A Descriptive Analysis on Canadian Municipal Road Networks: Challenges and Opportunities

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Abstract

Municipalities in Canada own and manage approximately 68% of local roads, 62% of collector roads, and 42% of arterial roads, representing a larger share of the public road network than that managed by provincial and federal governments. Despite Canada's vast geography, population and economic activity are highly concentrated within a limited number of urban centres located primarily along the United States border and along Lake Ontario, and St. Lawrence River. Comparison of 2016 and 2021 census data indicate population decline in many rural and some urban municipalities, including approximately 75% of municipalities in Newfoundland and Labrador, 57% in Saskatchewan, and 37% in Manitoba, with direct implications for municipal tax bases and the fiscal capacity to maintain roadway infrastructure. This study discusses a national, municipality-level descriptive analysis of Canadian road networks using demographic data from Statistics Canada, data and guidelines from Federation of Canadian Municipalities (FCM) and publicly available municipal road network inventories to characterize variations in road network size, functional class composition, demographic and economic context across Canada. The analysis will apply descriptive statistics and comparative assessment across population size classes and regions to examine patterns in asset burden, network composition, and management practices. The intended outcome of this work is to establish a national baseline describing structural differences in municipal roadway systems and identifying systematic challenges faced by municipalities of different sizes and characteristics. The results are expected to inform ongoing research on adaptive pavement or road management system strategies, data standardization, and policy approaches to support asset management at regional level.

Introduction

Municipal road networks shapes transportation systems in Canada, supporting the movement of people, goods, and services while enabling economic activity and connectivity. Municipal governments are responsible for most of the road network by extent, particularly local, collector and arterial roads that provide direct access to residential and commercial areas (1). This responsibility places municipalities at the forefront of infrastructure planning, maintenance, and service delivery.

Canadian municipalities face significant challenges in managing roadway infrastructure. A key issue is the growing infrastructure funding gap, driven by aging assets, increasing maintenance costs, and limited revenue. Municipalities rely heavily on property taxes, which do not expand proportionally with infrastructure demands, particularly in regions experiencing population decline or slow growth (2). At the same time, demographic trends indicate that population growth in Canada is unevenly distributed, with strong growth concentrated in major urban centres and stagnation or decline observed in many smaller municipalities (3). These trends have direct implications for municipal fiscal capacity and long-term infrastructure sustainability.

In addition to financial constraints, municipal road networks exhibit considerable heterogeneity across jurisdictions. Differences in network size, functional class distribution, and traffic demand contribute to varying levels of asset burden and operational complexity.

Existing research on transportation infrastructure in Canada has largely focused on pavement condition assessment, performance modeling, and investment prioritization (4). However, there is a lack of national-scale, municipality-level analyses that integrate demographic context with roadway asset characteristics. A descriptive understanding of how municipal road networks vary across population scales and geographic regions is essential to inform infrastructure policy, funding allocation, and asset management strategies.

This study addresses this gap by conducting a comprehensive descriptive analysis of Canadian municipal road networks using demographic data from Statistics Canada (2016 and 2021 Census), combined with roadway network data and supporting contextual indicators. Municipalities are categorized based on population size to examine differences in asset distribution and capacity. Furthermore, a clustering-based analytical framework is introduced to group municipalities with similar asset burden and structural demand characteristics, consistent with the Comprehensive Functional Class Score (CFCS) approach.

The findings of this study aim to highlight key challenges faced by municipalities, particularly those with limited fiscal capacity, while identifying opportunities for more efficient and equitable infrastructure management. By providing a national-level perspective, this research contributes to the development of data-driven decision-making frameworks for sustainable municipal roadway asset management in Canada.

Literature Review

Demographic characteristics, particularly population size, are fundamental in shaping municipal capacity for road management. Population size directly influences both revenue generation and infrastructure demand, making it a critical determinant of asset management capability.

Larger municipalities typically benefit from a broader property tax base and greater revenues, which enable higher levels of investment in data collection, asset management systems, and proactive rehabilitation strategies (5)(6). These municipalities are also more likely to implement advanced road management tools and adopt data-driven decision-making processes. In other hand, higher population levels are associated with increased traffic volumes and greater heavy vehicle activity, which accelerate pavement deterioration and increase life-cycle maintenance requirements (7). This creates a dual effect, where larger municipalities possess greater financial and technical capacity but also face higher infrastructure demand and wear.

In contrast, smaller municipalities often function under constrained fiscal and institutional capacity. Limited tax bases and staffing, and lack of technical expertise restrict their ability to implement comprehensive road management frameworks. As a result, these municipalities tend to rely more heavily on reactive maintenance approaches, even though they are exposed to similar climate-driven deterioration mechanisms as larger jurisdictions (6). This imbalance highlights the importance of considering demographic context in evaluating municipal road network management performance.

Municipal road networks across Canada vary in length and composition, ranging from less than one kilometre to several thousand kilometres in total length. Key network characteristics influencing pavement management include total network size, functional class distribution, and pavement type.

Functional classification defined as arterial, collector, and local roads represents a fundamental dimension of road management because it directly governs traffic, loading, and performance. Arterial roads are designed to carry high traffic volumes over longer distances with limited access, while collector roads balance mobility and access, and local roads primarily serve property access with lower traffic demand (Transportation Association of Canada, 2017). These functional differences translate into distinct structural and operational demands on pavement. Higher-order facilities, particularly arterials are subjected to significantly greater traffic loading, including a higher proportion of heavy vehicles, which are the primary contributors to pavement structural damage. Pavement deterioration is strongly related

to axle loading, with damage increasing as axle weight increases (7). Consequently, arterial and collector roads experience accelerated structural deterioration, including fatigue cracking, rutting, and subgrade deformation, requiring more frequent and costly rehabilitation interventions (9). In addition to structural demands, these road classes are associated with performance and serviceability requirements due to their role in supporting regional mobility, transit operations, and economic activity. As a result, agencies often prioritize higher-class roads for maintenance to maintain acceptable levels of service and minimize user costs.

From a network-level perspective, the proportion of arterial and collector roads within a municipal system is a key determinant of overall asset management burden. Municipalities with a higher share of these road classes must allocate a larger portion of their budgets toward preventive maintenance, rehabilitation, and performance monitoring. This not only increases direct lifecycle costs but also necessitates more advanced asset management practices, including data-driven condition assessment and optimized intervention planning (10). Conversely, networks dominated by local roads typically experience lower traffic loading and slower deterioration rates; however, they may still pose management challenges due to their extensive spatial coverage and cumulative maintenance requirements. The distribution of functional classes therefore introduces a structural imbalance in municipal road network management, where higher-class roads drive cost intensity and technical complexity, while lower-class roads contribute to scale-related maintenance demand. This dual effect underscores the importance of incorporating functional class composition into system-level analyses and decision-support frameworks, as it provides a more accurate representation of infrastructure burden than total network length alone.

