian streets such as Argyle and Granville streets in Halifax or one of the historic alleys in Downtown Victoria.

Approach

Spatial data were loaded into a single database using ArcGIS 10.4 (ESRI 2016). The datasets (i.e. the census tract boundary layers, selected road layers, and built-up area layers) were clipped to the extent of the respective census metropolitan area and projected to the UTM zone appropriate for the city within the NAD 1983 datum, in order to keep distance and area distortions to a minimum.

Both the built-up area and road network data were intersected with the census tract boundaries, so that the urban area and aggregated road length could be summarized at the census tract unit. In locations where roads function as a census tract boundary and exactly overlap with the polygon outline, the road length of that section was divided by two and added to each adjacent census tract in equal shares. For each census tract the sum of the length of all roads was divided by the population to determine the road length per resident value. Following these steps of geoprocessing, the values for each census tract were exported to data text file for statistical analysis.

RESULTS

Quantitative Patterns

Our analysis reveals a nonlinear relationship between net density and road length per resident in all cities, represented by power functions with exponents varying between -0.7 and -1.0 (Figure 1A). The relationship between population net density per hectare and road metres per resident is highly consistent across cities, with net density accounting for between 84% to 94% of the variation in road length per resident. The trend lines for each city are highly similar, as shown in Fig. 1B, suggesting a consistent geometric relationship between the two variables for all cities.

We find that this relationship stays roughly constant, regardless of the scale of the total urban population. The relationship also holds for both Edmonton and Calgary, our large-city references, suggesting that the correlation between road length per resident and net density is not specific to medium-sized cities. The shapes of scatter plots follow the pattern even if parts of the horizontal axis values are missing. This is e.g. the case in Victoria, which lacks densities below 4.6 residents per hectare, and Saskatoon and Sherbrooke, which lack high density census tracts (peaking at 42 and 47 residents per hectare, respectively).

Combining the census tracts for all cities, Figure 1C, yields a non-linear curve with an R^2 value of 0.90. The trend line for the correlation is $y = 81.90x^{0.89}$. Given this formula, we can break down the impact each single-unit increase in density has on road-length per resident, which we display in Table 1.

We find a highly consistent nonlinear relationship between net density and road length per resident across all nine cities, with a combined trend line of $y = 82x^{0.89}$, and variance of 0.90. This nonlinear relationship reveals a substantial difference between the road length per resident of low-density exurban neighbourhoods and inner-urban and suburban areas. (The difference is less substantial between medium-density suburban neighbourhoods and high-

density urban areas.) These findings suggest that below a certain threshold, low-density urban settlement patterns impose disproportionate costs in terms of linear infrastructure.

While trendlines for all nine cities broadly follow the same pattern, there are notable differences between them. London's trendline suggests that all of its higher-density census tracts (above 22 residents per hectare) tend to have the most efficient road lengths per resident compared with similarly-dense census tracts in other cities. However, its lower-density census tracts (below 15 residents per hectare) have comparatively inefficient road lengths per resident. Victoria reverses this pattern, with a trendline that suggests its densest areas (above 40 residents per hectare) have the least efficient road length per person values within the dataset, while its census tracts below 15 residents per hectare feature the second-most efficient road length per resident. Most regression curves of the analyzed cities intersect, i.e. they perform better or worse than other cities for specific ranges of net density. With R^2 values ranging between 0.82 and 0.94, these regression curves are largely reflective of the relationship between net density and road length per resident for each city.

Qualitative Patterns

All nine cities chosen for this study display similar qualitative patterns for the relationship between road lengths per resident and population density. We include two representative case studies in this article by analyzing maps of Halifax showing road length per resident (Figure 2) and population net density (Figure 3), and maps of Victoria showing road length per resident (Figure 4) and population net density (Figure 5). Similar patterns appear in all cities studied.

Downtown areas featuring high-density towers tend to range between 1 to 4 metres of road per resident, and in general, urban cores range between 1 to 6 metres per person. Older suburban neighbourhoods range between 3 to 7.5 metres of road per resident, meaning some of these neighbourhoods are as cost-efficient as downtown areas. It appears, however,

Figure 1. Road length per person drops by a power law with net density for nine Canadian cities (A). Trend lines show a consistent relationship across all nine cities (B). Combining all census tracts from all nine cities reveals a power law (C).

Table 1. The rate of change for road length per resident varies greatly among different levels of density. Stepping down from 28 to 27 residents per hectare adds road length at a rate three times faster than stepping down from 40 to 39. Stepping from 19 to 18 people per hectare, in turn, triples the rate again.

