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An accessibility-based methodology to prioritize public-transit investments: Application to older adults in three metropolitan regions in Canada

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ABSTRACT

As governments aim to promote a modal transfer away from motorized vehicles and toward transit, important investments in public-transit systems are becoming necessary. Prioritization of projects targeting underserved communities and careful choices between Fixed Route Transit (FRT) and Demand Responsive Transit (DRT) is therefore crucial to maximize benefits from investments. In this study, we develop a methodology to target and identify policy interventions to increase accessibility by public transit where it is low and apply it to serve older adults in three Canadian metropolitan areas. A conceptual framework is presented to inform the type of public transport (FRT or DRT) or land-use interventions most relevant to improve accessibility in each area. The methodology is then applied using existing accessibility to jobs by public transit at the Census Tract level and concentration of older adults. Multiple measures are tested for both criteria to assess the effect of methodological choices on policy recommendations. Findings show the selection process is sensitive to the measure used to quantify the concentration of older adults, but not to different job types as destinations. Socioeconomic and geographical differences are observed between the types of interventions proposed. The methodology developed in this study can be of value for practitioners as they aim to orient relevant policy changes to promote increased accessibility by public transit for underserved communities such as older adults. The framework and methodology developed can be easily adapted to different sociodemographic groups and different regions where jobs, census, GTFS and road network data are available.

1. Background

Making public transit efficient to attract users away from motorized vehicle is crucial as governments aim to promote the use of sustainable transport. Important investments in transport and land-use systems are necessary to promote equitable access to the destinations people wish to reach, which is essential to ensure the social inclusion of different population groups (El-Geneidy et al., 2016; van Wee, 2022). However, not all interventions will have the same effect on promoting usage of public transit. Indeed, considering the resources required to operate public-transit systems, prioritization is necessary to ensure that transport investments are directed towards cost-effective strategies that yield higher social benefits (Eliasson & Lundberg, 2012).

The differential ability for Fixed-Route-Transit (FRT) to be efficient depending on population densities has been recognized in both policy-development (Institute of Transportation Engineers, 1998; Kittelson & Associates et al., 2003) and academic research (Cui, DeWeese, et al., 2022; Diab, DeWeese, Chaloux, & El-Geneidy, 2021). For FRT to be viable it needs to be implemented in an area where population density is high enough to provide required ridership levels (Cui, DeWeese, et al., 2022; Diab et al., 2021; Institute of Transportation Engineers, 1998; Kittelson & Associates et al., 2003). In areas with low population density, Demand-Responsive-Transit (DRT) can be more financially suitable and sustainable (Archetti, Speranza, & Weyland, 2018; Djavadian & Chow, 2017; Ma, Chow, Klein, & Ma, 2021). DRT is an umbrella term that has been elaborated over the years to incorporate a wide array of transport services that follow a dynamic routing approach to provide users with flexible travel times as opposed to the conventional FRT,

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which operates on fixed routes and travel times (National Academies of Sciences, 2016, 2019; Papanikolaou, Basbas, Mintsis, & Taxiltaris, 2017; Shared Digital Mobility Committee, 2018). Among DRT approaches is the on-demand system, also referred to as microtransit, which is defined as a shared transport system that uses minibuses or vans to provide dynamic scheduling and pick-up/drop-off locations at low-density areas where operating FRT would be too costly (Archetti et al., 2018; Djavadian & Chow, 2017; Ma et al., 2021). In the last few years, this system has been incorporated as part of the public transit system to connect riders in lower-density environments to specific destinations through different paths that go through users' desired stop/pick up locations (Sanaullah, Alsaleh, Djavadian, & Farooq, 2021; Willem, 2020; Yan, Levine, & Zhao, 2019). Given that FRT and DRT provide transport solutions to significantly different contexts, being able to differentiate the urban environments where each alternative is appropriate is crucial when aiming for cost-efficient investments.

Beyond only the choice of the appropriate type of public-transit service, increased attention has been dedicated towards the integration of equity in the prioritization of public-transit service improvements (Lucas, 2012; Lucas, Martens, Di Ciommo, & Dupont-Kieffer, 2019; Martin, Lea, Winters, Hosford, & Simo, 2022; Taylor & Morris, 2015; U.S. Department of Transportation, 2022). For years, transport investments have used indicators such as congestion (Vickrey, 1969) and travel demand models (Oppenheim, 1995) to assess the needs for improved mobility. However, such measures and other current public-transit policies do not readily incorporate equity considerations which has led to widening inequities in various regions around the world (Taylor & Morris, 2015). To develop prioritization methodologies and strategies for transport investment that will help achieving equitable access for underserved populations, it is important to use tools such as accessibility (Iacono, Levinson, & El-Geneidy, 2008; Levinson, 2002; van Wee & Geurs, 2011).

Indeed, accessibility – or the ease of reaching destinations – is a crucial consideration when studying travel behavior across sociodemographic groups (Deboosere & El-Geneidy, 2018; Ermagun & Tilahun, 2020; Martens & Bastiaanssen, 2019; Mayaud, Tran, & Nuttall, 2019; van Wee, 2022; van Wee & Geurs, 2011), for which it is considered one of the most inclusive measures linking land-use and transport systems (El-Geneidy & Levinson, 2022; Levinson & Wu, 2020). In their accessibility framework, Geurs and van Wee (2004) separated the concept into four pillar components: transport (e.g. mode, infrastructures), land use (e.g. destinations), temporal (e.g. time of day) and individual (e.g. sociodemographic characteristics). Amongst the large array of accessibility measures, location-based measures, which focuses on the spatial distribution of specific destinations in relation to the location of those aiming to reach them, are the most common and easy to comprehend (Geurs & Ritsema van Eck, 2001; Horner, 2004; Miller, 2005; Vale, Saraiva, & Pereira, 2015). Past research has made use of accessibility measures to study equitable access to multiple destinations (Maharjan, Tilahun, & Ermagun, 2022), including jobs (Deboosere & El-Geneidy, 2018; Foth, Manaugh, & El-Geneidy, 2013), healthcare services (Neutens, 2015), and nonwork locations such as stores, childcare facilities, and religious organizations (Grengs, 2015). For example, Bocarejo and Oviedo (2012) utilized accessibility to evaluate transport policies such as cross subsidy fare system and a new BRT line as transport policies in Bogota. Comparing accessibility through different modes (i.e., public transit vs car) is also crucial when aiming to plan for equitable transit improvements (El-Geneidy & Levinson, 2022; Handy, 2005; Vale et al., 2015), especially for marginalized groups who do not have access to automobiles. Some variability can be found when comparing accessibility by public transit and by car, even when the same travel time threshold is applied, due to particularities of transport infrastructure and transit scheduling, among other factors. Generally, accessibility to jobs by car tends to be higher than by public transit, which implies a ratio of less than one for accessibility by public transit/accessibility by car (Blumenberg & Ong, 2001; Hess, 2005; Shen, 1998). This can indicate modal inequities in the ease of reaching destinations (Cui, Boisjoly, Serra, & El-Geneidy, 2022) which are crucial to integrate in transport planning processes.