Total network length is another critical factor, as municipalities with larger networks face higher cumulative maintenance and rehabilitation costs. The distribution of network length across functional classes further compounds this effect, as different classes require varying levels of intervention and investment.

This study contributes to the literature by introducing a clustering-based approach that combines structural demand (functional class and traffic), and demographic capacity (population) to group municipalities with similar road management challenges. This approach enables more meaningful clustering and supports the development of adaptive road management strategies tailored to different municipal contexts.

Methodology

This research considers two vital publicly available database such as demography and road network to identify challenges and opportunities in Canadian municipal road management. Census data from 2016 and 2021 were used to assess population dynamics across Canadian municipalities. Municipal population sizes range from uninhabited jurisdictions to large urban centres exceeding million residents. Given that municipal roadway infrastructure is largely funded through property tax revenues, population size and change were treated as key indicators of financial and institutional capacity for asset management. Municipalities were therefore stratified into three population-based classes: small (<5,000), mid-sized (5,000–50,000), and large (>50,000). All subsequent analyses were conducted within these classes at the provincial level to ensure comparability. Over the 2016–2021 period, population changes were found to be weakly coupled with roadway asset extent. The extent of municipal road networks remains relatively stable over short time horizons i.e five (05) years. Accordingly, a single cross-sectional road network dataset (2020) was adopted as a proxy for the study period, under the assumption of negligible network expansion or contraction.

The road network dataset was acquired from the Open Canada Data Portal and processed within the QGIS. A preliminary quality assessment and visual inspection were conducted to evaluate dataset completeness, consistency, and spatial integrity. Road segments were organized at the municipal level and classified according to functional road hierarchy, including local, collector, arterial, highway, and other roadway classes. Using QGIS geoprocessing and geometry calculation tools, total roadway length was computed for each municipality in meters and subsequently standardized to kilometers for analysis consistency.

Analysis and Findings

Figures 1 and 2 present the distribution of municipalities across provinces by population size in both absolute and proportional terms. Figure 1 shows that small municipalities numerically dominate in all provinces, particularly in Saskatchewan and Quebec, while large municipalities are limited in number across Canada. Figure 2 confirms this pattern in relative terms, indicating that small municipalities typically account for the vast majority (often over 80%) of municipalities within each province. While provinces such as Ontario, Quebec, and British Columbia exhibit higher counts and shares of mid-size and large municipalities, their overall municipal structure remains heavily skewed toward smaller jurisdictions. Together, the figures demonstrate that Canada's municipal system is predominantly composed of small municipalities, regardless of provincial variation in total counts. This consistent dominance has important implications for pavement management, as smaller municipalities generally operate with limited financial and technical capacity, influencing their ability to implement comprehensive and proactive asset management practices.

Figure 1: Distribution of municipalities across Canadian provinces

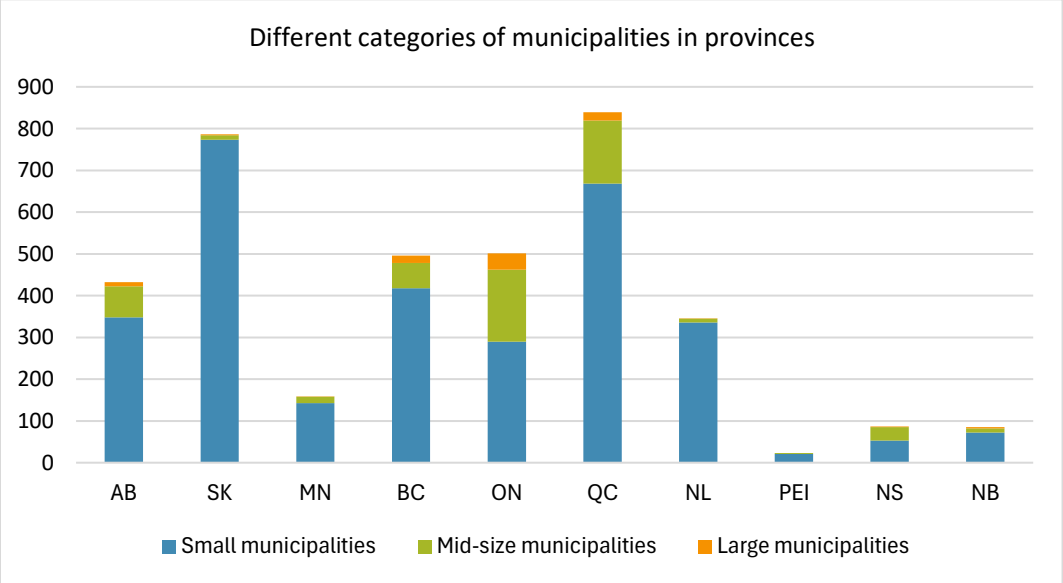
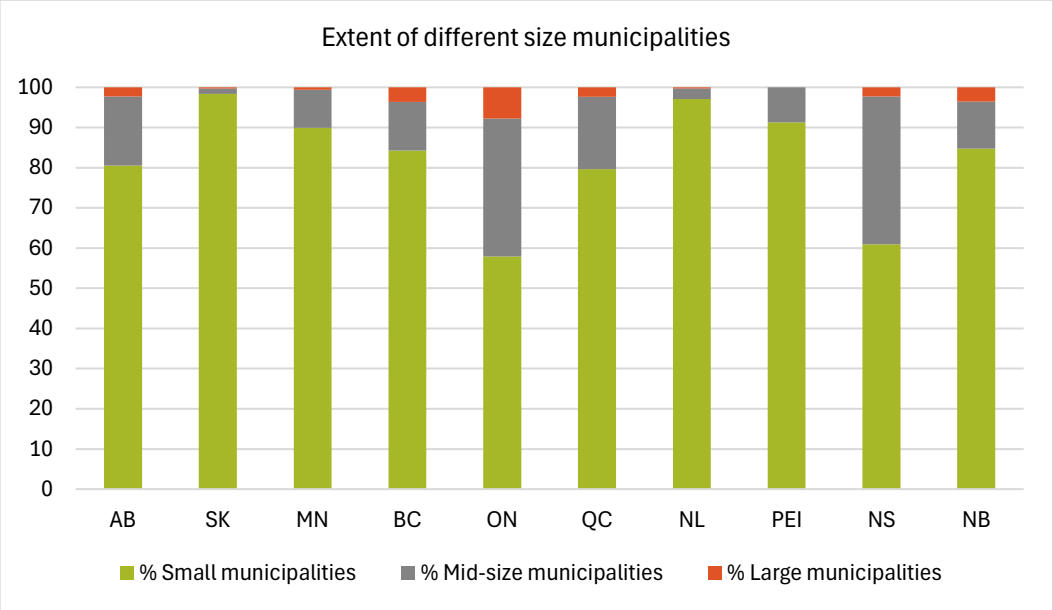


Figure 2: Percentage distribution of municipalities by population size across Canadian provinces



Small Municipalities

Municipalities with population size smaller than 5000 people are considered as small municipalities. Total 3120 municipal demographic and road network have been analyzed. Figure 3 represents the percentage distribution of population change in small municipalities across provinces (2016–2021), highlighting clear regional variation. Provinces such as British Columbia (approximately 65%), Manitoba (approximately 60%), Ontario (approximately 58%), Nova Scotia (approximately 60%), and New Brunswick (approximately 62%) are growth-dominated, with most municipalities experiencing population increases.

