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Evaluating equity and accessibility to jobs by public transport across Canada

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ABSTRACT

Accessibility, or the ease of reaching destinations, is increasingly being used and examined in both literature and practice. The most common accessibility metric, the cumulative opportunity measure, is often computed as the number of jobs that can be reached within a certain time frame. Aggregating all jobs, however, often inflates the opportunities that can be reached by socially vulnerable residents, which could feed into and/or generate inadequate policy decisions. This study therefore develops the measure of accessibility to low-income jobs for vulnerable residents by public transport, specifically taking into account realized travel times by these vulnerable individuals. This fine-grained measure, computed across 11 major Canadian cities, is a modified place-based accessibility metric that incorporates facets of person-based metrics, allowing planners and policy makers to propose more targeted interventions to improve the quality of life of their cities' most vulnerable populations. The study further allows for direct comparisons between the impacts of variation in accessibility levels between different regions to help create best practices in land use and transport planning.

1. Introduction

Transport and land use planning are inextricably linked. Although the modern concept of integrated transport and land use planning goes back to at least the 1930s (one could even argue as far back as 1846 when Charles Pearson suggested coupling housing estates and railway stations in London), interest seems to have been renewed after Calthorpe's proposal advocating transit-oriented developments and the rise of the New Urbanism movement (Barker and Robbins, 1963; Calthorpe, 1993; The Spectator, 1933). These shifts led to a new generation of transport professionals trying to move away from the dominant mobility planning paradigm, which had gained traction by traffic engineers in the 1950s and 1960s due to the dominance of the private automobile, towards the concept of accessibility planning (Proffitt et al., 2017).

Accessibility, or the ease of reaching destinations, is now increasingly being used to operationalize integrated land use and transport planning and to act as a performance indicator for these concepts (Boisjoly and El-Geneidy, 2017a). Indeed, metropolitan transport plans, such as those in London, Paris, Sydney and Atlanta, are now employing the concept, either as an independent goal or objective, or as part of an environmental justice assessment (Atlanta Regional Commission, 2016; Conseil régional d'Île-de-France, 2014; NSW Government, 2012; Transport for London, 2006).

Starting with Hansen (1959) (and somewhat later Wickstrom (1971), Ingram (1971) and Dalvi and Martin (1976), among others), a growing body of literature has been continuously refining the concept of accessibility (El-Geneidy and Levinson, 2006; El-Geneidy et al., 2016; Geurs and van Wee, 2004; Levinson, 1998, 2014; van Wee and Geurs, 2011). By far the most widely used metric for accessibility is the number of jobs an individual can reach within a set time limit (known as a cumulative opportunity measure) (Boisjoly and El-Geneidy, 2017b). One of the inherent strengths of this measure is that it makes comparisons between different socio-economic groups straightforward. It is thus not surprising that accessibility, especially in literature focusing on equity concerns, has often been used to identify which groups are being well served, and which are being underserved, or to predict who will benefit from a new transport or land use project (Foth et al., 2013). Contemporary research, however, relies on accessibility to jobs metrics that lack the ability to accurately discern between distinct populations; all jobs are usually counted as being accessible for everyone, as long as they can be reached.

This study refines the accessibility to jobs concept by developing a measure of accessibility to low-income jobs for vulnerable residents by public transport, and compares that to accessibility to all jobs experienced by the same group of residents across the 11 largest metropolitan regions in Canada. Such a metric has the advantage of specifically considering the opportunities that can be accessed by vulnerable groups, instead of grouping together e.g. finance and manufacturing jobs and assuming that these can be filled by everyone. Furthermore, the metric employs realized public transport travel times by low-income groups to correctly reflect the different characteristics between mode choice and commutes by different socio-economic populations. The finer granularity of this metric allows planners and urban decision makers to propose more targeted interventions, while the comparisons across cities enable us to highlight best practices in land use and

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Fig. 1. The eleven cities included in the analysis.

transport planning that can benefit vulnerable groups. As such, this is the first study to provide a comprehensive look at the state of accessibility in Canada's largest cities and to compare these cities in terms of the equity of their transport and land use systems. Fig. 1 shows the location of the 11 studied metropolitan regions across Canada.

The rest of this paper is structured as follows. The following section provides a literature review on accessibility metrics and the relationship between accessibility and equity. In section 3, the data and methodology used to calculate accessibility to both all jobs and low-income jobs is described, while section 4 compares accessibility measures across the different examined regions and discusses equity implications of these measures. Section 5 then discusses limitations and concludes this paper with policy recommendations.

2. Literature review

Accessibility, or the ease of reaching destinations, is a comprehensive metric measuring the interaction between land use and transportation (El-Geneidy and Levinson, 2006; Handy and Niemeier, 1997). The concept was first defined by Hansen (1959) as “the potential of opportunities for interaction”, and provides a measure for the variety and number of opportunities, or destinations, that can be reached from a certain point in space through the transportation network. As such, accessibility improves upon the concept of mobility by also considering potential and desirable destinations, instead of only examining an individual's ability to move.

Accessibility is generally understood to comprise four main components: land use, transportation, time, and the individual (Geurs and van Wee, 2004). Place-based accessibility metrics measure accessibility at a certain point in space, and usually only incorporate land use and transport factors due to data limitations. Person-based metrics, on the other hand, founded in space-time geography, focus on the individual, and thus also incorporate e.g. time budgets and socio-economic information (Geurs and van Wee, 2004).

Three common metrics of place-based accessibility exist. Cumulative opportunity measures of accessibility count how many destinations can be reached from a certain point in space within a certain time threshold using a certain mode, e.g. the number of grocery stores an individual can reach in 30 min by public transportation (Ingram, 1971; Morris et al., 1979; Wickstrom, 1971). Gravity-based accessibility measures, on the other hand, discount these destinations or opportunities by distance; the further an opportunity is, the less it contributes to accessibility (Hansen, 1959; Koenig, 1980). Such measures thus relax the assumption made by cumulative metrics that individuals stop travelling after a certain time threshold is reached, but are therefore more difficult to compute and communicate to varying audiences, reducing their chances to impact policy (Handy and Niemeier, 1997). A third set of commonly used measures are the utility-based accessibility metrics, which assign each destination with a specific utility and calculate the logsum of all destinations within a potential choice set (Handy and Niemeier, 1997). Utility-based accessibility can thus be computed as the denominator of the multinomial logit model. While such measures require extensive data collection, they can be converted into monetary units using Hicksian compensation variation, rendering them easier to communicate to urban decision makers (Geurs and van Wee, 2004; Niemeier, 1997). As several studies have found that the cumulative opportunities measure of accessibility is highly correlated to the gravity-based measure, and because the cumulative metric is the easiest to communicate to decision makers (El-Geneidy and Levinson, 2006), the cumulative measure has been adopted in recent studies comparing accessibility across cities (Owen et al., 2016).