The primary advantage of using accessibility as a performance tool for public-transit planning, is that it can be improved by changes in the public transport and/or the land-use systems (El-Geneidy & Levinson, 2022; Geurs & van Wee, 2004). Improvements in the land-use system can be achieved through changes in zoning regulations, while improvements in the transport system can be done through the addition of a new transit service and/or to an increase in the level of service of existing transit infrastructure. Still, the extent to which changes in public-transit services can promote increased accessibility is dependent on the characteristics of the transit service being implemented or improved (El-Geneidy & Levinson, 2022). Indeed, not all areas with low accessibility levels will see improvements in their accessibility using the same interventions nor will the same intervention be equally beneficial when applied across multiple areas of low accessibility. In order to integrate these considerations in practice, additional research needs to be conducted to bridge the scholarship on accessibility and public-transit service provision (i.e., FRT vs DRT). In this paper we seek to tackle this challenge by developing a methodology to (1) highlight priority areas to direct policy interventions aimed at improving accessibility levels by public transit for a specific social group and (2) identify the type of policy interventions (land use and transport) that need to be applied in each priority area. The comprehensive tool created is aimed to help planners when aiming to direct new transit investments in a way that promotes an equitable distribution of social benefits.

To test this tool, we apply it to a specific sociodemographic group, in this case older adults, across Canada's three biggest Metropolitan Areas – Toronto, Montréal and Vancouver. Older adults are selected as a case study population given their increased prevalence amongst the world's population (World Health Organization, 2021) and the growing interest of researchers and policy makers to better understand their needs and wellbeing (Ravensbergen, Van Liefferinge, Jimenez, Zhang, & El-Geneidy, 2022). Through using public transit and walking as transport modes, older adults can reach their recommended weekly physical activity time (Moniruzzaman, Páez, Nurul Habib, & Morency, 2013). However, as people age, they are more inclined to use private vehicles as their common travel mode to access their desired destinations (Nordbakke & Schwanen, 2015; O'Neill & Carr, 2022; Wasfi & Levinson, 2007), since driving tends to provide higher flexibility and mobility with low physical effort. Nevertheless, public transport remains as an important mode of transport for a large number of older adults as many will partially or totally lose their ability to drive due to health issues and/or social pressure as they age (Dickerson et al., 2019; Luiu, Tight, & Burrow, 2017; Musselwhite & Shergold, 2013). Past scholarship has linked this change to a reduction in older adults' ability to meet their mobility needs (Haustein & Siren, 2014), an increase in depressive symptoms (Choi & DiNitto, 2016) and reduced social participation levels (Duppen et al., 2019; Lamanna, Klinger, Liu, & Mirza, 2020; Pristavec, 2016; Qin, Xiang, & Taylor, 2020). Adequate access to public transit and accessibility to destinations through public transit is therefore essential for older adults to maintain their quality of life, and their sense of freedom and independence (Latham-Mintus, Manierre, & Miller, 2021; Shrestha, Millonig, Hounsell, & McDonald, 2017).

A recent systematic review on accessibility for older adults by Ravensbergen et al. (2022) revealed that 30-min has been the most commonly used travel time threshold to measure accessibility for this demographic. While jobs are the most common proxies for destinations used to measure accessibility for populations as a whole due to their data being the easiest to obtain (El-Geneidy & Levinson, 2022; Wu et al., 2021), destinations of interest used to assess accessibility for older adults vary greatly (Ravensbergen et al., 2022). A majority of studies have evaluated older adults' accessibility to healthcare destinations (Chen, Cheng, Chen, Chen, & Cao, 2021; Ermagun & Tilahun, 2020; Mayaud, Tran, & Nuttall, 2019; Mayaud, Tran, Pereira, & Nuttall, 2019; Patel, Tennant, & Kruger, 2018; Ruan & Zhang, 2018; Stentzel, Piegsa, Fredrich, Hoffmann, & van den Berg, 2016; Vrabková, Ertingerová, & Kukuliač, 2021; Zhang, Northridge, Jin, & Metcalf, 2018). However, such methodological choices are not readily justified and could be based on a biased assumption that older people are associated with illness (Ravensbergen et al., 2022). Other destinations commonly considered included parks (Cheng, Liao, & Zhu, 2021; Choi, Lee, & Basrak, 2021; Ermagun & Tilahun, 2020; Ouyang, Yin, & Wang, 2020; Park, Rigolon, Choi, Lyons, & Brewer, 2021) as well as grocery stores and other businesses (Choi et al., 2021; Ermagun & Tilahun, 2020; Lange & Norman, 2018).

