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ABSTRACT

Background
The lack of consistent measures of the cycling environment across communities hampers cycling research and policy action. Our goal was to develop the first national dataset in Canada for metrics of the cycling environment at the dissemination area (DA) level—the Canadian Bikeway Comfort and Safety (Can-BICS) metrics.

Data and methods
The Can-BICS metrics are area-level metrics based on the quantity of cycling infrastructure within a 1 km buffer of the population-weighted centroid of DAs. The base data are a national cycling network dataset derived from OpenStreetMap (OSM) (extracted January 25, 2022) and classified by high-, medium- and low-comfort facilities. A Can-BICS continuous metric (sum of cycling infrastructure per square kilometre weighted by comfort class) and Can-BICS categorical metric were derived and mapped for all 56,589 DAs in Canada. The Can-BICS metrics were correlated with other national datasets (2016 Canadian Active Living Environments [Can-ALE] and 2016 Census journey-to-work data) to test for associations between Can-BICS and related measures. Additionally, city staff were engaged to provide feedback on metrics during the development phase.

Results
One-third (34%) of neighbourhoods in Canada have no cycling infrastructure. According to the categorical measure, 5% of all DAs were assigned as the highest category of Can-BICS (corresponding to 6% of the population) and were nearly all within metro areas. The Can-BICS continuous metric had low correlation with bike-to-work rates (R = 0.29) and was more strongly correlated with sustainable-transportation-to-work rates (R = 0.56) and the Can-ALE metrics (R=0.62). These correlations were variable across cities.

Interpretation
The Can-BICS metrics provide national research- and practice-ready measures of cycling infrastructure. The metrics complement existing measures of walking and transit environments (Can-ALE), collectively providing a cohesive set of active living measures. The datasets and code are publicly available, facilitating updates as new infrastructure is built.

Keywords
Cycling infrastructure, active transportation, built environment, neighbourhood measures, surveillance

AUTHORS

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What is already known on this subject?

- Safe and comfortable infrastructure is vital for increasing cycling across Canada.
- Consistent national data on cycling infrastructure is lacking, hampering cycling research and policy action.

What does this study add?

- OSM Can-BICS metrics, DA-level metrics of the cycling environment for Canada, were developed based on open data (OSM) and categorized using the Can-BICS classification system.
- The OSM Can-BICS metrics provide national research- and practice-ready measures of cycling infrastructure.
- These cycling metrics complement existing measures of walking and transit environments and can be updated as new infrastructure is built.

While there have been recent efforts to develop national measures of active living environments for walking and transit in Canada,[1] there are no corresponding measures for cycling environments. For example, the Canadian Active Living Environments (Can-ALE) metrics include components for intersection density, dwelling density, destinations and transit (in the transit-specific measure) but exclude data on cycling facilities.[1] Cycling is the fastest growing mode of transportation in many Canadian communities[2] and has experienced major boosts during the COVID-19 pandemic.[3] Safe and comfortable cycling infrastructure is vital to get more people cycling, more often, for more trips.[4-6] Policy makers and researchers across the country working to improve conditions for cycling will be supported by a comprehensive map of cycling infrastructure and corresponding area-based metrics. For example, they will be able to identify areas with limited access to cycling infrastructure (e.g., potential sites for investment) or make comparisons across cities or through time with standardized research-ready metrics. Furthermore, metrics based on standardized areas facilitate linkages to sociodemographic, transportation and health datasets (e.g., census data, data from regional travel surveys and health survey data). In past work, spatial metrics have been incorporated to analyze the effects of cycling infrastructure on cycling behaviour,[6-8] make city- or neighbourhood-level comparisons[9,10] and assess inequities in accessibility.[11,12]

A wide array of metrics for cycling infrastructure have been used in the literature. These can be categorized into three types: area-based metrics[8,13] (e.g., the density of length in kilometres of infrastructure per square kilometre), population-based metrics[6] (e.g., the length of cycling lanes per 100,000 people) and road-network-based metrics[10] (e.g., the ratio of the length of cycling lanes to the total length of the street network). Spatial metrics have varied widely in terms of the cycling infrastructure included (e.g., sharrows [shared lanes] [13]), the level of traffic stress[14] and the scale (e.g., 500 m buffer [8], census tracts [7], neighbourhoods [14] or cities [12]).

The goal of this study was to develop area-level metrics of the cycling environment for Canada. The base dataset used was OpenStreetMap (OSM), the only national dataset of cycling infrastructure available.[15] Importantly, not all cycling infrastructure is equal in terms of comfort and safety. In our past work, OSM data were classified according to a standardized nomenclature—the Can-BICS classification system—which categorizes cycling infrastructure into three tiers (high-, medium- and low-comfort bikeways).[16] This process resulted in a national dataset of cycling infrastructure (OSM Can-BICS) with consistent bicycle nomenclature across jurisdictions ([17], currently under review). The current work aims to generate area-level metrics that characterize the extent of cycling infrastructure for all dissemination areas (DAs) in Canada. These new Can-BICS spatial metrics are presented in this paper alongside details on the metric development, comparison and descriptive results.