Páez et al. (2010) developed an accessibility measure that compromises between detailed person-based metrics and generalizable place-based measures, which “gives much needed flexibility to investigate accessibility trends specific to a population segment and a location in space” (see also (Páez et al., 2013)). Their accessibility indicator (a modified cumulative metric) uses model-based estimates of distance traveled which can differ by location and population segment, instead of using ad-hoc estimates that are not statistically supported. These distances are calculated from origin-destination travel surveys which provide intricate detail of where people live and work. Such information is however not widely available across Canada. As such, this paper intends to adapt the method described in Páez et al. (2010), by using commonly available census data to generate statistically valid travel time thresholds that improve realism compared to arbitrary thresholds.

Accessibility measures were developed with the intention of evaluating transport and land use systems, while simultaneously allowing for the ability to measure the effects of proposed plans and investment strategies (Morris et al., 1979). Accessibility is thus designed to accurately measure the benefits resulting from interacting land use and transport systems. Such benefits range from increased development potential in highly accessible locations (Ozbay et al., 2003), to land value premia generated by accessibility (Martínez and Viegas, 2009), decreased risks of social exclusion (Lucas, 2012), shorter unemployment duration for individuals experiencing high accessibility levels (Andersson et al., 2014; Korsu and Wenglenski, 2010), and lower unemployment rates among low-income households (Boisjoly et al., 2017; Hu, 2017). Furthermore, accessibility has been linked with shorter commutes (Levinson, 1998) and, in areas with high accessibility via public transport, higher incidences of public transport use (Foth et al., 2014; Owen and Levinson, 2015).

Accessibility is therefore often used to differentiate the effects of new transport plans between socio-economic groups: who stands to benefit and who will lose (Levinson, 2014; Manaugh and El-Geneidy, 2012; Martens, 2017)? Driven by such notions of equity, transport researchers have developed a vast amount of literature discussing accessibility and equity (see, among others, Bocarejo and Oviedo (2012); Delbosc and Currie (2011); Delmelle and Casas (2012); El-Geneidy et al. (2016); Foth et al. (2013); Guzman et al. (2017); Lucas et al. (2016); Páez et al. (2013); van Wee and Geurs (2011)). Two conflicting notions of equity exist, however. To achieve horizontal equity, accessibility should be equally divided across the entire population, regardless of individuals' socio-economic status. Vertical equity, on the other hand, would be achieved when those with the highest need experience the highest accessibility; the concept thus posits that socio-economically vulnerable populations should have higher accessibility (Karner and Niemeier, 2013; Martens, 2017).

While most scholars focus on measuring accessibility to jobs, accessibility has also been calculated to health care facilities, schools, grocery stores, and a myriad of other opportunities (Bissonnette et al., 2012; Grengs, 2015; Guagliardo, 2004; Luo and Wang, 2003; Mao and Nekorchuk, 2013; Páez et al., 2010). However, jobs remain the most prominent non-home destinations and are thus particularly useful in measuring an area's attractiveness (Owen et al., 2016). Accessibility to jobs, in addition to indicating how many jobs an individual might reach, also has the added benefit of providing a measure of nearby amenities; all services we'd like to reach, be they restaurants or the theatre, for example, employ a certain amount of people and are therefore measured within the accessibility to jobs framework. While some studies have examined and compared accessibility to jobs across different cities (Owen et al., 2016; Ramsey and Bell, 2014; Tomer et al., 2011), to our knowledge no such research has been undertaken in the Canadian context with a detailed focus on equity.

Despite the prominence of equity in accessibility research, there has been limited focus on specifically measuring accessibility to low-income or low-wage jobs. Such accessibility metrics provide a better representation of the state of access for vulnerable groups, as there are often non-spatial barriers to acquiring high-wage employment (Legrain et al., 2016). While most studies measuring accessibility to jobs often find that vulnerable groups experience higher accessibility levels (see for example Foth et al. (2013)), these studies usually do not specifically measure access to low-income jobs, i.e., to destinations that are more valuable for socially vulnerable populations (Legrain et al., 2016).

This study contributes to the growing body of literature on accessibility to jobs in three major ways. Firstly, we move away from the use of arbitrary time limits usually used in cumulative measures of accessibility, and instead compute the average commute (once for all commuters, and once for low-income commuters) to determine the time threshold, thereby more accurately modelling people's activity spheres. Secondly, along with calculating accessibility to all jobs, we also discern accessibility to low-income jobs, and specifically measure the latter for vulnerable groups. Finally, this paper is the first to compare such measures and the consequent equity of the transport and land use interaction across eleven major Canadian metropolitan areas, in order to provide a more holistic view on the equity of public transport provision in Canada. Such a comparison can help inform other cities and regional planning agencies and generate best practices in accessibility planning to benefit vulnerable segments of the population.

3. Data and methodology

To compute the accessibility to jobs metric, public transport schedules across the eleven cities were gathered in the General Transit Feed Specification (GTFS) format from their respective transport agencies. Transit schedules were obtained for March 2017, or, when not available, for the available dates closest to this date. For large metropolitan areas with multiple providers, the schedules from all agencies were obtained with overlapping schedule dates.

Transit schedules were subsequently imported into a geographic information system through the *Add GTFS to a network dataset* add-on for ArcGIS. A joint network between the public transport network and the streets was then created. Travel times between census tract centroids were computed based on the joint network through a fastest route calculation during the morning peak at 8 AM on a regular Tuesday. By creating a joint network, the algorithm did not force the fastest path to solely choose public transportation: when a route between two census tracts was faster by walking, the walking route was thus designated as the fastest. The computation for public transport travel time incorporated access time, waiting time, transfer time when applicable, in-vehicle time, and egress time.