Overall, methodological justifications have been limited for the choice of destinations used in accessibility studies focusing on older adults (Ravensbergen et al., 2022), with current scholarship reporting a variety of relevant destinations for older adults including groceries, restaurants and other retail businesses (Chudyk et al., 2015; Winters et al., 2015). This problem is an example of the current limitation of accessibility approaches, where the policy and equity impacts of different methodological choices made to generate accessibility measures are not often considered. When discussing accessibility for older adults, it is particularly important to distinguish between the ease of reaching destinations, as previously defined, and universal accessibility which relates to how the built environment at the micro-scale accommodate people with different levels of physical and psychological abilities (Church & Marston, 2003; Unsworth, So, Chua, Gudimetla, & Naweed, 2019). While the two concepts have been combined in past research to look at the ease of reaching destinations for people with disabilities (Grisé, Boisjoly, Maguire, & El-Geneidy, 2019), the fact remains that they generally entail complimentary interventions at different scale. To avoid confusion, this study uses the term accessibility solely to refer to the ease of reaching destinations. The concept of universal accessibility will still be discussed along with the results at the end of the paper, but it will not be a central point of the analysis.

By combining the identification of areas which suffer from poor accessibility by public transit and sociodemographic characteristics, this study will aim to help better orient choices in the type of service implemented and their location to maximize benefits to underserved communities, such as older adults. The findings of this study will help in identifying priority areas in these three cities where public-transit and/or land-use changes are required to promote the healthy aging. On a broader scale, the methodology and conceptual framework developed in this study could be applied to other underserved groups as well as in other regions to evaluate priority areas and most importantly the type of interventions needed to increase accessibility by public transit while considering equity.

2. Methodology

In this study, we propose a four-step framework to highlight priority areas for public-transport policy interventions for a specific social group and identify the type of policy interventions that should be applied in each priority area. These five steps are:

1. *Data collection*: Collection of necessary data and index calculation;
2. *Accessibility assessment:* Assessing car and transit accessibility levels;
3. *Scenario analysis:* Creation, analysis and selection of areas for proposed interventions; and
4. *Policy identification:* Identifying policy interventions for the selected priority areas.

2.1. Data collection

Four data sources are needed to apply the proposed framework: sociodemographic data, opportunity-location data, the urban road network, and public-transit routes and schedules. Sociodemographic data is used to evaluate areas where the social group of focus is more prevalent. Spatial distribution of opportunities, the urban road network, and public-transit schedules are used to assess the access to opportunities of the urban areas analyzed. For this study, all data was collected for the three largest Canadian Metropolitan Areas (CMAs): Toronto, Montréal, and Vancouver. These CMAs were chosen because they represent developed urban environments with mature transit systems as well as comparable proportions of older adults, population densities and public-transit mode shares (Table 1) thus allowing more easily for comparison across regional contexts.

In terms of sociodemographic data, information regarding total population and density of the social group of interest is needed; older adults, in the case of this study. This information is commonly available in population censuses for most social groups of interest. To identify urban areas where older adults are predominant in each analyzed city, we use sociodemographic information from the 2016 Canadian Census. For the purposes of this study, we consider as older adults all people aged 65 and older. Census data was collected at the census-tract (CT) level (Statistics Canada, 2016) using the *cancensus* R package (von Bergmann, Shkolnik, & Jacobs, 2021) for Toronto (1148 CTs), Montréal (951 CTs) and Vancouver (474 CTs). Three CT-level characteristics are directly extracted from the census to characterize urban areas in terms of their older-adult population: proportion of older adults in the CT (P_O), number of older adults in the CT (N_O), and density of older adults in the CT (D_O). Additionally, an older-adult index (I_O) was calculated for each CT as the sum of the Z-scores of the three previously mentioned measures.

In terms of accessibility measures, we use job locations as a proxy of spatial distribution of opportunities. The number of jobs in an area have been used repeatedly in the literature as a proxy of the number and diversity of opportunities that an area provides (Deboosere & El-Geneidy, 2018; Srour, Kockelman, & Dunn, 2002). Job-location data was acquired at the CT-level from the 2016 Canadian Census in the form of commute trips for each census metropolitan area (Statistics Canada, 2018). In addition to collecting the total number of jobs in each CT, we gathered the number of jobs for two of the most commonly analyzed purposes for older adults in the literature (Ravensbergen et al., 2022): retail purposes, and healthcare and social services. While parks and green spaces are among the most commonly studied destinations when assessing accessibility for older adults, we decided to not include them in our analysis given they represent drastically different type of destinations. The street network, which is needed to assess travel times, was obtained from OpenStreetMap (OSM) through the *osmextract* R package (Gilardi & Lovelace, 2021). The OSM network is complete and accurate for most major cities, with more than 80% coverage worldwide (Barrington-Leigh & Millard-Ball, 2017). Public transport schedules were gathered in the General Transit Feed Specification (GTFS) format, allowing for our estimations of transit travel time to account for walking, waiting, and transfer times. GTFS data was retrieved from transitfeeds.com (Open Mobility Data, 2023), which archives public transit data from over 650 locations worldwide. Although there is a considerably larger availability of GTFS data for cities in the Global North, transitfeeds.com includes data in all continents except for Antarctica.

Table 1
Descriptive statistics of studied CMAs.

Characteristics	Toronto	Montréal	Vancouver
Area (km^2)	5906	4604	2883
Total Population	5,928,035	4,098,930	2,463,430
Proportion of older adults (%)	14.48	16.39	15.72
Population Density (hab/km^2)	1003.73	890.30	854.47
Median Household Income ($CAD)	78,373	61,790	72,662
Public-transit mode share (%)	25.56	23.63	21.68

Data source: Statistics Canada (2016)

2.2. Accessibility assessment

To apply the proposed framework, any quantitative measure of access to opportunities may be used. We recommend calculating accessibility measures considering departure times and destinations that are relevant for the social group of focus. The accessibility measures of choice need to be calculated for public transit and private car. Transit accessibility measures are used for selecting priority areas for investment, whereas car accessibility is needed to orient the appropriate policy interventions needed in a priority area.