In contrast, population decline is prominent in Newfoundland and Labrador (approximately 75%) and Prince Edward Island (approximately 70%), with Alberta and Saskatchewan also showing majority decline (around 55–60%). Quebec presents a distinct pattern, with strong growth (approximately 65%) alongside a high share of unchanged municipalities (approximately 30%), indicating relative stability. Overall, the figure demonstrates that while some provinces show growth-dominated patterns, population decline exceeds growth in others, particularly in Atlantic Canada and parts of the Prairies. This has important implications for municipal capacity, as a high proportion of declining municipalities can lead to shrinking tax bases, reduced investment capacity, and increased challenges in sustaining roadway infrastructure.

Figure 3: Percentage distribution of population changes in small municipalities

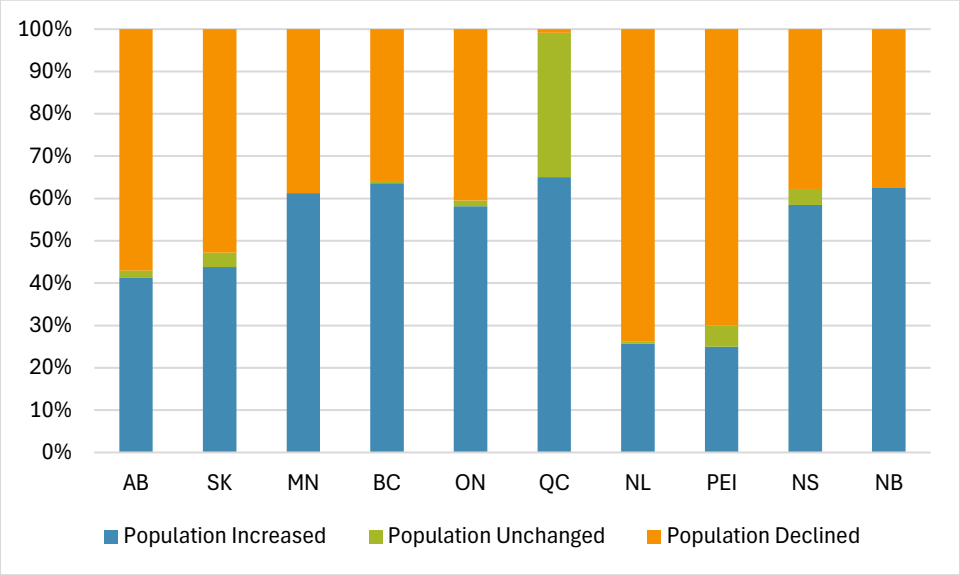


Figure 4 presents the functional composition of municipal road networks across provinces. The results indicate a clear dominance of local roads, which typically account for approximately 75% to over 90% of total network length in most provinces. This suggests that municipal systems are primarily oriented toward local access rather than mobility. Collector roads form a moderate share (generally between 8% and 40%), while arterial roads represent the smallest proportion, often below 20%, with a few exceptions showing higher values. Overall, the composition highlights relatively low structural complexity in many municipal networks, with limited presence of higher-order road classes.

Figure 5 illustrates the number of municipalities lacking specific functional road classes. A substantial number of municipalities across several provinces do not have arterial roads, and many also lack collector roads. In contrast, almost all municipalities have local roads, confirming their universal role in providing access. The absence of arterial and collector roads in many jurisdictions indicates that a simplified road hierarchy is common.