Jobs data was acquired through Statistics Canada, from the 2016 Census, in the form of commute tables for each Canadian province. The tables present the number of commuters, by personal total income and mode of transport, working in each census tract; both residents commuting within the same census tract as those coming from outside are counted. Abstracting unfilled positions, the total amount of individuals working in each census tract is an accurate proxy for the number of jobs in each tract.

To define the threshold for low-wage jobs, the incomes from the commuting tables were used (i.e., the total income of the individual commuting to a job). While these might not necessarily perfectly reflect the wage obtained from a certain job (e.g. it would overestimate a job's wage for individuals with two or more jobs, as their total income would be higher than any one of the two wages), the commuting tables provide a comprehensive and uniform way to define a job's wage across all Canadian provinces and metropolitan areas. To reflect local variances in the cost of living and wage distribution, the low-income threshold was determined individually for each metropolitan area as follows: the 30% lowest paying jobs in each city were designated low-income. As income was only available in brackets, the closest bracket was chosen as the threshold (e.g. if 29% of the jobs would fall within or below the $20,000–$30,000 bracket, then $30,000 would be the threshold).

Based on census tract travel times and jobs data, accessibility was computed via a cumulative accessibility metric as follows:

$$\mathrm{A}_j = \sum_i O_i f\left(t_{ij}\right) \text{and } f\left(t_{ij}\right) = \begin{cases} 1 \; if \;\; t_{ij} \leq t_{threshold} \\ 0 \; if \;\; t_{ij} > t_{threshold} \end{cases}.$$

where A_j is the accessibility in census tract j, O_i is the number of jobs in census tract i, t_{ij} is the travel time between census tracts i and j, and $t_{threshold}$ is the average duration of a commute by public transport in the region.

Accessibility to low-income jobs was calculated as follows:

$$ALI_j = \frac{\sum_k O_k}{\sum_k LI_k} \sum_i LI_i f\left(t_{ij}\right) \text{and } f\left(t_{ij}\right) = \begin{cases} 1 \; if \;\; t_{ij} \leq t_{threshold, low-income} \\ 0 \; if \;\; t_{ij} > t_{threshold, low-income} \end{cases}$$

where ALI_j is the accessibility to low-income jobs in census tract j, LI_i is the number of low-income jobs in census tract i, t_{ij} is the travel time between census tracts i and j, and $t_{threshold,\ low-income}$ is the average duration of a commute by public transport in the region for those travelling to low-income jobs. $\frac{\sum_k O_k}{\sum_k LI_k}$ represents the ratio of all jobs to low-

Table 1
Summary statistics for the 11 metropolitan areas.

Metropolitan area	Population	Total number of jobs	Population density (pop/km^2)	Median household income (CAD)	Unemployment rate (%)	Average commute (min)	Average commute threshold (min)	Average low-income commute (min)	Average low-income commute threshold (min)	Low-income threshold (CAD)
Calgary	1,392,609	585,860	272.5	99,583	9.3	58.29	60	56.84	55	40,000
Edmonton	1,321,426	551,140	140.0	94,447	8.5	63.95	65	53.62	55	40,000
Halifax	403,390	180,860	73.4	69,522	7.3	60.14	60	54.15	55	30,000
Kitchener – Cambridge – Waterloo	523,894	227,500	480.1	77,229	6.4	45.88	45	45.90	45	30,000
London	494,069	199,090	185.6	64,743	7.3	49.23	50	51.42	50	30,000
Montreal	4,098,927	1,750,605	890.2	61,790	7.5	50.51	50	45.85	45	30,000
Ottawa – Gatineau	1,323,783	594,745	195.6	82,053	7.0	54.93	55	49.99	50	40,000
Quebec	800,296	374,680	234.8	65,359	4.6	50.26	50	46.37	45	30,000
Toronto – Hamilton[†]	7,055,433	2,935,930	862.4	78,437	7.6	58.37	60	52.41	50	30,000
Vancouver	2,463,431	1,004,375	854.6	72,662	5.8	49.86	50	47.41	45	30,000
Winnipeg	778,489	343,365	147.0	70,795	6.3	43.00	45	42.38	40	30,000

[†] Refers to the Greater Toronto and Hamilton Area, and includes the Toronto, Hamilton, and Oshawa census metropolitan areas.

income jobs in the metropolitan area (close to 10/3 per definition) and is used to scale accessibility to low-income jobs so that it is directly comparable to the accessibility to all jobs measure for every region.

The average travel time for all public transport commuters was calculated by multiplying the number of individuals using public transport going from each census tract to each other census tract by the travel time between these census tracts, resulting in total public transport travel time in the region. This number was subsequently divided by the total number of public transport commuters to obtain average travel time in the region. For low-income commuters, a similar method was employed, but only low-income commuters (i.e., those commuting to the 30% lowest income jobs) were taken into account in the calculations. Thus, for each metropolitan area, the average commute for all workers and the average commute for low-income workers was computed separately. To calculate accessibility, the average commutes were rounded up or down to the nearest multiple of 5 min.

To discern accessibility levels by socio-economic groups, a vulnerability index was estimated at the census tract level. The indicator is composed of the following variables, based on the index for Canadian cities developed by Foth et al. (2013) using information obtained from Statistics Canada 2016 census data:

- Median household income
- Unemployment rate
- The percentage of the population that has immigrated within the last 5 years
- The percentage of households that spend more than 30% of their total income on housing rent

The final vulnerability index is given by the sum of the z-scores of the latter three variables, minus the z-score for the median household income. A high indicator therefore reveals high vulnerability (i.e., low income, high unemployment rates, a high percentage of recent immigrants, and a high percentage of households living in unaffordable housing). A census tract was subsequently designated as vulnerable if it was within the 20% census tracts with the highest index.