In this study, we calculated cumulative opportunity indicators by transit and car for each census tract in each analyzed metropolitan area. To calculate these indicators, we computed transit travel times between CT centroids for a typical weekday morning using the r5r R package (Pereira, Saraiva, Herszenhut, Braga, & Conway, 2021, p. 21262). CTs were chosen as units of analysis given the job data was obtained at this level and that any unnecessary manipulation of the data would introduce bias in the accessibility calculations. The number of jobs in each census tract was estimated using the census commute flows. It is assumed that the number of people commuting to a certain CT is an appropriate proxy for the number of jobs available in that CT. To calculate transit travel times, the necessary inputs for r5r are the GTFS schedule data, and the OSM street network for each region. The number of accessible jobs by transit for each CT is then computed by adding up the number of jobs available at all the census tracts accessible within 30 min on a typical Tuesday morning at 10 a.m., as older people tend to travel at off-peak times (Ravensbergen et al., 2022). As for the car accessibility measures, the census commute flows were used to calculate the number of jobs accessible within 30 min of car travel for each CT. However, r5r allows only the free-flow travel times to be calculated for car trips. To estimate congested car travel times, which provide a more accurate measure of accessibility, the congestion conditions procured from the Google API from 2017 were used, and a region-dependent parking search time was added to each car travel time (5.63 min for Montréal, 8.3 min for Toronto and 6 min for Vancouver) (Kapatsila, Palacios, Grisé, & El-Geneidy, 2023).

For priority-area selection, all transit trips were assumed to start at 10 a.m. given that this departure time is more frequent for older adults than peak hours (ARTM, 2018). Using these transit travel times, cumulative opportunity indicators were calculated with a 30-min threshold for three sets of destinations: healthcare and social services jobs (A_H), retail jobs (A_R), and total number of jobs (A_T).

2.3. Scenario analysis

The identification of priority areas for transport interventions is done by focusing on two dimensions of analysis: accessibility by public transport, and spatial prevalence of the social group of focus. In the case of this study, which focuses on older adults, the main objective is to identify areas of low accessibility to jobs by transit where older-adult populations are prevalent. While older adults are generally retired and do not need to access job positions, accessibility to jobs is used as a proxy of the service and opportunities that public transport can give to older adults. In this study, priority-area identification is done at the CT level for three Canadian Census Metropolitan Areas (CMA): Toronto, Montréal, and Vancouver. A CT is selected as a priority area if two conditions are met: (1) accessibility to jobs by transit is below its CMA's median, and (2) its older-adult prevalence is above its CMA's median. Given that accessibility can be measured to different kinds of destinations, and because older-adult prevalence can be measured in multiple ways, several scenarios of priority-area selection can be calculated. We recommend calculating multiple scenarios and comparing them to sensitize the importance of methodological choices on the selection of priority areas.

To evaluate the implications of focusing on accessibility to different job types, priority areas were selected by fixing the older-adult measure to proportion of older adults (P_O) while varying across the three accessibility measures (A_H, A_R, A_T). Then, using the percentage of overlap in selected CTs between each pair of scenario, which is based on the Pearson correlation coefficient, we assess the correlation between these three scenarios. This allows to conclude if focusing on healthcare or retail jobs yields significantly different results than considering all jobs. Once the accessibility measure is defined, the same process can be conducted to evaluate the effect of varying population-prevalence measures. In the case of this study, to evaluate the implications of choosing different measures of older-adult population prevalence, we create different scenarios to select priority areas by fixing the accessibility measure to all jobs (A_T) while varying the four older-adult measures (P_O, N_O, D_O, I_O). Subsequently, to select a desired scenario, we compare the selected areas by: total CT surface area, mean percentage of urbanized land, mean distance to the city's Central Business District (CBD), mean population density, and mean household income. These characteristics help guide the scenario selection based on the planning criteria for investment. For instance, if the public-transit investments are aimed for lower-income older-adult populations, such scenario can be selected accordingly.

2.4. Policy identification

As accessibility is a function of both transport and land use, for an investment in public transit to be effective, there must be destinations accessible for people to go to. If a new transit service is provided in an environment where destinations are limited (i.e. land use is the primary limiting component to accessibility levels) then the new service will not lead to significant changes in overall accessibility levels. The accessibility ratio between transit and car can be used to understand the role played by land use in limiting accessibility.

Let us consider the following transit-car accessibility ratio: $= A_{transit}/A_{car}$, where $A_{transit}$ is accessibility by transit and A_{car} is accessibility by car. Given that car travel times are often a fraction of transit travel times, the transit-car accessibility ratio will often be a value between 0 and 1. When the ratio is closer to one, accessibility by transit is close to that of the car. Thus, when focusing only on selected priority areas, which are

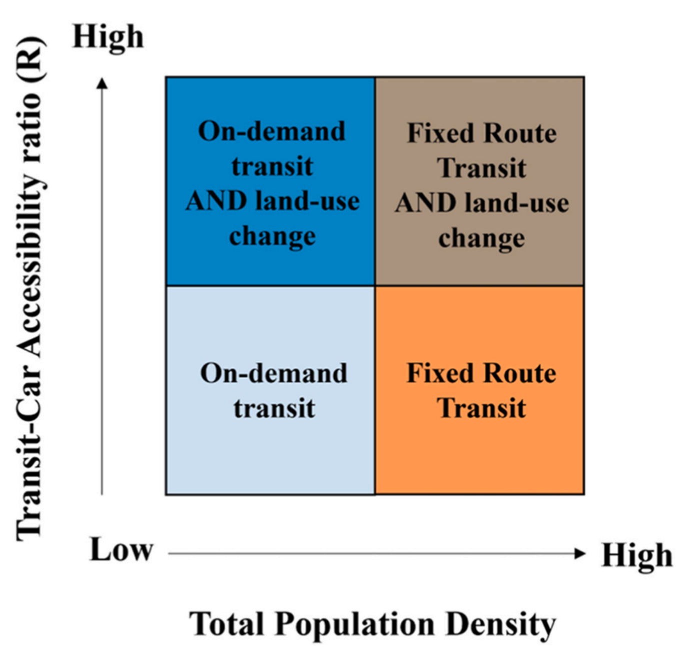

Fig. 1. Conceptual categorization of interventions aimed at increasing accessibility by transit in areas where it is poor.

areas of low transit accessibility, having a high transit-car accessibility ratio (closer to 1) means that accessibility by car is also low. This therefore entails that there is an overall lack of destinations accessible within the time threshold considered from that origin point. In turn, this suggests that the low accessibility can at least be partly attributed to a deficiency in the land-use component of accessibility.