Figure 4: Road network composition in small municipalities

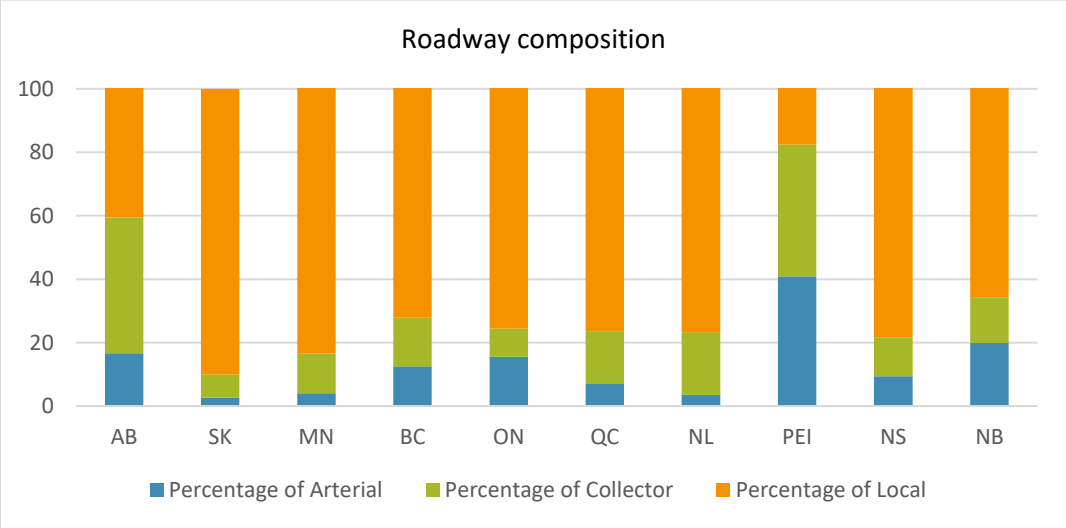


Figure 5: Missing roads by functional class in small municipalities

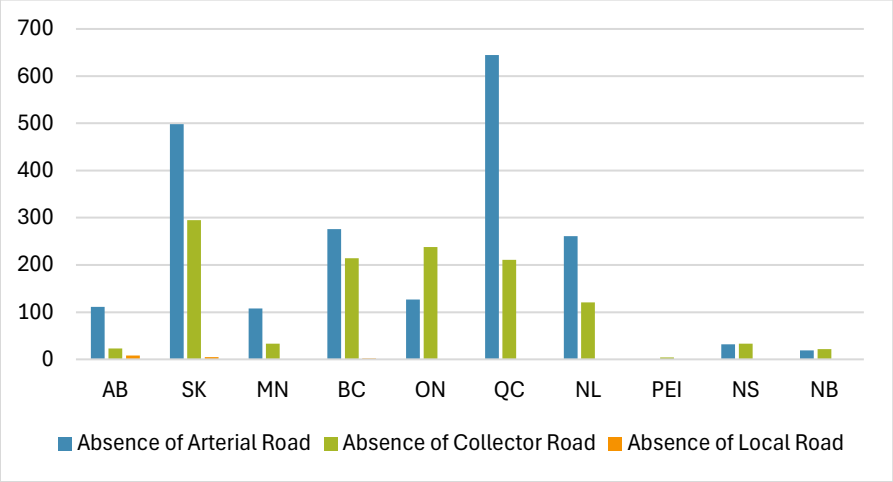
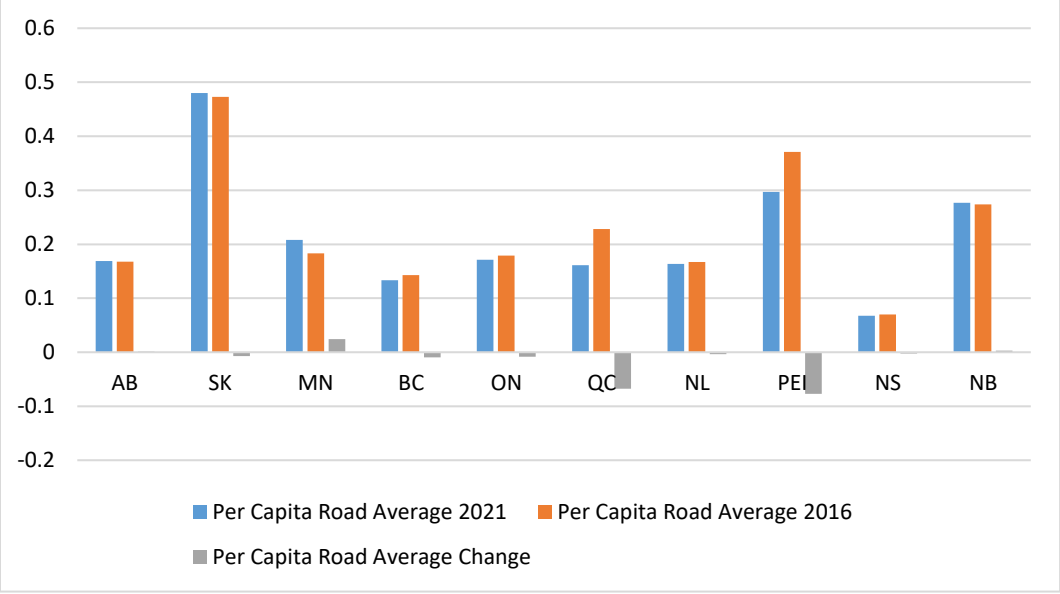


Figure 6 presents per capita road network burden for small municipalities across provinces for 2016 and 2021, along with the corresponding change over time. The results indicate substantial variation in infrastructure burden relative to population. Saskatchewan exhibits the highest per capita road length (0.48), followed by Prince Edward Island (0.29) and New Brunswick (0.27), reflecting a significant infrastructure burden relative to small population bases. In contrast, Nova Scotia (0.07) and British Columbia (0.13) show comparatively lower per capita values, indicating a more balanced relationship between population and road network size.

Most municipalities in the provinces show negative changes reflecting reduced burden due to population growth relative to infrastructure. A few provinces, such as Manitoba (+0.0245), Alberta (+0.0012), and New Brunswick (+0.0033), show positive changes, indicating an increase in burden, likely due to population decline. Overall, changes are driven primarily by demographic shifts rather than changes in road network size.

Figure 6: Per capita road network burden in small municipalities



Mid-Size Municipalities

Municipalities with population size over 5000 people but under 50000 people have been considered as mid size municipalities. Data from 540 municipalities were analyzed. **Figure 7** presents the percentage distribution of population change in mid-size municipalities across provinces (2016–2021). Population growth dominates in most provinces, with Manitoba (approximately 93%), Ontario (approximately 91%), British Columbia (approximately 90%), and Quebec (approximately 85%) showing a strong majority of municipalities experiencing population increases. This indicates that mid-size municipalities are generally growth-oriented and demographically stable.

In contrast, Newfoundland and Labrador stands out, where population decline (approximately 67%) exceeds growth, indicating a contraction trend in mid-size municipalities. Alberta and Saskatchewan show more balanced patterns, though growth still exceeds decline. Prince Edward Island exhibits complete growth (100%), though based on a very small number of municipalities, while Nova Scotia (approximately 66%) and New Brunswick (approximately 70%) also show moderate growth dominance. Overall, the figure demonstrates that mid-size municipalities are predominantly growth-driven across Canada, with only a few regional exceptions, suggesting relatively stronger demographic stability compared to smaller municipalities.

Figure 7: Percentage distribution of population changes in mid-size municipalities

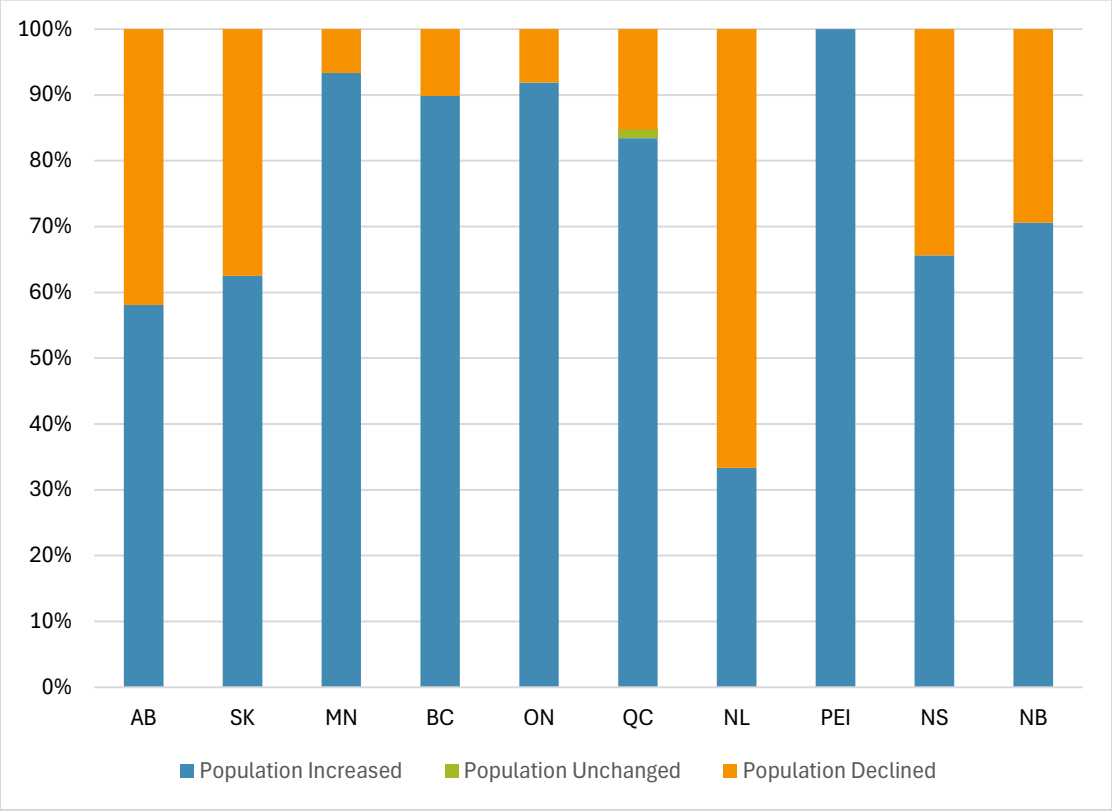


Figure 8 shows the functional composition of road networks in mid-size municipalities across provinces. Local roads dominate in all provinces, typically accounting for over 75% to 90% of the network. Arterial roads represent a relatively small share (generally <20%), while collector roads vary moderately across provinces. It should be noted that the percentage values were calculated using the AVERAGEIF function, excluding municipalities where a given road class was absent (i.e., 0% values). As a result, the reported percentages represent conditional averages, reflecting only municipalities where that road class exists. This approach avoids downward bias but implies that the actual overall share of arterial and collector