Density [ppl/ ha]	m/resident added	Change	Density [ppl/ ha]	m/resident added	Change
40	0.069	0.003	20	0.254	0.022
39	0.072	0.003	19	0.280	0.026
38	0.076	0.004	18	0.310	0.030
37	0.079	0.004	17	0.345	0.035
36	0.084	0.004	16	0.387	0.042
35	0.088	0.005	15	0.437	0.050
34	0.093	0.005	14	0.498	0.061
33	0.099	0.005	13	0.574	0.075
32	0.104	0.006	12	0.666	0.093
31	0.111	0.006	11	0.785	0.119
30	0.118	0.007	10	0.940	0.155
29	0.126	0.008	9	1.147	0.207
28	0.134	0.009	8	1.433	0.286
27	0.144	0.010	7	1.844	0.411
26	0.155	0.011	6	2.468	0.623
25	0.167	0.012	5	3.482	1.015
24	0.180	0.013	4	5.308	1.826
23	0.195	0.015	3	9.139	3.832
22	0.212	0.017	2	19.659	10.519
21	0.231	0.019	1	72.811	53.152

that many of these areas may have a low road length per resident because they have relatively large blocks, which may undermine other goals, such as walkability (Frank et al., 2008).

The findings suggest that a quantitative threshold exists between various growth patterns. Nearly all inner-suburban and urban neighbourhoods have a road length per resident of less than 7.5 metres, whereas low-density exurban neighbourhoods have values above 10 metres per resident.

Rural areas within census metropolitan areas tend to have between 10 to 100 metres of road per resident, with some roads used primarily for regional transportation and not local residential transportation. However, both Halifax and Victoria also have a number of exurban suburbs where roads do not connect to any destination other than local homes, but which have a road length per resident between 10 and 16 metres. The average road length per resident in such exurban suburbs amounts to 13.2 metres,

Aménagement et politique au Canada 2020

CIP-ICU & ACUPP-APUCU 9 Canadian Planning and Policy 2020

Figure 4. Road length per person values for census tracts throughout the urban area of Victoria

Figure 5. Net density values for census tracts throughout the urban area of Victoria

Shorter Roads go a Long Way

almost three times higher than the corresponding 4.7-metre average for all of Halifax's urban and inner suburban areas.

Apart from the earlier mentioned morphological variations, no obvious difference between road length per resident values could be observed between urban areas built before and after 1945. A comparison of road length per resident maps with historic outlines of Halifax and Victoria did not result in any observable differences between areas built prior to and in the two decades following the Second World War.

Only in more recent decades, neighbourhoods with lower road length efficiencies began to emerge. The oldest geospatial datasets of historic urban footprints from the Statistics Canada built-up area files (2016) date back to 1971. Figure 6 and Figure 7 present the earlier shown road length per resident maps with an overlay of urban footprints from 1971 and 2011.

Analyzing these figures, there is an observable tendency of exurban areas with road lengths per resident of 10 metres being developed at larger scale between 1971 and 2011. This finding suggests that despite the rise in private vehicle usage during the 1950s and 1960s, road lengths per resident were largely unaffected during these decades. However, as the proliferation of private-vehicle usage continued, it eventually began to affect the design of land subdivisions and efficiency of roads.

DISCUSSION

Comparison with existing literature

These results diverge from previous analyses of the impact of density on infrastructure costs, which tend to assume that a certain reduction in density yields a specific increase in costs. In Burchell et al.'s *The Costs of Sprawl – Revisited* (1998), the authors estimate dispersed growth increases costs of providing roads by 75%, schools by 95%, and utilities by 80%. See also Carruthers and Úlfarsson (2008), Fallah et al (2010) as well as Hortas-Rico and Solé-

Ollé (2010). Lambert and Meyer (2006) find that a 10% drop in population density increases the amount of time required for emergency services to arrive at accidents by 10.4%.

As opposed to these studies that suggest a linear relationship between density and infrastructure cost, our analysis of road length per resident reveals a non-linear relationship with population net density. As demonstrated in Table 1 of our results, adding or removing density to a neighbourhood will have different effects on its infrastructure efficiency in relative terms, depending on the starting point of a neighbourhood's density in absolute terms.

Similarly, our results do not support the suggestion that this relationship between density and road-network efficiency shifts with total population scale (Bettencourt *et al.* 2007, Bettencourt, et al., 2013; Kühnert and West 2006, Lobo *et al.* 2013). Low-density developments can increase the total length of roads at a greater rate than they increase population. This observation is consistent with the research of Arcaute et al. (2014), who have shown that population size by itself is insufficient to predict the growth of urban characteristics such as road surface areas.