Data and methods

Study design

For all DAs in Canada, metrics were calculated based on the quantity of low-, medium- and high-comfort cycling infrastructure available. All analysis was completed using R, and the spatial metrics were mapped using ArcGIS. The approach to metric development was based on the Can-ALE index, a Canada-wide summary measure of intersection density, dwelling density and point-of-interest density at the DA level.[1] In the development of a comparable measure for cycling infrastructure, a range of possible metrics was considered. The decisions for metric selection were based on an examination across a spectrum of contexts. Approaches included statistical correlations with Can-ALE metrics, sustainable transportation rates from the census at the DA level, and consultation with local municipalities to confirm the infrastructure classifications and decisions regarding metric selection. The Can-BICS metrics were developed through initial testing in Vancouver and

Montréal and mapping and evaluation with seven other municipalities across five provinces. The methods were then applied to generate metrics for all 56,589 DAs in Canada.

Data

The Can-BICS metrics were developed from OSM Can-BICS, a national network of cycling facility data developed from OSM and classified to Can-BICS categories.[17] Details and supporting images for the Can-BICS classification scheme are available in a related publication[16] or, alternatively, in a web-based report available here: https://chatrlab.ca/projects/the-canadian-bikeway-comfort-and-safety-can-bics-classification-system/.[18] Under the Can-BICS classification scheme, high-comfort facilities are considered the lowest-stress facilities and include separated bike paths, cycle tracks and local street bikeways.[16,18] Medium-comfort bikeways are paved multi-use paths—considered comfortable for some people—and low-comfort bikeways are painted bike lanes—high-stress routes that are comfortable for few people. Nonconforming facilities, which are all other types of infrastructure that do not offer safety and comfort benefits or meet design guidance standards (e.g., sharrows, unpaved multi-use paths and other mixed-traffic local roads) are also included in OSM Can-BICS.

We used the OSM Can-BICS dataset released in January 2022 (available in shapefile format from https://arcg.is/0PyqOu and based on an OSM extract from January 25, 2022). All high-, medium- and low-comfort bikeways were selected for inclusion in the Can-BICS metric, and all nonconforming bikeways were excluded as they do not meet the safety and comfort criteria. Correlation analyses with various outcomes were used to test associations with related measures. The available national data on active transportation use were the sustainable-transportation-to-work and the bike-to-work totals from Statistics Canada's 2016 Census data.[19] The number of people taking public transit, cycling and walking as their main mode of commuting is captured by the sustainable-transportation-to-work total (Question 43 a: "Main mode of commuting for the employed labour force aged 15 years and over in private households with a usual place of work or no fixed workplace address—25% sample data"). The bike-to-work rates and the sustainable-transportation-to-work rates were calculated for each DA by dividing the number of bike or sustainable transportation (bike, walking and transit) commuters by the total sample of commuters in the census data. The available national data on the active living environment were Can-ALE. The correlation analysis used the 2016 Can-ALE summary index measure, available for 56,089 DAs across Canada.[1,20] The Can-ALE index for a DA is the sum of the *z*-scores for each active living environment characteristic (intersection density, dwelling density and point-of-interest density).

Canadian Bikeway Comfort and Safety metrics

The Can-BICS metrics are area-based metrics that capture the quantity of cycling infrastructure (high, medium or low). The spatial unit of analysis is a 1 km circular buffer around population-weighted DA centroids. The continuous Can-BICS metric is the weighted sum of high-comfort kilometres (× 3), medium-comfort kilometres (× 2) and low-comfort kilometres (× 1) within the buffer, normalized by the land area (square kilometres) within the buffer. Using the buffer-based approach avoids the issue of cycling infrastructure along DA boundaries, the edges of which typically align with major roads. Population-weighted DA centroids (i.e., centroids weighted by dissemination block populations) rather than geographic DA centroids were used, as population centroids focus on the land area that the majority of the population has access to.

The Can-BICS metrics include both a continuous measure (sum of kilometres of cycling infrastructure per square kilometre of land area weighted by comfort class), and a categorical measure that was created for ease of visualization and comparison. Categories were developed using k-medians clustering, classifying the total kilometre values in each buffer area into five categories, where Category 1 represents the lowest level of infrastructure and Category 5 represents the highest level of infrastructure. K-medians is a clustering algorithm used to group units (i.e., DAs) such that the sum of the differences between all the units in each cluster and its median value are minimized. K-medians clustering was used instead of k-means clustering because of right skewness of the distribution of total kilometres of cycling infrastructure resulting from many DAs having zero kilometres.

Analysis

Analyses were run on the full dataset of DAs (n = 56,589 DAs), with sensitivity analyses only in DAs from census metropolitan areas (CMAs) or only in DAs from specific cities. Two-thirds (64%) of Canada's 56,589 DAs are within CMAs and are home to 71% of the Canadian population. The analysis looked at the distribution of DAs and their respective populations across Can-BICS categories and was visualized in maps of selected cities.