roads would be lower if all municipalities were included. Overall, the figure indicates that mid-size municipalities exhibit a more developed road hierarchy than smaller municipalities, but their networks remain largely dominated by local roads with limited higher-order infrastructure.

Figure 8: Road network composition in mid-size municipalities

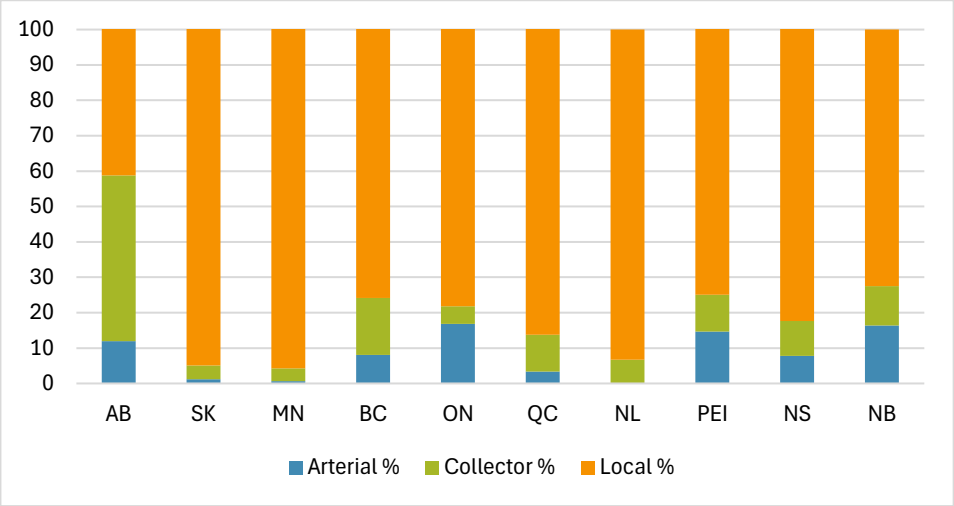


Figure 9 presents the number of mid-size municipalities lacking specific road classes across provinces. The results show that while most mid-size municipalities have a complete road hierarchy, notable exceptions exist. Quebec stands out with the highest number of municipalities lacking arterial (~130) and collector (~75) roads, followed by Ontario, which also shows a meaningful absence of collector roads (~40). Other provinces exhibit only limited instances of missing road classes, and the absence of local roads is negligible across all regions.

Figure 9: Missing roads by functional class in mid-size municipalities

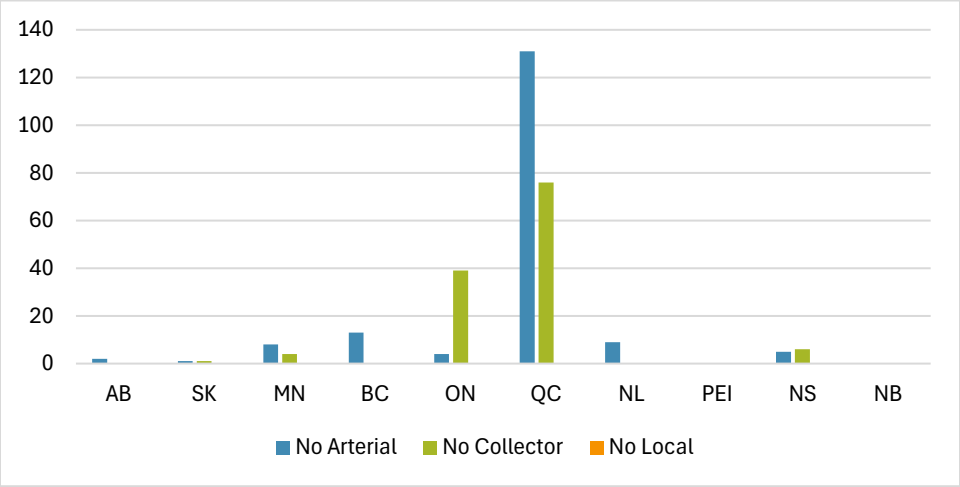
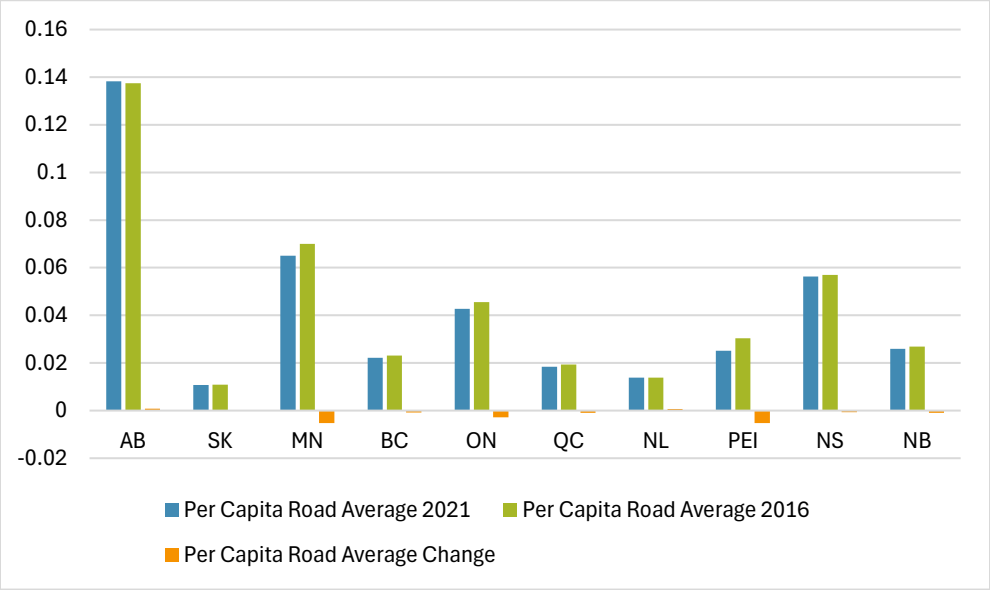


Figure 10 presents per capita road network burden in mid-size municipalities for 2016 and 2021, along with the corresponding change. Overall, per capita road values are relatively low and consistent across provinces, indicating a more balanced relationship between population and infrastructure compared to smaller municipalities. Alberta shows the highest burden (0.14), while provinces such as Saskatchewan and Newfoundland and Labrador exhibit the lowest values. Changes between 2016 and 2021 are minimal across most provinces, suggesting that road network extent has remained largely stable. Slight

negative changes observed in Manitoba, Ontario, and Prince Edward Island indicate a reduction in per capita burden, due to population growth relative to fixed infrastructure.