The trend for the relationship identified between density and road length per resident across city neighbourhoods resembles the pattern identified by Müller et al. (2013), who revealed a negative non-linear relationship between a city's overall density and road length per resident. They find a variance in this relationship of 0.88, similar to the 0.90 variance we measure between neighbourhoods. Our results reinforce the pattern identified by Muller, yet on a much finer scale, demonstrating disproportionately high increases in road length per resident in low-density census tracts.

The case for road length per resident as a new metric in urban planning literature

While any spatial analysis of settlements – whether in the academic or professional context – does routinely involve some reference to population densities, the measurement of road length per resident

Figure 6. Road length per person values compared with spatial development over time in Halifax
CIP-ICU & ACUPP-APUCU 13 Canadian Planning and Policy 2020

Figure 7. Road length per person values compared with spatial development over time in Victoria

Shorter Roads go a Long Way

has received comparatively little attention until now. However, the results of this study show that road length per resident may be a more suitable metric in some contexts, and provides advantages in the interpretation and communication of research results related to density.

Measuring road length per resident has several advantages over population density alone. First, it more directly measures the source of many costs, including maintenance, snow clearing, and road construction. Population density, in contrast, underrepresents the costs generated by low-density neighbourhoods. The non-linearity of the relationship between net density and road length per resident means that the lowest-density exurban communities (characterized by local-serving roads, rather than long-distance rural roads, in areas with less than 10 residents per hectare) generate disproportionately large infrastructure costs per person. For example, exurban areas in Halifax have 2.8 times more road length per resident than inner suburban and urban census tracts.

Road patterns have a long-term impact on municipal finances, because once street networks are established, they tend to change little over centuries (Gudmundsson & Mohajeri, 2013). During the 2015/16 fiscal year, the cost of road maintenance (road repairs and snow removal, no utilities) per lane km amounted to \$14,798 (Halifax Regional Municipality, 2017). Since the vast majority of streets in of Halifax (apart from provincial highways, which were excluded from the sample of this study) are two-lane streets, it can be assumed for illustrative purposes that the overall maintenance cost of a street kilometre equals to approximately \$30,000. This means that in areas on the Halifax Peninsula (i.e. the urban core) with road lengths per resident of 4 m, the per capita road maintenance cost is approximately \$120. This compares to a cost of \$438 per resident in an external suburb reaching a road length per resident of 14.6 metres. Such an easily comprehensible attribution of cost is easier to communicate than population density considerations. This is particularly the case if the methodology would be extended to other areas of municipal

services such as utilities or garbage pickup, even though the calculation of those service could be more complicated due to higher differentiation of service levels across neighbourhoods.

Road length per resident may also be a valuable measure for communicating the benefits of compact growth to the public. Despite the popularity of density as a development goal among planners, the public often associates density with negative attributes, such as overcrowding (Choldin, 1978, Winston, 2010). Furthermore, the relationship between reduced infrastructure per person and reduced costs per person may be more intuitive for the public to appreciate than the connection between density and costs. However, our findings also demonstrate that the advantages of increasing population density are not infinite. While a certain number of people added to a low-density area may lead to a dramatic change in road length per resident, adding the same number to a high-density area will affect the road length per resident value to a much lesser extent. Adding population may contribute to tax revenue, but its benefit for reducing infrastructure costs per person are less substantial at higher densities.

Second, road length per resident can be used to assess the efficiency of contiguous urban versus fragmented exurban developments without needing to categorize land into built or non-built, a process which can introduce errors and ambiguities. The difference between the population density and road length per resident metrics becomes evident when comparing maps of Halifax and Victoria.

The built-up area files from Statistics Canada (2016) provide an opportunity for differentiation between gross density and net density by identifying urbanized areas in the cities included in this study. However, a comparison of road length per resident maps (Figures 2 and 4) with the population net density maps (Figures 3 and 5) points to some limitations of the density concept: while the preparation of the built-up area files excluded large tracts of natural lands, the aerial imagery processing was not as sensitive as to exclude smaller, municipal parks. For example, an area covered by a large park in the south end of Halifax diminishes the net density val-

Shorter Roads go a Long Way

ue for that census tract to the lowest on the Halifax Peninsula. However, the character of the neighbourhoods around the park is rather compact, which is reflected in a 4.4 metres of road length per resident value for the same census tract.