A vertical equity indicator was calculated based on the vulnerability index to discern if accessibility to low-income jobs is equitably distributed within Canada's metropolitan areas. Accordingly, the Spearman's rank correlation coefficient between the vulnerability index and accessibility levels was computed, based on Mortazavi and Akbarzadeh (2017) (see also Nazari Adli and Donovan (2018)). The coefficient is 1 if the census tract with the highest vulnerability has the highest accessibility levels, the census tract with the second highest vulnerability has the second highest accessibility levels, and the census tract with the lowest vulnerability has the lowest accessibility levels. As such, the correlation coefficient measures if those with the highest need also have the highest access. The vertical equity indicator was then computed by standardizing the correlation coefficient so that the highest coefficient among all 11 Canadian cities in this study was equal to 1:

$$\begin{aligned} \textit{Vertical equity indicator} &= \frac{\rho_{rAccess,rVulnerability}}{\rho_{max}} \\ &= \frac{1}{\rho_{max}} \frac{cov(rAccess, rVulnerability)}{\sigma_{rAccess}\sigma_{rVulnerability}} \end{aligned}$$

where $\rho_{rAccess,\ rVulnerability}$ is the Pearson correlation coefficient applied to the rank of accessibility (to low-income jobs) and the rank of the vulnerability index, ρ_{max} is the maximum correlation coefficient for all Canadian cities, *cov* denotes the covariance matrix between the ranked variables, and $\sigma_r$presents the standard deviation of the ranked variable.

Note that the vertical equity indicator only measures if an increased need corresponds to an increased accessibility, and provides no indication of how much larger this increased need or accessibility is or should be. Assume, for example, a situation where there are two cities, A and B. City A is divided into two regions, where the most vulnerable region has an accessibility of 10, and the least vulnerable region an accessibility of 1. City B is also composed of two regions, with the most vulnerable neighbourhood having an accessibility of 100, and the least vulnerable area an accessibility of 1. The vertical equity indicator would assign a score of 1 to both cities, as in both the ranking of need corresponds to the ranking of vulnerability/disadvantage.

4. Results and discussion

Table 1 presents summary statistics for the eleven metropolitan areas included in this study. Note that Toronto-Hamilton refers to the entire Greater Toronto and Hamilton Area and thus includes the Toronto, Hamilton, and Oshawa census metropolitan areas as defined by Statistics Canada. The eleven included areas represent the ten largest cities in terms of metropolitan population, plus Halifax to represent Atlantic Canada. This subset of Canadian cities includes a wide variety of contexts, from large megalopolises such as Toronto, to smaller regional centres such as London and Halifax.

However, the size of a metropolitan area does not seem to be reflected in average commute times by public transport: in most cities this figure hovers between 45 and 60 min, with Winnipeg residents experiencing the shortest commutes. This might be explained by better public transport provision (such as the presence of commuter rail, subways and elevated rail) in larger cities such as Toronto, Montreal and Vancouver.

On average, low-income workers have shorter commutes. This difference is especially profound in Edmonton, where low-income workers travel 10 min less than average, while in London and Kitchener-Cambridge-Waterloo, low-wage commuters are forced to travel longer than average, although the difference is not large. Thus, computing accessibility at the same threshold for both low-income workers and all commuters would generally overestimate the activity spheres of vulnerable populations and thereby result in overestimates of accessibility levels. As these estimates could then feed into policy, they might result in biased recommendations that could negatively affect low-income workers.

Note that in London and Kitchener-Cambridge-Waterloo, low-income workers travel longer on average, resulting in a higher threshold for the calculation of their accessibility. This raises questions about choice: are low-income groups in these two cities indeed willing to travel longer, or are they travelling longer because their choices are constrained? Comparing with the nine other cities in this study, the latter seems more plausible; this might indicate a limitation on the use of realized travel times for the calculation of accessibility. Such an approach therefore requires planners to be intimately knowledgeable about local circumstances to choose appropriate accessibility indicators and thresholds.

Figs. 2 and 3 present a comparison between accessibility to all jobs and accessibility to low-income jobs in Canada's three largest cities: Toronto, Montreal and Vancouver. Average accessibility levels appear to be related to a city's size and its number of jobs. Torontonians experience the largest accessibility levels on average (around 423,000 jobs in an average commute), while Vancouver inhabitants can only reach 210,000 jobs in an average commute. The average accessibility level in Montreal is 365,000 jobs.

Distinct patterns of access can be discerned from the maps: accessibility generally drops off with increasing distance from the central business district, but along rapid transit lines – commuter rail and the subway in Toronto and Montreal, or the Skytrain in Vancouver – accessibility levels, to both low-income jobs and all jobs, remain higher, reflecting the benefits conveyed by fast and frequent modes of transport. While subways seem to generate a linear pattern of high access, commuter rails only induce high access at stations, mirroring differences in stop spacing between the two heavy-rail modes. Local employment centres, on the other hand, have a minor effect on accessibility levels, as the jobs present in these areas are often dwarfed in number by those located in the central business district, or because these centres were co-located with rapid transit stops (such as at the Scarborough Centre Station in the Greater Toronto and Hamilton Area).

Vulnerable Montreal residents (i.e., those residents living in the 20% most vulnerable census tracts) are more fortunate than those in Toronto in terms of accessibility to low-income jobs: vulnerable Montrealers can access around 137,000 low-income jobs (an accessibility of 461,000 jobs using the $\frac{\sum_k O_k}{\sum_k LI_k}$ scaling factor (p. 6)), while vulnerable Torontonians can only reach 100,000 in an average commute for low-income residents (335,000 scaled jobs), even though the number of low-income jobs in Toronto is much higher.

In Fig. 4, a comparison between average accessibility levels, to all jobs and to low-income jobs, for all cities included in this study can be seen, which again confirms the difference in access between Toronto and Montreal as noted above. The blue bars represent the commonly used accessibility to all jobs metric, while the red bars show the average of the former metric in socially vulnerable neighbourhoods. The orange bars represent the new metric of accessibility to low-income jobs, averaged for socially vulnerable neighbourhoods (note that the number of low-income jobs was scaled by the ratio of all jobs to low-income jobs so that the metrics are directly comparable).