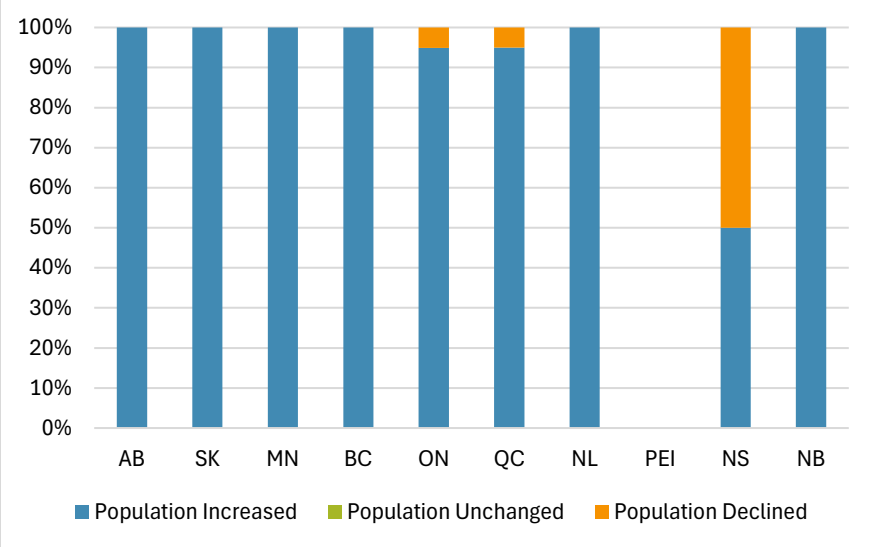
Figure 10: Per capita road network burden in mid-size municipalities



Large Municipalities

Municipalities with population size more than 50000 have been considered as large municipalities and data from 95 municipalities were analyzed. Based on this dataset figure 11 shows that the percentage distribution of population changes in large municipalities across provinces (2016–2021). The results show a near-universal pattern of population growth, with most provinces exhibiting 100% growth among large municipalities. Nova Scotia appears as an exception, where a portion of municipalities show population decline; however, this result is based on a very small sample size and should be interpreted with caution. Ontario and Quebec also show strong growth trends, reinforcing the concentration of population in larger urban centres. Overall, the figure demonstrates that large municipalities are consistently growth-driven, highlighting their role as primary centres of population concentration and infrastructure demand.

Figure 11: Percentage distribution of population changes in large municipalities



Local roads remain the dominant component in most provinces, generally accounting for over 70% to 90% of the network. However, compared to small and mid-size municipalities, large municipalities exhibit a more developed road hierarchy, with higher proportions of arterial and collector roads. Collector roads represent a notable share in provinces such as Alberta and British Columbia, while arterial roads are more prominent in provinces like Ontario and New Brunswick, indicating greater structural complexity and mobility function. In contrast, provinces such as Saskatchewan and Manitoba show very limited arterial presence, though these results may be influenced by the small number of large municipalities. Overall, the figure indicates that large municipalities maintain more balanced and hierarchical road networks, with increased representation of higher-order roads compared to smaller municipalities, reflecting greater traffic demand and functional requirements.

Figure 12: Road network composition in large municipalities

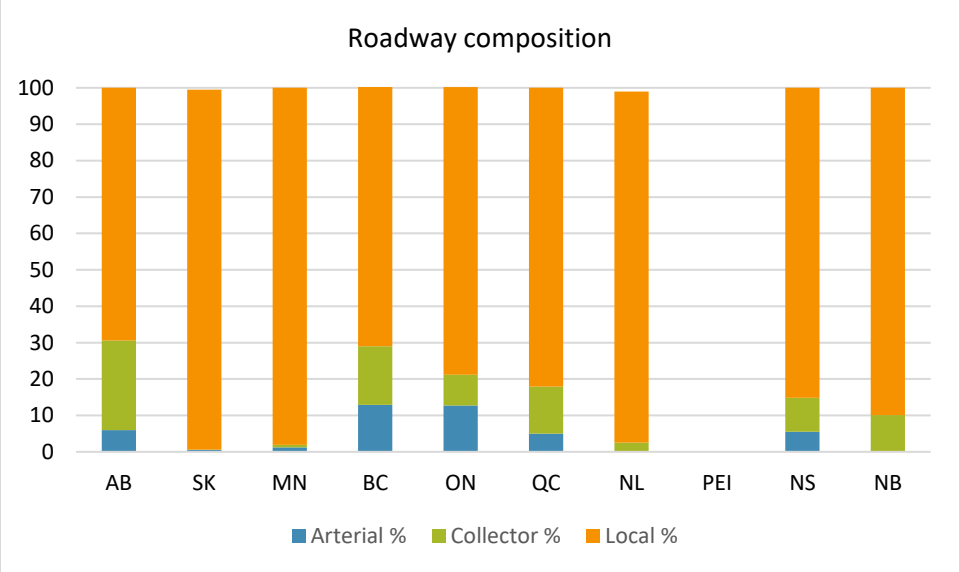


Figure 13 presents the number of large municipalities lacking specific road classes across provinces. The results show that most large municipalities have a complete road hierarchy, with very few instances of missing road classes. Quebec is the only province with a noticeable number of municipalities lacking arterial (13) and collector (9) roads, while Ontario shows a minimal absence of collector roads (1). All other provinces exhibit negligible or no absence, and no municipalities lack local roads. When interpreted alongside the composition figure, these results confirm that large municipalities generally maintain well-developed and complete transportation networks, with arterial, collector, and local roads present in most cases. The limited absence observed in Quebec may reflect local variations or classification differences rather than a systemic pattern.