For correlation analyses, there is no best way to validate a national dataset of the cycling environment given that the completeness and quality of open data are dramatically different across cities.[21] In terms of an available national dataset, measures of the cycling environment could correlate with measures of active transportation behaviours or other measures of active living environments. Therefore, Pearson's correlation coefficients were calculated between the continuous Can-BICS metric and bike-to-work rates, sustainable-transportation-to-work rates and Can-ALE indexes. Results are presented with the Can-BICS continuous measure (i.e., weighted kilometres per square kilometre), and for each of the metric subcomponents (kilometres per square kilometre of high-, medium- and low-comfort cycling infrastructure). For correlation with the bike-to-work mode share, DAs with no reported commute cycling (i.e., 0% bike-to-work rates) were excluded. For the correlations, the Can-BICS continuous metric was used (available for n = 56,589 DAs). This was correlated with the

Table 1
Summary statistics for the Canadian Bikeway Comfort and Safety continuous metric‡

Summary statistics	Total weighted km sum‡/km²	Total km/km²	High comfort km/km²	Medium comfort km/km²	Low comfort km/km²
Minimum	0.0	0.0	0.0	0.0	0.0
25th percentile	0.0	0.0	0.0	0.0	0.0
Median	0.9	0.6	0.0	0.0	0.0
Average	1.8	1.0	0.2	0.4	0.4
75th percentile	2.7	1.5	0.2	0.5	0.5
Maximum	24.3	10.3	7.1	5.4	4.6

‡ Weighted sum = high-comfort km × 3, medium-comfort km × 2 and low-comfort km × 1
Sources: Infrastructure data from OpenStreetMap contributors (2022) and metrics from Canadian Bikeway Comfort and Safety (2022).

Can-ALE metrics (available for 56,089 DAs), census bike-to-work data (available for 13,879 DAs with non-zero values) and sustainable-transportation-to-work rates (available for 54,950 DAs). Sensitivity analyses were run to look at correlations within CMAs and specific cities.

Metric development

The choices for the Can-BICS development were guided by past literature and, specifically, by the foundational work to develop the Can-ALE measures.[1] Our guiding principles were to develop a metric that was nationally useful (e.g., across different contexts) and one that explicitly recognized comfort and safety differences in cycling infrastructure. Initial testing of metrics explored options around the relevant buffer size, network versus Euclidean buffers, the inclusion of land area only in the denominator and weighting of infrastructure types.

First, multiple buffer sizes (from 1 km to 5 km) were compared to determine the ideal spatial unit size. Buffer sizes greater than or equal to 3 km led to an averaging of values across DAs because of more overlapping buffers, producing little spatial variation within cities. The 1 km circular buffer was selected as the final unit of analysis given its ability to highlight smaller areas with more bicycle facilities that were not shown with the 2 km buffer.

Circular buffers were also compared with road network buffers for the different buffer sizes. The road-network-based approach is dependent upon road connectivity and road density and, therefore, captured a smaller area than the circular buffer. In testing sites (city of Vancouver), both road network and circular buffers had comparable correlations with cycling-to-work and Can-ALE measures. Considering this, the decision was made to use a circular buffer, as there was no trade-off for the additional computational resources required to scale up a road network buffer nationally. The Can-ALE methodology also uses circular buffers.[20]

The Can-BICS metrics use land area as the denominator, excluding bodies of water. In our testing in British Columbia and Quebec, metrics with a denominator that used only land area more intuitively represented the level of infrastructure by Can-BICS category. This was particularly clear for small DAs that bordered water. A denominator of total area (including bodies of water) meant that areas with water were assigned to a lower Can-BICS category relative to inland DAs with comparable infrastructure. The strength of the correlation with bike-to-work rates, sustainable-transportation-to-work rates and Can-ALE indexes was also slightly higher when normalizing by land area only.

Finally, both unweighted (1:1:1 for high-, medium- and low-comfort infrastructure) and weighted (2:2:1 and 3:2:1) versions of the metrics were considered and discussed, with the latter resonating best with the research team and city staff in numerous municipalities. A non-weighted metric led to areas with many kilometres of low-comfort cycling facilities problematically having equal or better Can-BICS scores than areas with fewer kilometres but higher-comfort infrastructure. A weighting where medium- and high-comfort infrastructure were assigned an equal weight (× 2) led to a similar issue.

Results

Canadian Bikeway Comfort and Safety continuous metric

Within the 1 km buffers of DAs, the total kilometres of cycling infrastructure ranged from 0 to 28.5 km, with this highest value observed in downtown Vancouver. Nationally, the average Can-BICS continuous metric (weighted kilometres per square kilometre) was 1.7 km/km², with a maximum of 24.3 km/km² (Table 1). About one-third (34%) of DAs had no cycling infrastructure at all (this was 13% for the subset of DAs that were within CMAs). Overall, 40% of DAs did not have any medium- or high-comfort infrastructure (19% for the DAs within CMAs).

Canadian Bikeway Comfort and Safety categorical metric

Table 2 shows the summary statistics for the Can-BICS categorical measure, and Figure 1 illustrates the relative distribution overall (Panel 1A) and the stratified distribution by DAs within (Panel 1B) and outside (Panel 1C) CMAs. By the Can-BICS categorical measure, nearly half (45%) of DAs were classified in the lowest Can-BICS category (Category 1) (Table 2). At the other extreme, 5% of DAs, corresponding to 6% of the Canadian population, were in the highest Can-BICS category (Category 5). Within CMAs, there was a more even distribution across Can-BICS categories, with one-quarter of DAs each assigned Categories 1 through 3, and the remaining quarter of DAs assigned Category 4 or 5 (Figure 1B).