A city's size does not fully predict average accessibility levels; in Vancouver, for example, an average resident can only access as much opportunities as in Edmonton, Ottawa, or Calgary, which are home to around 700,000 less people and 400,000 less jobs. Similarly, inhabitants of Kitchener-Cambridge-Waterloo and London have lower accessibility than those in Halifax, even though the latter city houses 100,000 less residents. The explanation for such discrepancies are to be found in the particular allocation of land uses and the speed, frequency and coverage of the transport systems present in these cities, as well as their geographic circumstances (Vancouver, for example, is located next to an ocean and has many bays running through it).

Note the large differences between accessibility to *all* jobs for vulnerable groups (red) and accessibility to *low-income* jobs for vulnerable groups (orange). These discrepancies can be explained by the difference in spatial allocation and distribution of low-income jobs versus all jobs, and by the different activity spheres and thus travel times realized by vulnerable groups. In all cities (except for Kitchener – Cambridge – Waterloo), accessibility for vulnerable individuals would have been overestimated with the commonly used all jobs metric by between 6% (in London) and 87% (in Toronto). Policy makers in Toronto only having access to an all jobs metric would thus conclude that vulnerable groups are better off than other residents. However, focusing only on low-income jobs that can be accessed by these individuals, this is clearly not the case. The average gap between accessibility to all jobs for vulnerable groups and low-income jobs for vulnerable groups is 33%, highlighting the importance of employing different accessibility metrics for distinct groups.

In all cities, except for Toronto and Calgary, vulnerable groups still have access to a larger number of relevant job opportunities than average; vertical equity thus appears high in most Canadian metropolitan areas. Nevertheless, the variation between accessibility to all jobs and accessibility to low-income jobs for vulnerable groups (especially in Toronto) highlights the benefits of calculating these two metrics separately.

It is important to note that using the same travel time thresholds for all income groups to derive accessibility measures can lead to a measure of equity that does not represent the actual levels of accessibility experienced by low-income groups, as, for most cities, this artificially increases the distance low-income commuters are willing to travel. Table 2 shows average accessibility to all jobs and to adjusted low-income jobs using cumulative accessibility measures with thresholds based on average travel times for all income groups. In all examined regions, the average accessibility to low-income jobs is higher than the

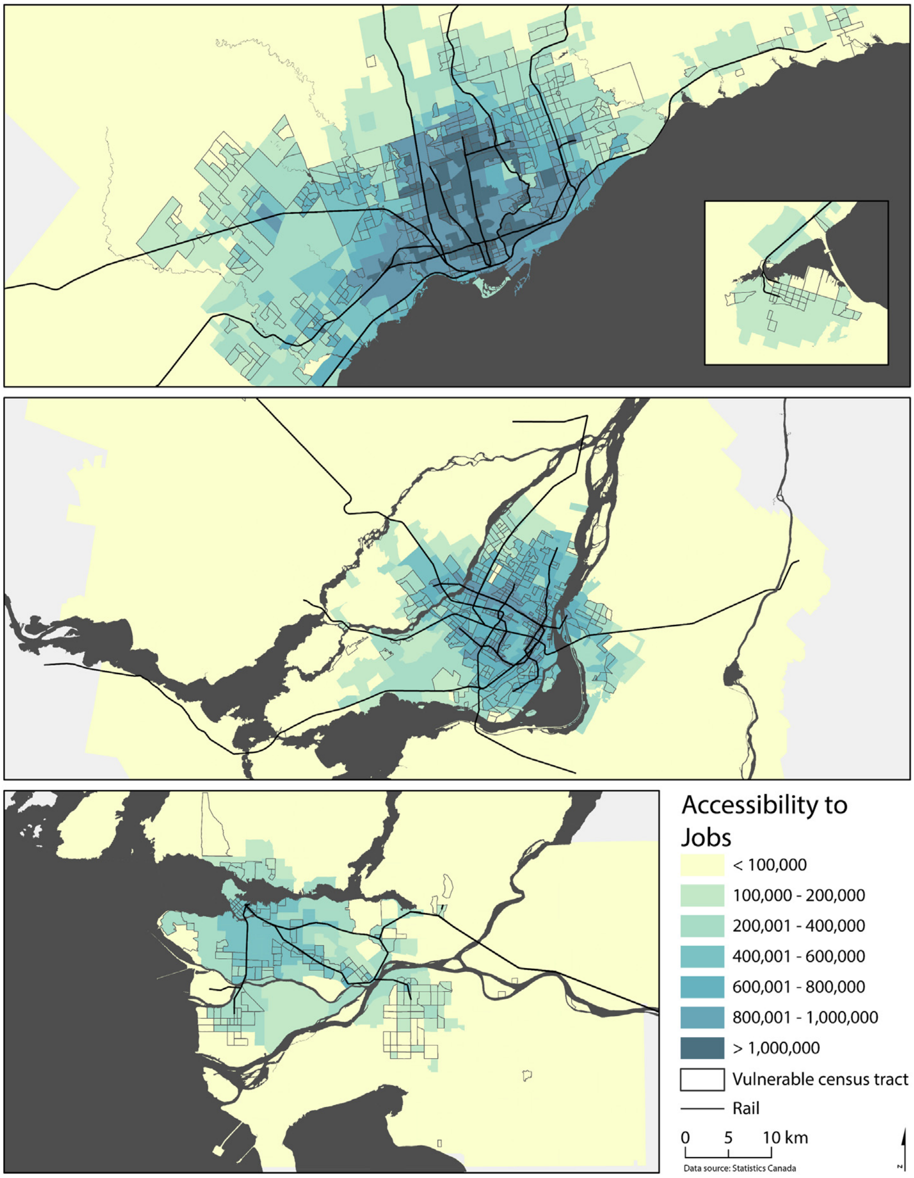

Fig. 2. Accessibility to all jobs in Toronto, Montreal and Vancouver.

average accessibility to all jobs. The differences between the measures in Fig. 4 and Table 2 highlight that the low vertical equity noted in Toronto and Calgary can be accounted for by differences in travel distances between low-income and non-low-income commuters, which could be related to preferences in home-location choice (e.g., high-income households might opt to live further from city centres where larger homes are available). A detailed examination of this phenomenon, however, requires further analysis that is outside of the scope of this study.