Figure 13: Missing roads by functional class in large municipalities

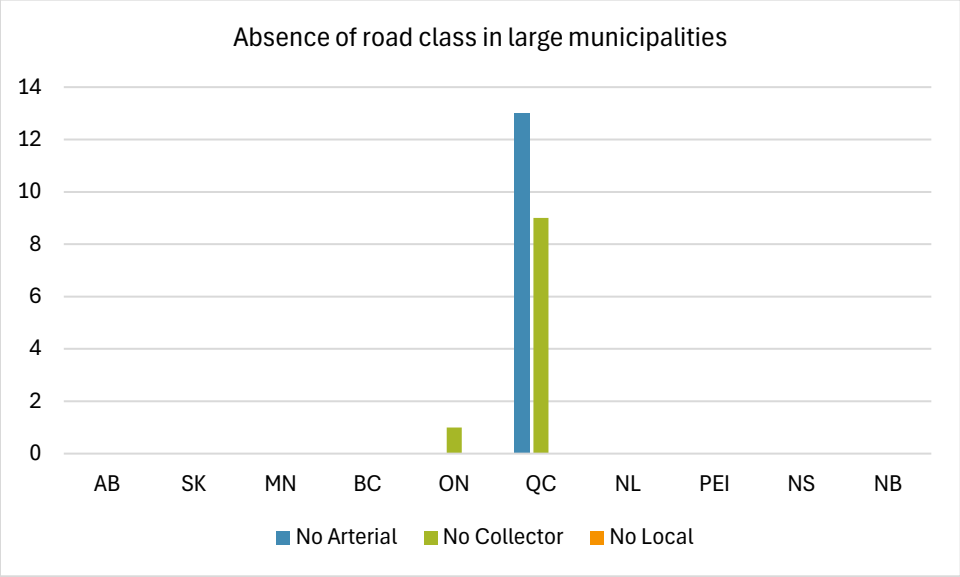
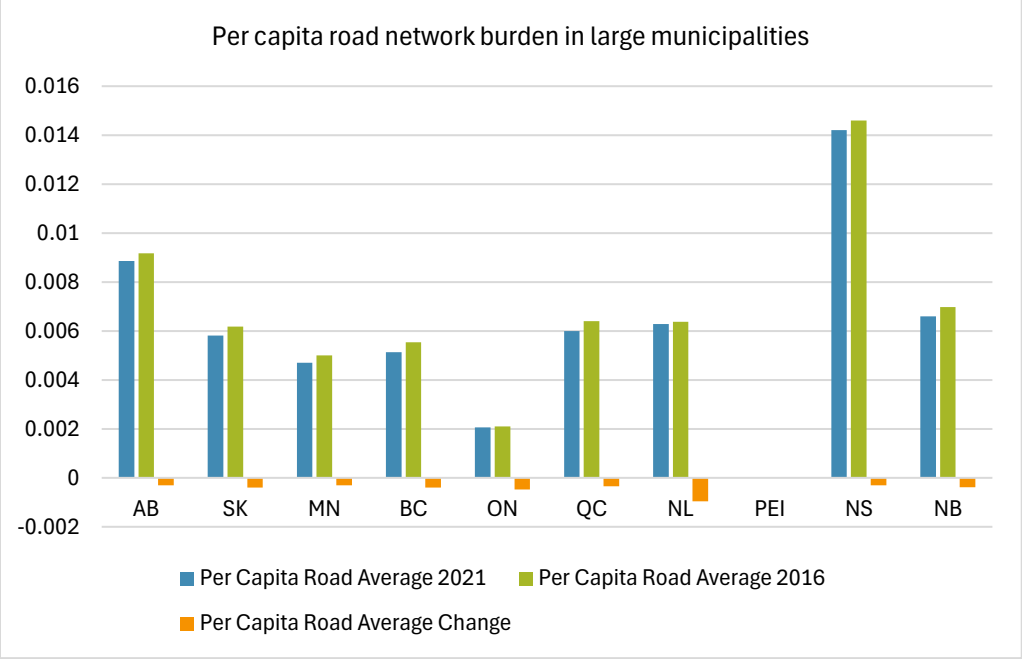


Figure 14 presents per capita road network burden in large municipalities for 2016 and 2021, along with the corresponding change. Overall, per capita values are very low across all provinces, reflecting a high population base relative to road network size and therefore a lower infrastructure burden per resident compared to small and mid-size municipalities. Variations across provinces are minimal, with Nova Scotia showing the highest per capita value (0.014), while Ontario exhibits one of the lowest (0.002). Changes between 2016 and 2021 are negligible in most cases, with slight negative trends indicating minor reductions in per capita burden, due to population growth relative to stable infrastructure.

Figure 14: Per capita road network burden in large municipalities



Comprehensive Functional Class Score (CFCS)

The Comprehensive Functional Class Score (CFCS) provides a quantitative framework to interpret the structural differences observed across small, mid-size, and large municipalities by capturing functional road ownership and associated management burden. CFCS translates the distribution of arterial, collector, and local roads into a standardized score reflecting the extent and complexity of infrastructure responsibility. Higher scores indicate greater ownership of higher-order roads and therefore increased structural demand, data requirements, and financial burden, while lower scores reflect simpler, local-dominated systems.

Table 1: Distribution of municipal road ownership by functional class of roads (Guha et al., 2025)

Class of road	Ownership distribution and score				
	4	3	2	1	0
Score Ownership Level	Very High	High	Moderate	Low	None
Arterial	15% or more	10%-14.99%	7%-9.99%	Less than 7%	0%
Collector	20% or more	15%-19.99%	10%-14.99%	Less than 10%	0%
Local	85% or more	75%-84.99%	65%-74.99%	Less than 65%	0%

Functional class composition was quantified using a weighted scoring framework based on predefined ownership thresholds for arterial, collector, and local roads (Table 1). Municipalities were categorized into percentage-based ownership bins for each road class and assigned ordinal scores $s_b \in \{0,1,2,3,4\}$, where 0 indicates no ownership and 4 represents very high ownership.

For each population group and functional class c, an expected score $E[S_c]$was calculated as the weighted average of bin scores:

$$E[S_c] = \frac{\sum_b n_b \ s_b}{N} (i)$$

where $n_b$is the number of municipalities in bin b, $s_b$is the corresponding score, and $N$is the total number of municipalities in the population group.

The Comprehensive Functional Class Score (CFCS) was then computed as the sum of expected scores across all road classes:

$$CFCS = E[S_{\text{arterial}}] + E[S_{\text{collector}}] + E[S_{\text{local}}](ii)$$

Figure 15 presents the spatial distribution of the average estimated CFCS score across provinces for small, mid-size, and large municipalities. CFCS reflects the structural complexity and functional burden of municipal road networks, with higher values indicating greater ownership of arterial and collector roads.