Given these previous considerations, for each priority-area selected, the intervention required can be determined by our proposed conceptual framework, shown in Fig. 1. The interventions we consider to improve accessibility include FRT, DRT, and land-use changes. The appropriate intervention for an area will be determined by its total population density and its transit-car accessibility ratio. Higher values of the transit-car accessibility ratio (R) indicate that, in addition to improvements in transit services, land-use changes are needed for accessibility improvement. These land-use changes would include both densification and diversification of non-residential land uses.

Although our proposed framework focuses on interventions aimed at a specific social group – older adults in the case study presented in this work – any public transport intervention will supply an option to the totality of a population in an area. Thus, the decision of improving transit supply in an area through the implementation of FRT or DRT is made based on total population density. No fixed threshold at which to change from on-demand to FRT has been agreed upon to be adopted across contexts given that local realities greatly influence overall public-transit ridership. As such, using a region-specific approach to define what is considered to be high or low transit-car accessibility ratio and population density allows to define interventions in priority areas without imposing an out-of-context limit.

For the presented case study, which focuses on older-adults, we classify each selected priority area in one of the four quadrants of Fig. 1 according to its CMA's median value of transit-car accessibility ratio and its CMA's median total population density. This process of classification of priority areas helps illustrate the relevance of not only identifying areas of intervention, but also differentiating the types of intervention necessary according to the area's specific land use and transport needs.

3. Results

With steps *1. Data collection* and *2. Accessibility assessment* having already been detailed for the case study used in this study (i.e., older adults in Toronto, Montréal and Vancouver) in sections 3.1 and 3.2, this section will detail the application of steps *3. Scenario analysis* and *4. Policy identification* to the selected population and regions of interest.

3.1. Scenario analysis: results

The percentages of overlap in the selected CTs between scenarios using different type of jobs to calculate accessibility (A_H, A_R, A_T) are presented in Table 2. Using the different types of jobs as proxies for accessibility destinations led to a similar selection of CT for priority interventions for all three regions (>0.75). For all three CMAs, the correlation was the lowest between the CTs selected using accessibility to healthcare and social service jobs (A_H) versus those selected using retail jobs (A_R) (0.75–0.91).

The CTs selected for each of the three scenario using different types of jobs were all similar in terms of total selected CT area, mean population density, mean household income, mean distance to the CBD, and mean proportion of urbanized land (Table 3). Accessibility to all jobs (A_T) was chosen as the proxy for destinations for the rest of the analysis given that it had a higher correlation with the two other types of destinations tested.

The percentages of overlap in selected CTs between scenarios using different categorization of older adults' prevalence are presented in Table 4. The percentage of overlap in CTs selected using the census-derived measures of older adults' populations – proportion (P_O), number (N_O) and density (D_O) – have medium to low values. Using older adults' density (D_O) yielded CT selections that were consistently more different to those selected using the other two measures. On the contrary, the older adults' index (I_O) systematically had the highest level of overlap in CTs selected with all the other measures. Given the medium to large variability between the CTs selected based on each of the measures used, the results for each of these scenarios were mapped and are shown in Fig. 2.

Table 2
Percentage of overlap in selected CTs between scenarios using different job types to generate accessibility measures.

Scenarios using accessibility to different job types	Toronto			Montréal			Vancouver		
	A_T	A_H	A_R	A_T	A_H	A_R	A_T	A_H	A_R
All jobs (A_T)	100	80	88	1.00	0.88	0.92	1.00	0.91	0.96
Healthcare and social services jobs (A_H)	80	100	75	0.88	1.00	0.83	0.91	1.00	0.91
Retail jobs (A_R)	88	75	100	0.92	0.83	1.00	0.96	0.91	1.00

Table 3
Descriptive statistics of selected CTs for each scenario based on accessibility to different job types.

CMA/Scenarios	Total selected CT area (km^2)	Selected CTs' mean urbanized land (%)	Mean CT distance to CBD (km)	Mean Population Density (hab/km^2)	Mean Household Income ($)
Toronto	5906	74.3%	22	1004	78,373
All jobs (A_T)	3695	65.1%	28	350	83,598
Healthcare and social services jobs (A_H)	3787	65.7%	29	324	81,619
Retail jobs (A_R)	3623	65.3%	29	360	85,421
Montréal	4604	74.9%	15	890	61,790
All jobs (A_T)	1581	73.8%	21	671	66,780
Healthcare and social services jobs (A_H)	1613	74.4%	22	644	64,973
Retail jobs (A_R)	1599	74.2%	22	668	66,906
Vancouver	2883	48.7%	19	854	72,662
All jobs (A_T)	875	64.6%	24	645	85,021
Healthcare and social services jobs (A_H)	1023	64.0%	24	503	77,202
Retail jobs (A_R)	1047	64.7%	24	544	85,615

Table 4
Percentage of overlap in selected CTs between scenarios using different measures of older adults' geographical concentration.