The vertical equity of accessibility to low-income jobs is further illustrated in Fig. 5. The x-axis represents standardized average accessibility to low-income jobs (where the highest accessibility level across the cities is one), while the y-axis shows the vertical equity indicator of these accessibility levels. A city at point (1,1) represents the ideal situation: an area where there are high levels of access to low-income jobs overall and where this access is equitably distributed across different socio-economic groups, i.e., where the census tracts with the highest need experience the highest accessibility; this appears to be the case in Montreal. In contrast, both accessibility and vertical equity in Calgary are low: vulnerable residents do not have more access to low-income jobs than their wealthier counterparts. In the smaller cities included in this study (Halifax, London, Kitchener-Cambridge-Waterloo, Winnipeg, and Quebec) vertical equity is close to one, although average accessibility levels are low. Thus, in these smaller cities, vulnerable residents have higher accessibility to low-income jobs than other residents, but they still experience low access overall. Note that the circle size represents the size of each metropolitan area's population.

To further illustrate the importance of distinguishing between accessibility to all jobs and accessibility to low-income jobs, we plotted these two metrics against transit modal share, see Fig. 6. Transit accessibility has been shown to be correlated with public transport mode share (Owen and Levinson, 2015), and as such the effects of access on mode share provide a representative example demonstrating the significance of employing two separate accessibility metrics. The difference between the two accessibility levels can again be distinguished: accessibility to low-income jobs for vulnerable groups is, for most cities, higher than the regular accessibility metric.

Importantly, the effect of the accessibility metric on transit modal share differs between the two measures. While for every increase of 100,000 jobs in the regular accessibility measure, modal share increases by 4.25%, the comparable figure for the low-income accessibility metric

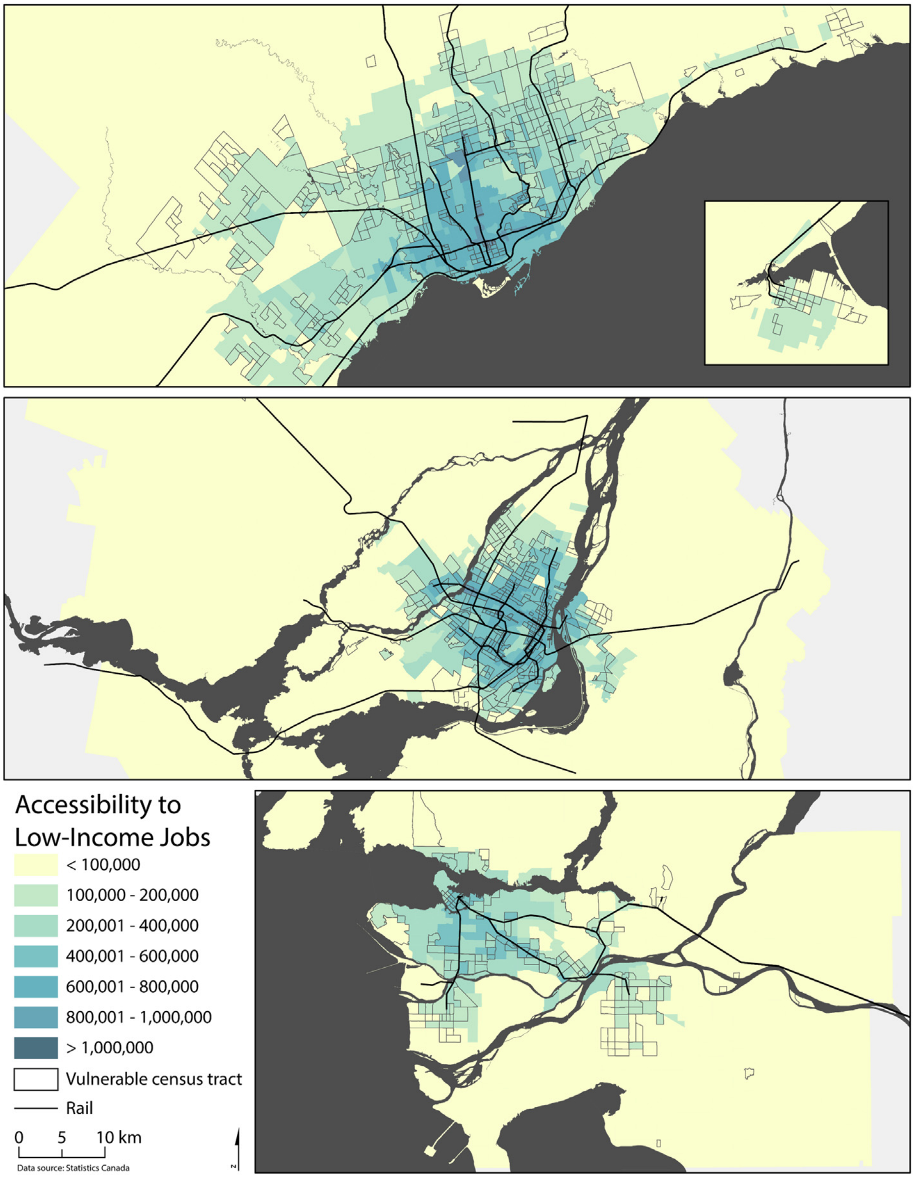

Fig. 3. Accessibility to low-income jobs in Toronto, Montreal and Vancouver.