Maps of Can-BICS metrics in four example cities are provided in Figure 2 (data for all cities are available at

Table 2
Summary statistics of the five Canadian Bikeway Comfort and Safety categories, nationally, stratified by census metropolitan area, and within selected cities

	Category 1 (low)	Category 2	Category 3	Category 4	Category 5 (high)
All DAs (n=56,589)					
Number of DAs	25,395	11,710	9,827	6,691	2,966
Percentage of DAs	45.0	21.0	17.0	12.0	5.0
Percentage of the Canadian population	40.0	22.0	19.0	13.0	6.0
Bike-to-work rate					
Average	0.6	1.1	1.7	2.6	5.9
Standard deviation	2.0	2.6	3.4	4.3	5.9
Sustainable-transportation-to-work rate					
Average	10.4	17.8	23.1	29.1	48.2
Standard deviation	11.7	14.1	23.1	29.1	21.2
DAs within CMAs (n=36,169)					
Number of DAs	9,046	9,147	8,764	6,276	2,936
Percentage of DAs that are within CMAs	25.0	25.3	24.2	17.4	8.1
Percentage of the population living within CMAs	45.0	21.0	17.0	12.0	5.0
DAs outside CMAs (n=20,420)					
Number of DAs	16,349	2,563	1,063	415	30
Percentage of DAs that are outside CMAs	80.1	12.6	5.2	2.0	0.1
Percentage of the population living outside CMAs	77.1	14.3	6.0	2.4	0.2
Bicycle infrastructure (weighted sum, km/km2)					
Range					
Minimum	0.0	0.6	2.0	3.6	6.3
Maximum	0.6	2.0	3.6	6.3	24.3
Average	0.1	1.3	2.7	4.6	9.1
Median	0.0	1.2	2.7	4.5	8.1
			percent of DAs		
Summaries by city					
Large cities (population size greater than 500,000)					
Toronto, Ontario	28.6	30.1	24.1	13.5	3.8
Montréal, Quebec	3.3	15.8	26.3	23.8	30.8
Calgary, Alberta	3.6	13.6	30.9	35.6	16.3
Ottawa, Ontario	14.4	18.4	24.8	27.0	15.5
Edmonton, Alberta	7.8	18.4	28.8	33.0	12.0
Winnipeg, Manitoba	22.2	37.7	24.7	12.3	3.1
Vancouver, British Columbia	...	1.9	6.4	28.4	63.2
Québec, Quebec	13.0	25.8	31.0	22.2	7.9
Small to medium-sized cities (population size less than 500,000)					
Halifax, Nova Scotia	53.0	31.8	11.3	3.0	0.8
London, Ontario	24.9	41.8	22.3	11.1	...
Saskatoon, Saskatchewan	49.7	34.8	11.6	3.9	...
Regina, Saskatchewan	27.2	29.6	19.7	23.2	0.3
St. John's, Newfoundland and Labrador	72.4	20.0	7.6	...	...
Victoria, British Columbia	4.8	16.6	26.2	42.8	9.7
Charlottetown, Prince Edward Island	13.8	23.1	53.8	9.2	...
Whitehorse, Yukon	40.7	48.1	11.1	...	...

... not applicable

Notes: DA = dissemination area; CMA = census metropolitan area.

Sources: Infrastructure data from OpenStreetMap contributors (2022), metrics from Canadian Bikeway Comfort and Safety (2022), and boundaries and populations from Statistics Canada (2016). DA = Dissemination Areas, CMA = Census Metropolitan Areas

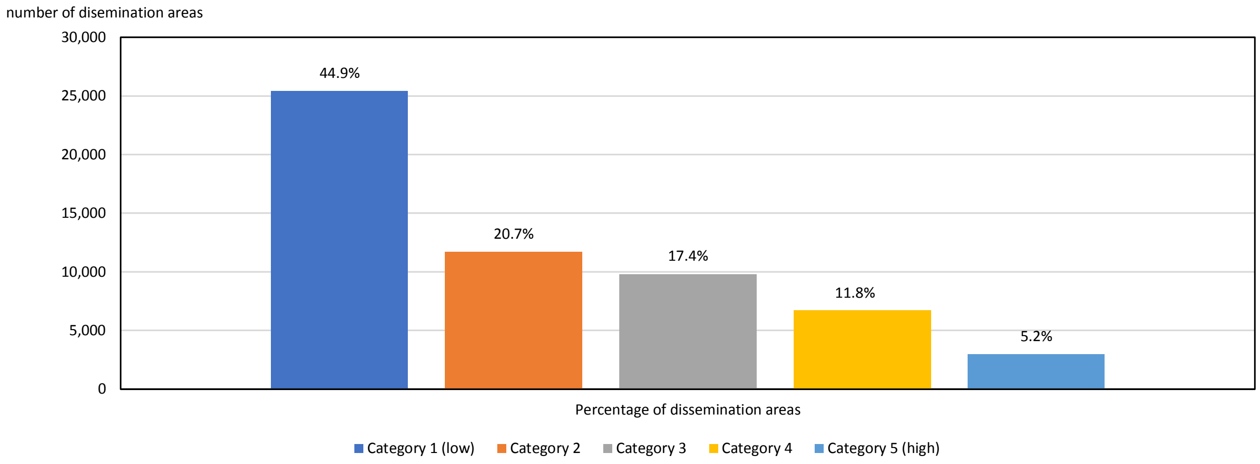
https://arcg.is/1X9iem0). While the administrative boundaries (e.g., census subdivisions) vary in how much less-developed surrounding areas they include, the data suggest substantial variability in cycling environments across cities. Among large cities (population greater than 500,000), Vancouver had the highest proportion of DAs with supportive environments (63% of DAs were Category 5), followed by Montréal (31% of DAs were Category 5) (Table 3). Vancouver also had no DAs assigned as Category 1 (Figure 2). Many of the small to medium-sized cities (London, Saskatoon, St. John's, Charlottetown and Whitehorse) had no DAs with a Can-BICS Category 5. The bike-to-work and sustainable-transportation-to-work rates increased by category, with a substantially higher increase from Category 4 to Category 5.