Scenarios using different measure of older adults' prevalence	Toronto				Montréal				Vancouver			
	P_O	N_O	D_O	I_O	P_O	N_O	D_O	I_O	P_O	N_O	D_O	I_O
Proportion of older adults (P_O)	100	56	42	78	100	60	44	82	100	54	42	75
Number of older adults (N_O)	56	100	39	72	60	100	32	71	54	100	37	75
Older Adults density (D_O)	42	39	100	51	44	32	100	49	42	37	100	49
Older adults index (I_O)	78	72	51	100	82	71	49	100	75	75	49	100

The differences between each scenario were also reflected in the descriptive statistics of the CTs selected using each of the older adults' measures (Table 5). Across all three regions, scenarios using the density of older adults (D_O) led to the selection of CTs covering significantly smaller, more urbanized areas closer to the CBD than the other three metrics. Areas selected with this metric led to the selection of areas that had median household incomes notably lower than the other three measures. The scenario using the older adults' index (I_O) yielded values across all characteristics but proportion of urbanized land that were situated in between those of the scenarios using P_O and N_O – which selected for larger, less dense CTs further from the CBD and with higher mean household income and the scenario using D_O. Given the observed heightened differences between the census-derived metrics (P_O, N_O, D_O), it was decided to select the scenario using the older adults' index (I_O) for the rest of the analysis.

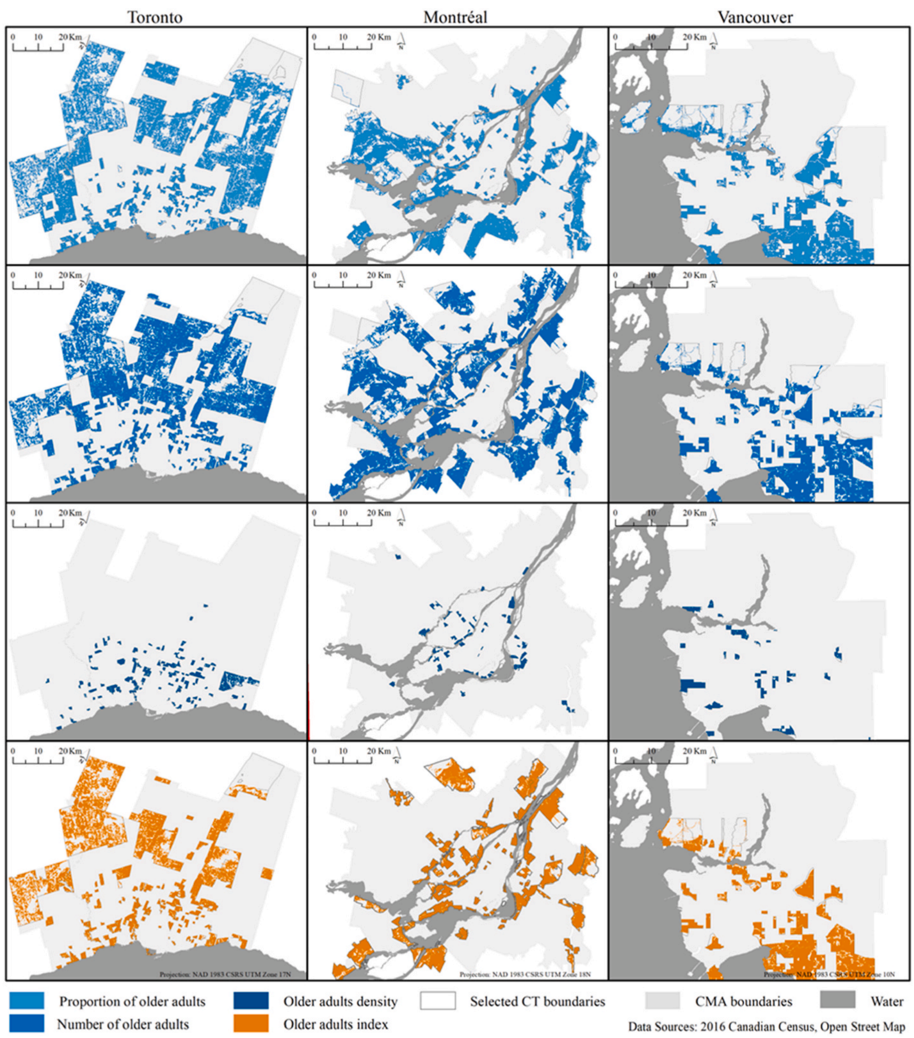

Fig. 2. CTs selected using different measures of older adults' geographical concentration for Toronto, Montréal and Vancouver.

Table 5
Descriptive statistics for scenarios based on different measures of older adults' geographical concentration.

CMA/Scenarios	Total selected CT area (km^2)	Selected CTs' mean urbanized land (%)	Mean CT distance to CBD (km)	Mean Population Density (hab/km^2)	Mean Household Income ($)
Toronto	5906	74.3%	22	1004	78,373
Proportion of older adults (P_o)	3695	65.1%	28	350	83,598
Number of older adults (N_o)	3345	69.6%	29	535	86,838
Density of older adults (D_o)	241	90.5%	22	3562	69,599
Older adults index (I_o)	2192	63.4%	26	580	81,067
Montréal	4604	74.9%	15	890	61,790
Proportion of older adults (P_o)	1581	73.8%	21	671	66,780
Number of older adults (N_o)	2345	74.4%	23	698	70,969
Density of older adults (D_o)	92	94.8%	17	3942	56,122
Older adults index (I_o)	1002	79.1%	21	1079	66,089
Vancouver	2883	48.7%	19	854	72,662
Proportion of older adults (P_o)	875	64.6%	24	645	85,021
Number of older adults (N_o)	825	69.2%	24	908	82,305
Density of older adults (D_o)	81	93.5%	22	3583	72,925
Older adults index (I_o)	583	75.0%	24	942	81,397

3.2. Policy identification: results

Final priority interventions selected for new public-transit investment to promote aging in place determined using accessibility to all jobs (A_T) as well as the older adults' index (I_O) are presented in Figs. 3–5. In these figures, CTs are identified and colored based on the relevant intervention to increase accessibility by public transit using the conceptual framework presented in Fig. 1 (*Section 4.4 Policy identification*). As such, interventions are categorized as one of the following four options: 1) On-demand public transit; 2) Land-use changes and on-demand