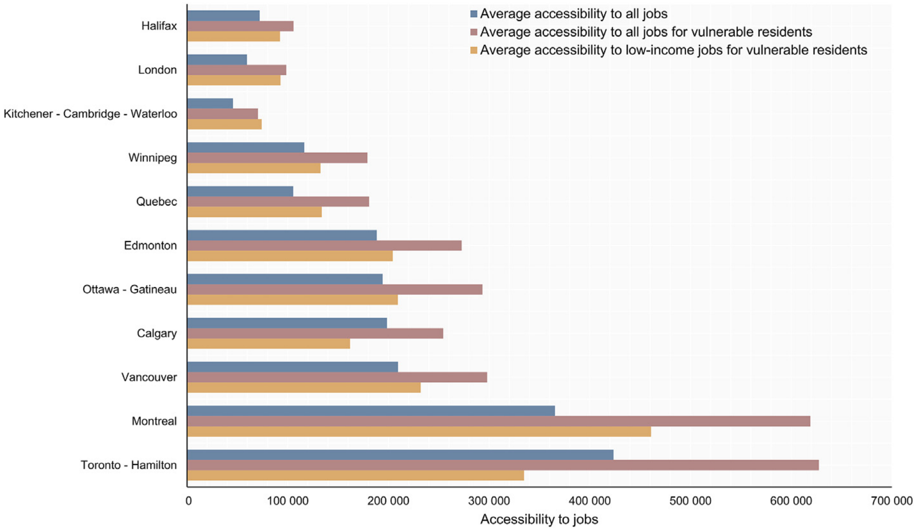

Fig. 4. Comparison of accessibility to all jobs and accessibility to low-income jobs.

Table 2
Average accessibility using constant time thresholds for all income groups.

	Time threshold (min)	Average accessibility to all jobs	Average accessibility to low-income jobs for vulnerable residents[a]
Calgary	60	198,598	216,452
Edmonton	65	191,164	261,492
Halifax	60	69,800	98,932
Kitchener – Cambridge – Waterloo	45	46,126	74,379
London	50	59,499	90,785
Montreal	50	365,411	571,476
Ottawa – Gatineau	55	193,604	250,651
Quebec	50	105,422	165,928
Toronto – Hamilton	60	422,909	577,296
Vancouver	50	209,555	289,542
Winnipeg	45	116,411	167,820

[a] The total number of accessible low-income jobs is multiplied by the ratio of low-income jobs to total jobs to enable direct comparisons.

for vulnerable groups is 6.50%. Recall that low-income accessibility was scaled by the ratio of all jobs to low-income jobs, and is therefore directly comparable to accessibility to all jobs; the contrast in effect sizes is therefore not due to a lower number of low-income jobs. Thus, vulnerable populations appear to be more sensitive to changes in accessibility to jobs they can access – had decisions been based on the regular accessibility metric, they would have considerably underestimated the effect of increasing accessibility to low-income jobs for vulnerable residents. Future research could examine the effects of accessibility to low-income jobs in further detail through various statistical approaches.

5. Conclusion

This study has developed the metric of accessibility to low-income jobs for vulnerable residents, which, in contrast with commonly used measures of accessibility to all jobs, provides policy makers and urban planners with a more fine-grained tool to examine the effects of new transport plans and projects across different socio-economic populations. In effect, this detailed accessibility measure provides a first step towards the segmentation of different groups within accessibility literature and practice – a common occurrence in studies on the different types of cyclists and public transport users (Damant-Sirois et al., 2014; Jensen, 1999; Krizek and El-Geneidy, 2007). Through such a segmentation approach, the benefits of both place-based and people-based accessibility metrics can be reconciled, namely the communicability and data requirements of place-based measures, combined with the detail common in people-based metrics.

There exists, however, considerable tension between the desired detail, required computational methods and ease of communication of varying accessibility metrics. The methods described in this article have been selected to prioritize communicability and ease of computation, increasing their likelihood of being used by planning practitioners. As such, some geographical detail has been lost due to the use of census tract geographies, while 'person-based' detail has been lost due to the aggregation of the population in only two groups. The two thresholds that were used for these two groups present further limitations to this study; it can be unclear whether accessibility differences are driven by land use and transport factors, or by the thresholds. However, it is important to note that these thresholds were empirically derived from revealed commuting behaviour, and thus reflect the lived experience of each population group, and therefore also the accessibility levels they experience. Whether the computed thresholds are limited by constraint or desire should not play a role when we solely intend to calculate a measure of experienced accessibility and compare across groups, as constraint or desire do not influence the fact that some groups experience higher accessibility levels than others. The distinction is however valuable when practitioners aim to decrease accessibility discrepancies between populations. Future research could therefore examine to what extent thresholds and consequent accessibility metrics are driven by desire or constraint. If constraint plays the larger role, then practitioners could focus on removing this by providing more and/or faster mobility options to increase people's activity spheres. When desire limits accessibility levels, the creation of affordable housing near existing jobs might be the better solution. The use of different thresholds further strengthens the comparisons across cities, as this does not

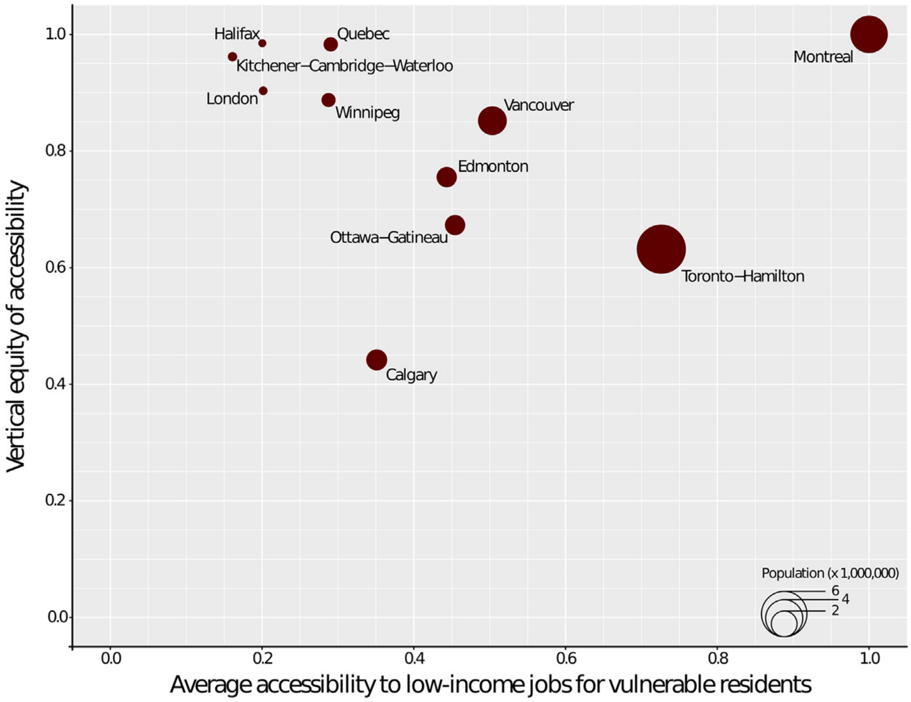

Fig. 5. Accessibility and vertical equity across the eleven metropolitan areas.