Correlation analysis

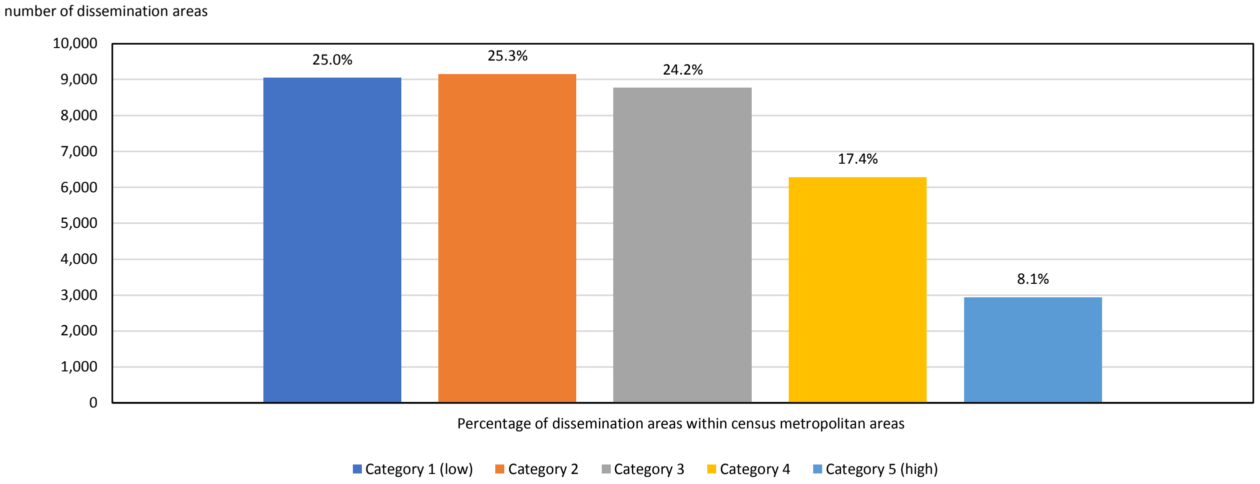
Table 3 provides national and city-specific correlations. The continuous Can-BICS metric (amount of infrastructure within a 1 km buffer weighted by comfort class) had a low correlation with DA bike-to-work rates (R = 0.29) but was more strongly correlated with the sustainable-transportation-to-work rates (R = 0.56) and the Can-ALE index (R = 0.62). When the components for each of the three Can-BICS comfort classes are examined individually, the kilometres of high-comfort infrastructure were most strongly associated with bike-to-work rates (R = 0.31), sustainable-transportation-to-work rates (R = 0.53) and the Can-ALE index (R = 0.59). Medium-comfort routes had little to no correlation with the bike-to-work rates, sustainable-transportation-to-work rates and Can-ALE index (R = 0 to 0.21). The sensitivity analysis indicates that the correlations between Can-BICS measures and bike-to-work and

Figure 1
Distribution of the categorical metric for the Canadian Bikeway Comfort and Safety across dissemination areas within and outside census metropolitan areas

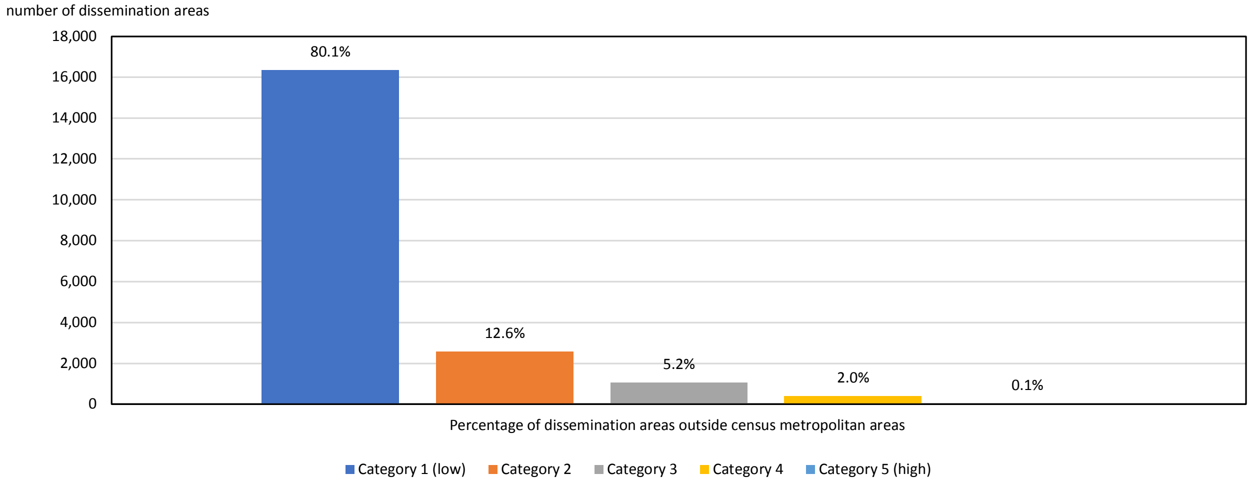
A - Distribution of dissemination areas (n=56,589) by Canadian Bikeway Comfort and Safety category