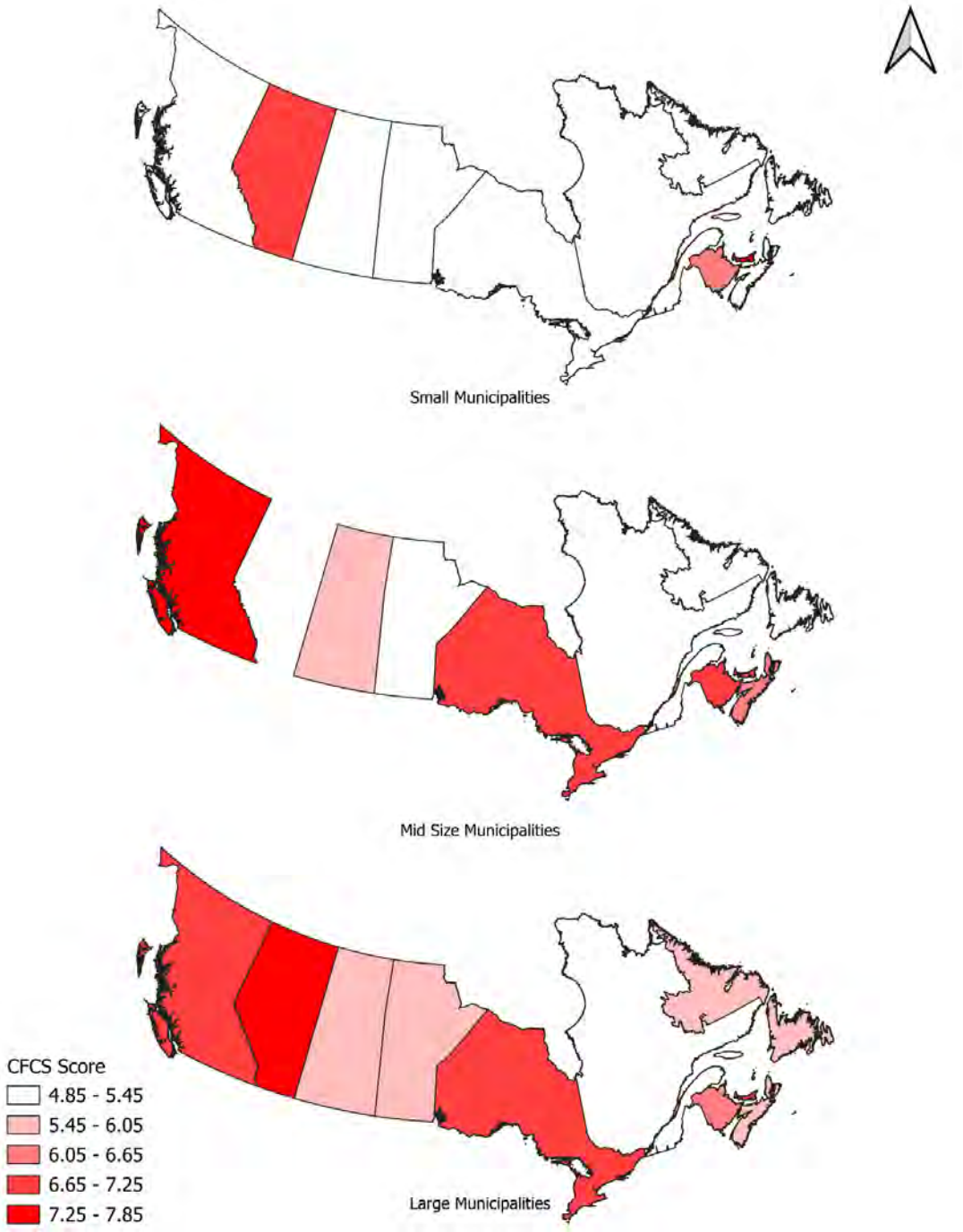
For small municipalities, CFCS values are generally low to moderate, indicating limited functional hierarchy and dominance of local roads. Only a few provinces show relatively higher scores, suggesting localized increases in arterial or collector ownership.

For mid-size municipalities, CFCS values increase across most provinces, reflecting a transition toward more developed road hierarchies. Provinces such as British Columbia, Ontario, and parts of Atlantic

Canada exhibit higher scores, indicating increased structural demand and more balanced distribution of road classes.

For large municipalities, CFCS values are consistently higher and more spatially concentrated, particularly in provinces such as British Columbia and Ontario. This reflects well-developed, hierarchical road networks with significant arterial and collector presence, supporting higher traffic volumes and mobility functions.

Figure 15: Spatial distribution of municipal CFCS score across provinces



Conclusion

From the descriptive analysis of municipal demography, road network and integrating CFCS score following conclusions can be drawn:

Small municipalities

- *Challenges:* characterized by low CFCS values, reflecting limited ownership of arterial and collector roads and a dominance of local networks. However, this structural simplicity is offset by high per capita road burden, particularly in provinces such as Saskatchewan and Newfoundland and Labrador. Coupled with widespread population decline, this creates a critical imbalance where municipalities must maintain relatively extensive infrastructure with shrinking financial capacity. The absence of higher-order roads further limits network functionality and prioritization strategies, while constrained institutional capacity often results in reactive maintenance practices, increasing long-term costs and asset deterioration.
- *Opportunities:* Despite these constraints, the simplicity captured by low CFCS presents opportunities for standardized and cost-efficient maintenance strategies, particularly for local roads. The identification of high-burden, low-complexity systems supports the development of capacity-adaptive PMS frameworks, including regional asset management partnerships, shared data systems, simplified condition assessment methods and targeted provincial funding based on burden indicators

Mid-size municipalities

- *Challenges:* exhibit moderate CFCS values, indicating increased ownership of arterial and collector roads and thus greater structural demand. While population growth is dominant, rising traffic volumes and service expectations introduce pressure on expanding infrastructure systems. Variability in road class presence as shown by partial absence of arterial and/or collector roads suggests uneven network development, complicating planning and prioritization.
- *Opportunities:* This group of municipalities represents the optimal transition stage in municipal road management. With balanced per capita burden and improving CFCS, mid-size municipalities are well-positioned to implement proactive, data-driven management system, lifecycle cost optimization strategies, early adoption of predictive maintenance tools. CFCS highlights their evolving complexity, while stable burden conditions provide the capacity to act. These municipalities offer the greatest opportunity for preventing future inefficiencies before reaching large-scale complexity.

Large municipalities

- *Challenges:* exhibit high CFCS values, reflecting complex and well-developed road hierarchies with significant arterial and collector networks. While per capita burden is low due to population scale, these systems face challenges due to high traffic loading and accelerated deterioration complex maintenance prioritization across multiple road classes, increased expectations for mobility, safety, and multimodal integration. These factors result in high absolute costs and operational complexity, despite favorable per capita conditions.
- *Opportunities:* Large municipalities benefit from economies of scale, allowing them to leverage advanced management tools, integrated transportation and asset management systems and data-rich environments for performance optimization. CFCS effectively captures their structural demand, enabling network-level optimization strategies and efficient allocation of resources across road classes.

Limitations

This study has some limitations related to data availability and methodological assumption. Demographic and road network data were not available for all municipalities across Canada. As a result, some municipalities were excluded from the analysis, which may affect the completeness and representativeness of the findings. The analysis assumes that municipal road network size remains stable over the 2016–2021 period. Changes in road network size, including expansion or contraction, were not explicitly accounted for, as such variations are generally limited over short timeframes (five years). While this assumption is reasonable for broad, system-level analysis, it may overlook localized infrastructure changes in rapidly growing or developing municipalities. These limitations should be considered when interpreting the results.

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