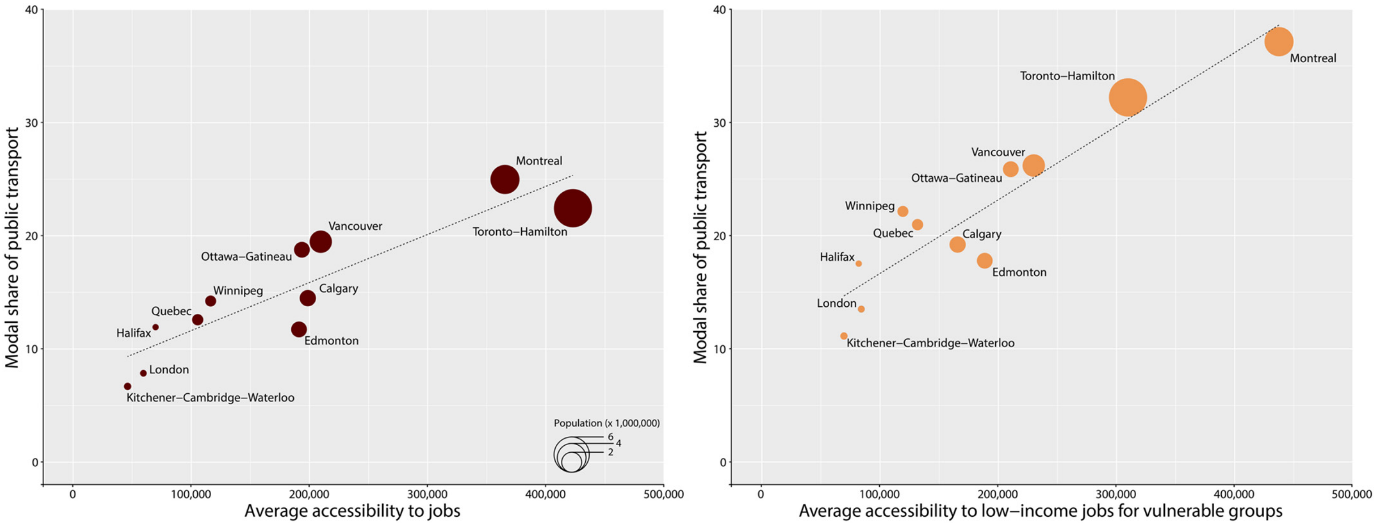

Fig. 6. Accessibility and public transport mode share.

unfairly penalize either larger or smaller cities, as would be the case with constant travel time thresholds (absolute counts with constant thresholds would favour larger cities, as they have more jobs, whereas relative percentages would favour smaller cities because a larger part of the metropolitan region can be reached within the time threshold).

Note that this study employed data and calculated travel times at the census tract level. Due to the somewhat large geographical scope of the census tract, computed transit travel times might not be fully representative of actual travel times, especially in larger, peripheral areas. However, the census tract was chosen as it is the geographical scale at which the most reliable and consistent job and wage data was available across Canada. Moreover, as most socially vulnerable census tracts are closer to inner cities and are thus smaller, this limitation should not substantially impact accessibility levels experienced by low-income populations. Further studies could examine cities individually at smaller scales, data permitting. Furthermore, travel times were all computed at a single departure time (8 AM), which might skew the accessibility results as transit service can vary considerably at different times of the day (especially for low-frequency services). The analysis did also not include competition for jobs, which might differ between wage categories, potentially alleviating or further exacerbating the burden on vulnerable groups. A future study could explore the effects of job market tightness on accessibility levels using the competitive accessibility metric created by Shen (1998).

This study has compared accessibility to all jobs by public transport and the new metric of accessibility to low-income jobs for vulnerable groups for eleven metropolitan areas in Canada, ranging from large metropolises to smaller regional cities. On average, Toronto residents experience the highest accessibility levels. When focusing on low-income jobs, however, vulnerable groups are better off in Montreal in terms of accessibility, even though the total number of low-income jobs is lower than in Toronto. This could be related to the clustering of vulnerable groups around the city centre and near major public transport corridors in Montreal, compared to Toronto where there exists considerable suburbanization of vulnerable groups. Such phenomena can be mitigated in two ways. Firstly, additional affordable housing can be provided near city centres to allow vulnerable populations to live closer to most job opportunities. Secondly, a fast and direct public transport system can be further developed to serve suburbanized and disadvantaged groups to provide them with appropriate access to their desired destinations.

Overall, it appears that vulnerable individuals experience higher accessibility levels than their fellow residents in their respective cities, although this trend does not appear in Toronto and Calgary; these latter cities lag behind their counterparts in terms of vertical equity. The discrepancies between the two accessibility metrics were further highlighted by comparing the effects of access on public transport mode share: vulnerable residents are more sensitive to accessibility changes and therefore stand to benefit more from targeted accessibility improvements. Note that different travel time thresholds were used to derive the measures of accessibility to all jobs and to low-income jobs, resulting in an equity analysis where the actual behavior of each group is accounted for to bypass some of the limitations from which cumulative opportunity metrics suffer compared to gravity-based measures. The use of the same threshold to derive accessibility for both groups can lead to a different equity analysis output that does not represent the actual travel behavior of both groups. Nevertheless, further research could be conducted to better understand the differences between these two measures.

Planners and urban decision makers, and in turn their policy recommendations, can thus benefit greatly from employing more detailed and segmented accessibility metrics. This further presents the necessity for Canadian policy makers to adopt an accessibility planning framework, as exists in the United Kingdom (Department for Transport, 2005). The segmentation approach taken in this article can strengthen the identification of local and strategic planning needs and lead to population and location-specific solutions. Future research could therefore examine how segmented accessibility analysis can further strengthen the planning process through the adoption of an accessibility planning framework in the Canadian context, and thereby drive policy changes that benefit all.

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