Similarly, the census tract of the North End of the Halifax Peninsula includes an industrial area with very large blocks covered by industrial and military land uses. Consequently, the net population density value of 19.3 residents per hectare is deceptively low for that area while the road length per resident value of 5.7 metres better portrays the character of the neighbourhoods within the census tract boundaries.

The comparison of road length per resident maps and population net density maps in Victoria offers complementary insights. On the one hand, the census tract of the South Oak Bay area has – similarly to the South End of Halifax – a deceptively low net population density value due to the presence of the Victoria Golf Club and Anderson Hill Park. The value of 6 metres road length per resident is better suited to describe the character of densely built neighbourhoods surrounding these green spaces. On the other hand, the Uplands neighbourhood of Victoria features very large lots and sprawling, windy roads throughout the entire subdivision. The low net population density value could be wrongly attributed to the presence of the Uplands Park within that census tract. However, the road length per resident value of 10.1 metres shows in this case that the morphology of street patterns plays an important role in the low efficiency of infrastructure provision for the area.

The examples illustrate why the usage of population density concepts is problematic. Even though the net density measurement is better suited to analyze infrastructure efficiencies than gross density, it is still susceptible to errors stemming from attribution of non-residential areas to the unit of analysis and the modified areal unit problem. The concept of road length per resident is not influenced by these variables in the same way and therefore constitutes a more robust way of analyzing settlement efficiencies.

Limitations and future research

The concept of road length per resident suffers from several limitations. Neighbourhoods with short blocks and high density may have the same road length per resident as neighbourhoods with long blocks and relatively lower densities, since less total road length is necessary to accommodate longer blocks. Neighborhoods of different forms and densities can therefore feature the same road length per resident values.

Larger blocks may reduce road-maintenance costs for municipalities, yet they are also correlated with a low active transportation mode share (Frank, et al. 2008; Marshall & Garrick, 2010). While road length per resident is directly tied to certain costs, it is by itself likely insufficient to make predictions on other important outcomes of urban design, such as health (Tam, 2017), pollution (Brugge, Durant, & Rioux, 2007), congestion (Dachis, 2013), and road wear and tear (Litman, 2009).

Road length per resident does provide researchers with less information than lane length per resident. While a cross-country analysis of lane metres was not possible due to the lack of data consistency, future research should analyze the relationship of traffic lane lengths with population density across urban geographies. This point is also closely related to another limitation of road length per resident: the lack of distinction between different levels of service. When road length per resident is used to describe efficiencies of public expenditure of road maintenance, it does not take into account that central areas of cities may receive higher maintenance priorities (e.g. higher snow plowing frequencies) and therefore create disproportionately higher maintenance costs.

Future research should include calculations of road length per resident and employment locations, since both households and businesses pay taxes and generate road users. Using a combined measure, mixed-use urban cores featuring many jobs will perform significantly better than single-use residential neighbourhoods. Road length per resident and employment may therefore better identify urban growth

Shorter Roads go a Long Way

patterns that are efficient both in terms of costs and walkability. Our results also show that some cities have road-length-per resident values other than those predicted by the average trend line within specific ranges of net density. These findings encourage further research into the potential ability to classify urban road morphologies that contribute to better or worse road efficiency outcomes.

Future research should also investigate the relationship between road length per resident and land economics. Since road length per resident is related to certain areas of municipal expenditure, it would be of interest to contrast these values with property assessment values, which are the main factor influencing municipal tax income.

CONCLUSION

These findings reveal that road length per resident varies non-linearly with density for the sub-geographies of cities, and in a manner relatively consistent across cities. The research also suggests that municipalities should avoid approving developments in the lowest category of density, below 10 residents per hectare, where the road length per resident tends to be many times higher than in other suburban neighbourhoods. Since road length per resident expresses a direct relationship between an important category of infrastructure costs, it could also constitute a valuable measure for urban growth targets.

These findings may help cities and other municipalities to better define growth targets and development strategies. In particular, the results suggest that a critical strategy for reducing overall road length per resident is to establish policies that prevent the lowest-density developments, which tend to have a disproportionately large impact on linear infrastructure costs per person. To our knowledge, the District of Nanaimo and City of Colwood in British Columbia are the only local governments in Canada using road length per resident for growth measurement (Regional District of Nanaimo, 2015; City of Colwood, 2019). Our results support the adaptation

of this measure for widespread use. Future research suggestions of this article may likely lead to further applications in urban policy making and governance.

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Shorter Roads go a Long Way

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