B - Dissemination areas within Canadian Bikeway Comfort and Safety category (n=36,169)



C - Dissemination areas outside census metropolitan areas (n=20,420)



Sources: Infrastructure data from OpenStreetMap contributors (2022), metrics from Canadian Bikeway Comfort and Safety (2022) and boundaries from Statistics Canada (2016).

sustainable-transportation-to-work rates are stronger for DAs within CMAs than those outside CMAs (Appendix Table A.1), suggesting that the associations are stronger within urban environments.

Correlations also varied by city (Table 3). For example, in Montréal, the continuous Can-BICS metric had a particularly high correlation with bike-to-work rates (R = 0.58). However, in Regina and St. John’s, there were negative correlations with bike-to-work rates and negative or no correlation with the Can-ALE index and sustainable-transportation-to-work rates (see Table 3). In Victoria, Can-BICS also had a negative correlation with bike-to-work rates but had relatively high correlations with sustainable-transportation-to-work rates (R = 0.58) and the Can-ALE index (R = 0.77). Among larger cities, only Vancouver had no correlation with bike-to-work rates. In Vancouver, the downtown has a high density of bicycle infrastructure and cycling volumes may be high, but bike-to-work rates (which are geolocated to trip origins) are lower for people living in the downtown core. The variable correlations with bike-to-work rates may have been a function of restricting to DAs with non-zero cycling rates—25% (13,879 DAs) had non-zero bike-to-work rates and were included in the correlation analyses. This proportion varied by city. Population size and kilometres of infrastructure alone did not explain the variation in correlations.

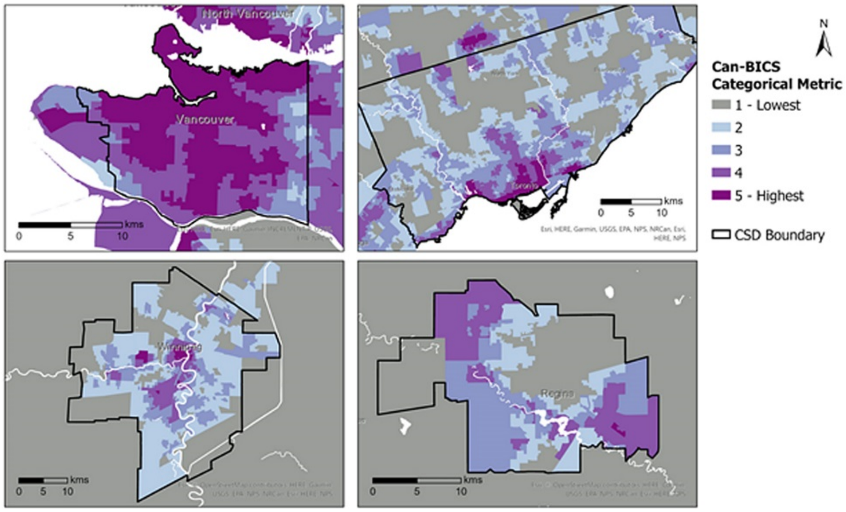
Discussion

This paper presents the development process and summary data for the first national dataset of cycling infrastructure metrics in Canada. The Can-BICS metrics consider the kilometres of cycling infrastructure weighted according to the three-tier Can-BICS comfort classification. The Can-BICS metrics align with the approach applied in the Can-ALE national dataset and thus allow for integration in future research with Can-ALE measures, census DA-level data, the Canadian Community Health Survey, Statistics Canada proximity measures and various environmental measures (greenness, air pollution, gentrification, etc.) available through CANUE (the Canadian pUrban Environmental Health Research Consortium). The metric can aid in a range of applications relating to accessibility; equity; and the assessment of the relationships between cycling infrastructure and other factors, such as population health, travel behaviours and road safety.

It stands out that many areas in Canada lack cycling infrastructure. According to the Can-BICS categorical metric, 5% of DAs, corresponding to 6% of the population, were assigned the highest category for cycling environments. Rates of cycling and sustainable transportation in the most supportive environments (5.9% of commuters cycling, and 48.2% of commuters using sustainable transportation in DAs with a Category 5) were substantially higher than those in the next level (2.6% of commuters cycling, and 29.1% of commuters using sustainable transportation in DAs with a Category 4). Conversely, nearly half (45%) of DAs in Canada had the lowest Can-BICS category (Category 1). Even within metropolitan areas, one-quarter of DAs were assigned the lowest category. Many of Canada’s metropolitan areas include rural areas, and this could explain, in part, the relatively large proportion of DAs with low Can-BICS rankings. In the lowest category, there was very little cycling to work (0.6% of commuters, on average) or use of sustainable modes (10.4%).