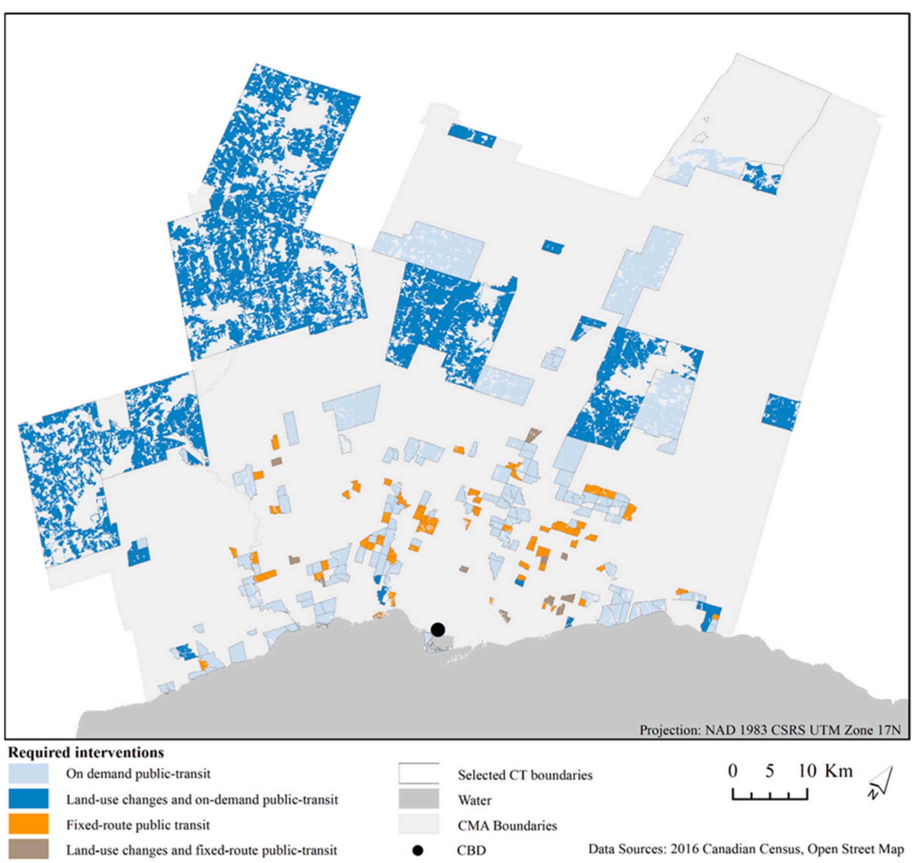

Fig. 3. Recommended priority CTs by intervention type for the Toronto CMA.

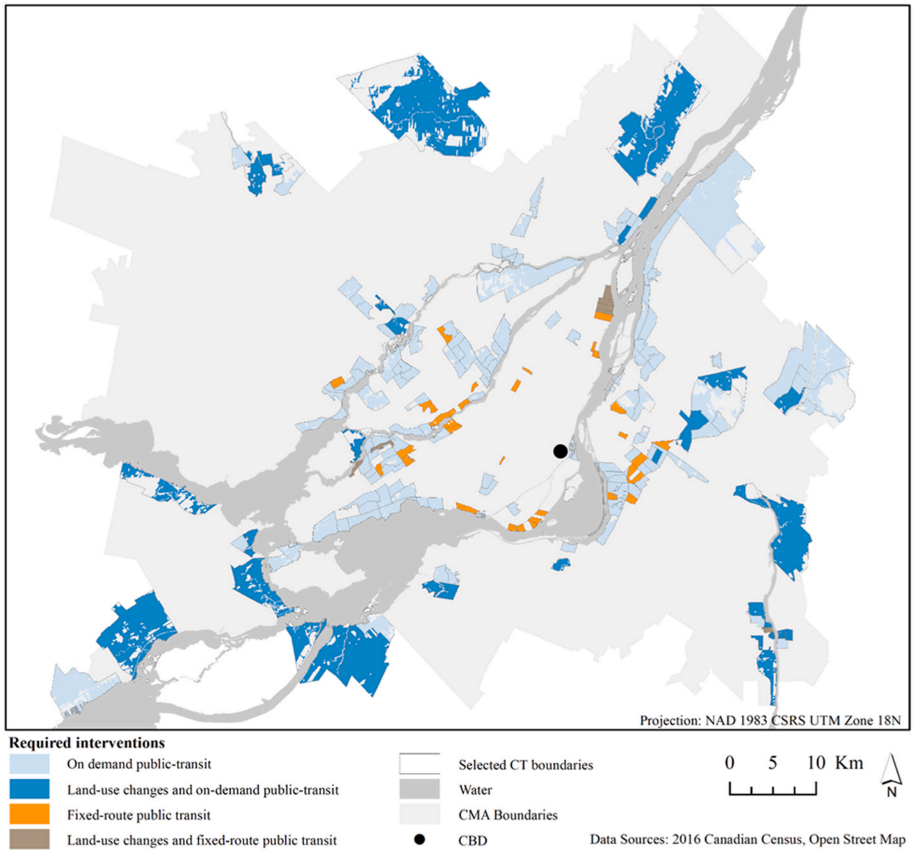

Fig. 4. Recommended priority CTs by intervention type for the Montréal CMA.