Figure 2

Canadian Bikeway Comfort and Safety categorical metric in four city census subdivisions



Sources: Infrastructure data from OpenStreetMap contributors (2022), metrics from Canadian Bikeway Comfort and Safety (2022) and boundaries from Statistics Canada (2016).

Table 3

Pearson correlations between the Can-BICS continuous metric, metric components, and bike-to-work rates, sustainable-transportation-to-work rates, and the Can-ALE index (overall and in 16 CSDs)[§]

	Continuous Can-BICS metric (weighted sum of km per km^2)					
	Average bike-to-work (percent)	**Correlation with bike-to-work rates**	**Average sustainable-transportation-to-work (percent)**	**Correlation with sustainable-transportation-to-work rates**	**Average ALE Index**	**Correlation with ALE Index**
Total weighted km sum[††] / km^2	…	0.29 [‡]	…	0.56 [‡]	…	0.62 [‡]
Total kms / km^2	…	0.29 [‡]	…	0.54 [‡]	…	0.61 [‡]
High comfort kms / km^2	…	0.31 [‡]	…	0.53 [‡]	…	0.59 [‡]
Medium comfort kms / km^2	…	0.00 [‡]	…	0.18 [‡]	…	0.22 [‡]
Low comfort kms / km^2	…	0.22 [‡]	…	0.38 [‡]	…	0.42 [‡]
Correlations by CSD with Can-BICS continuous metric (weighted km/km^2)						
Large cities (population size > 500,000)						
Toronto	3.0	0.21	44.8	0.53	3.96	0.65
Montréal	3.7	0.58	48.6	0.53	3.46	0.63
Calgary	2.0	0.28	22.7	0.53	1.12	0.55
Ottawa	3.0	0.30	31.1	0.57	1.20	0.66
Edmonton	1.5	0.19	21.3	0.49	0.27	0.65
Winnipeg	2.0	0.12	23.0	0.46	1.03	0.48
Vancouver	6.3	0.00	46.3	0.55	4.31	0.83
Québec	1.8	0.37	25.6	0.58	1.13	0.47
Small-medium cities (population size < 500,000)						
Halifax	1.1	0.02	22.4	0.63	-0.16	0.70
London	1.3	-0.02	17.3	0.22	-0.11	0.36
Saskatoon	2.7	0.31	14.0	0.48	0.08	0.33
Regina	1.3	-0.29	12.3	-0.23	0.23	0.05
St. John's	0.3	-0.41	15.3	-0.01	0.08	-0.03
Victoria	11.3	-0.23	46.2	0.58	2.79	0.77
Charlottetown	0.9	0.10	17.7	0.64	0.61	0.65
Whitehorse	2.9	0.16	18.1	0.50	-1.52	0.58

… not applicable

[‡] significant correlations ($p < 0.05$)

[††] Weighted sum = High comfort kms × 3 + Medium comfort kms × 2 + Low comfort kms × 1

[§] Number of DAs included in correlation: bike-to-work = 13,879 (non zero values), sustainable-transportation-to-work rates = 54,950; Can-ALE = 56,08

Notes: DA = Dissemination area; CSD = Census subdvision; Can-ALE = Canadian Active Living Environments.

Sources: Infrastructure data from OpenStreetMap contributors (2022); metrics from Can-BICS (2022) and Can-ALE (2016); and boundaries, populations, and transportation-to-work rates from Statistics Canada (2016).

While there is no best way of validating measures of the cycling environment, the Can-BICS metrics were correlated to some degree with available measures of the active living environment and sustainable transportation behaviours. Correlations varied between cities. For example, Regina and St. John's had low correlations that may be explained by the scarcity of cycling infrastructure in their downtown areas. The Can-ALE metric is largely a measure of density (intersections, dwellings and points of interest). A very strong correlation between Can-BICS and Can-ALE may not necessarily be expected for several reasons. First, some high-density areas may have substantial cycling infrastructure (i.e., protected bicycle lanes in a downtown core) but residents living there do not cycle to work. This was seen in Vancouver, where the highest density of infrastructure is in the downtown core—common routes and destinations—but downtown residents disproportionately walk to work. Commute data are attributed to home location and not to the destination or the routes used. This pattern was seen in Victoria where bike-to-work rates are very high in areas like Fairfield and Oak Bay despite these areas not having substantial bicycle infrastructure (these are areas where many people may choose to cycle to work based on proximity to destination and the provision of infrastructure along their routes). Second, across Canada, there is cycling infrastructure through more rural areas that serves to connect communities or provide tourism and recreation opportunities. Stakeholders who were involved in the development of the metrics emphasized that it was important for us to include rural areas, even where bike-to-work rates may be low. Unfortunately, the census captures only commuting for the primary mode of travel, which is not reflective of all active travel behaviour; bike-to-work trips comprise around 30% of all cycling trips.[22] Furthermore, medium-comfort infrastructure was most common nationally, and these multi-use paths are known to serve a high proportion of recreational trips. While crowdsourced big data such as Strava Metro or StreetLight offer potential as measures of cyclist volumes, they are not readily available for research or surveillance at the national scale.[23]

In addition to associations with Can-ALE and the census rates, the development of the continuous metric was further guided by consultation with staff in seven Canadian cities. Meetings with city planning and Geographic Information System staff provided valuable insights in the development of the metrics, including consistent feedback on a preference for weighting by comfort level rather than an unweighted metric. In consultation with smaller cities where pedestrian and cyclist volumes are lower, multi-use paths (medium-comfort kilometres with a weight of two) and compact gravel paths in parks (nonconforming kilometres that were omitted) were also perceived as providing relatively high comfort for cyclists, despite research evidence that safety along multi-use paths may be less than along bike-only paths.[24]. Although the Can-BICS continuous metric was ultimately weighted, the Can-BICS metrics dataset also includes continuous measures for the number of kilometres of high, medium, low and nonconforming infrastructure. These data could allow users to create different weightings depending on project goals or to explore how the three comfort classes compare in a city-specific study context.

The Can-BICS metric was developed using the OSM Can-BICS national dataset of cycling infrastructure, which relies on OSM data, a community-led mapping endeavour. Our past accuracy assessment of the OSM Can-BICS in 15 Canadian cities estimated that the OSM classification had an estimated accuracy of 76 ± 3% for presence or absence of infrastructure and 71 ± 4% for comfort class and that the OSM had, on average, a higher accuracy than open data sources for infrastructure identification and classification by infrastructure type and comfort level.[17] High-comfort infrastructure was underestimated, and low-comfort infrastructure was slightly overestimated.[17] The accuracy of the metric will improve through future community contributions to OSM and, subsequently, the OSM Can-BICS network dataset. The code for the OSM Can-BICS network dataset and for developing the Can-BICS metrics is publicly available (https://github.com/streckereck/osm_can_bics/tree/Metrics/code/metrics). This can facilitate future updates to this dataset.

This project was national in scope and aimed to develop metrics that could be applied nationally. Decisions may not apply perfectly to all communities. Our sensitivity analysis showed correlations were stronger for DAs within CMAs (more urban) than those outside CMAs. Even within those urban DAs, the strength and direction of correlations between Can-BICS and related measures varied across cities. The 1 km buffer approach was determined to be well suited for capturing variation in most urban areas, which have smaller DAs. However, in more rural areas with larger DAs, the buffer area was often larger than the DA. To compensate for this, we used population-weighted rather than geographic centroids. In other DAs that border bodies of water, the 1 km buffer could include cycling infrastructure across a body of water that is not easily accessible. The intention of these metrics is not to compare urban and rural areas, given the variation in DA sizes between such areas and the differences in the density of road networks. Other metrics of cycling infrastructure have considered normalizing by the total length of the road network.[10,12,25] This may be more suitable for studies that wish to compare rural and urban areas. Similarly, normalizing by population can be advantageous as it would capture the relationship between the supply of comfortable cycling infrastructure and potential demand (i.e., density of people living nearby to access it). The Can-BICS metrics aim to create measures of the environmental conditions without explicitly considering the underlying population (although DAs range in population from 400 to 700 people). Additional work may look at capturing connectivity or accessibility aspects of the cycling environment.

Conclusion

The development and testing of Can-BICS metrics, new measures of the amount of cycling infrastructure for all communities in Canada, at the neighbourhood level are presented in this paper. The Can-BICS metrics and the underlying data are available to explore on an interactive map (https://tinyurl.com/ytdk5eth), along with additional details on the project. As an open science project, the code is publicly available to facilitate the calculation of future versions of Can-BICS metrics as new infrastructure investments are made or with new mapping to OSM.

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Appendix Table A.1
Pearson correlations between the Canadian Bikeway Comfort and Safety continuous metric, metric components and bike-to-work and sustainable-transportation-to-work rates, for dissemination areas within and outside census metropolitan areas

	Continuous Can-BICS metric (weighted sum of km/km^2)		
	Correlation with bike-to-work rates	Correlation with sustainable-transportation-to-work rates	Correlation with ALE index
Within CMAs (n=36,169 DAs)			
Total weighted km sum[‡]/km^2	0.32	0.51	0.54
Total km/km^2	0.32	0.49	0.51
High-comfort km/km^2	0.34	0.51	0.55
Medium-comfort km/km^2	-0.07	0.06	0.07
Low-comfort km/km^2	0.25	0.31	0.32
Outside CMAs (n=20,420 DAs)			
Total weighted km sum[‡]/km^2	0.07	0.19	0.58
Total km/km^2	0.05	0.18	0.58
High-comfort km/km^2	0.06	0.15	0.36
Medium-comfort km/km^2	0.07	0.15	0.45
Low-comfort km/km^2	-0.01	0.10	0.39

[‡] Weighted sum = High-comfort km × 3, medium-comfort km × 2 and low-comfort km × 1.

Notes: DA = dissemination area; CMA = census metropolitan area; ALE = active living environment; Can-BICS = Canadian Bikeway Comfort and Safety.

Sources: Infrastructure data from OpenStreetMap contributors (2022), metrics from Can-BICS (2022), and boundaries and populations from Statistics Canada (2016).

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