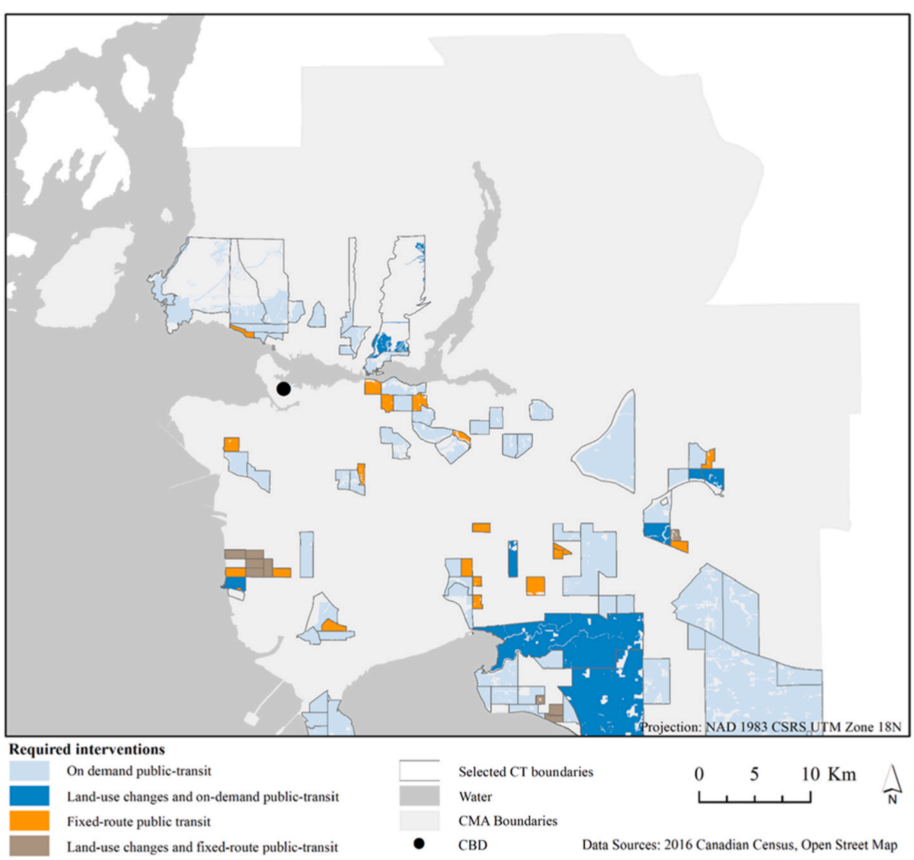

Fig. 5. Recommended priority CTs by intervention type for the Vancouver CMA.

Table 6
Descriptive statistics for each proposed policy to increase accessibility by public transit.

CMA/Scenarios	Total selected CT area (km^2)	Selected CTs' mean urbanized land (%)	Mean CT distance to CBD (km)	Mean Population Density (hab/km^2)	Mean Household Income ($)
Toronto CMA	5906	74.3%	22	1004	78,373
Total selected CTs	2192	63.4%	26	580	81,067
On-Demand Transit	721	63.9%	25	921	88,606
On-Demand Transit & Land use	1391	61.3%	46	119	91,191
Fixed Route Transit	67	95.4%	20	5535	65,614
Fixed Route Transit & Land Use	14	95.7%	19	5146	65,741
Montréal CMA	4604	74.9%	15	890	61,790
Total selected CTs	1002	79.0%	21	1079	66,089
On-Demand Transit	508	79.7%	20	1347	70,905
On-Demand Transit & Land use	454	77.1%	32	447	60,913
Fixed Route Transit	33	92.9%	12	4918	55,852
Fixed Route Transit & Land Use	7	99.4%	21	4646	52,590
Vancouver CMA	2883	48.7%	19	854	72,662
Total selected CTs	583	75.0%	24	942	81,397
On-Demand Transit	403	73.7%	24	843	86,412
On-Demand Transit & Land use	143	73.3%	31	398	77,606
Fixed Route Transit	25	95.3%	20	4367	72,269
Fixed Route Transit & Land Use	10	98.4%	26	3821	69,497

public transit; 3) Fixed-route public transit; and 4) Land-use changes and fixed-route public transit.

Looking at the descriptive statistics of the CTs assigned to each of the four interventions in Table 6, clear differences can be observed between the different interventions across the three regions. On the geographical side, CTs identified as requiring on-demand transit (with and without land-use changes) represent a majority of the land covered by the priority areas selected. These CTs have a significantly lower proportion of urbanized land than CTs selected for Fixed Route Transit (with and without land-use changes). On the opposite, CTs selected for FRT have proportions of urbanized land largely above the regional average across the three regions. CTs requiring both on-demand transit and land-use changes are the furthest from the CBD across the three regions by significant margins while the other three types of interventions are at a similar distance with their order varying slightly across cities. It should be noted that an important number of CTs selected for interventions in Montréal are situated on the south shore of the Saint-Lawrence River (Fig. 4) which is, while geographically close to Montréal's CBD, still only connected through few bridges.

Population-wise, as population density was used in the selection process to differentiate between on-demand transit and FRT, a clear difference can be observed between these two groups of interventions for this variable. Still, it is important to highlight that CTs where land-use changes are recommended – both in combination with on-demand transit and with FRT – have lower population densities than the CTs where the same type of transit service is suggested but without the land-use changes. For example, in Toronto, CTs selected for FRT only have an average population density of 5535 people/km^2 while those recommended for combined FRT, and land-use changes have an average population density of 5146 people/km^2.

On the socio-economic side, the combination of all priority CTs selected for each region have a median household income value higher than their region, with this reality being more pronounced in Vancouver ($81,397 for selected CTs vs $72,662 for the region). Still, differences are present between the types of intervention. CTs recommended for on-demand transit (with and without land-use changes) have higher median household incomes compared to the areas selected for FRT (with and without land-use changes). This disparity is at the highest in the Toronto CMA ($88,606 and $91,191 for on-demand transit with and without land-use changes respectively vs $65,741 and $65,614 for FRT with and without land-use changes respectively), where the regional median household income is the highest of the three studied regions ($78,373). Additionally, across all regions, CTs selected for FRT (with or without land-use changes) have a median household income that is lower than the CMA average, with Vancouver being the region where this gap is the smallest ($69,497 and $72,269 for FRT with and without land-use changes respectively vs $72,662 at the CMA level). Lastly, whereas in Toronto CTs requiring on-demand transit and land-use changes have a higher median household income ($91,191) than those requiring only on-demand transit ($88,606), the opposite can be observed in Montréal ($60,913 and $70,905 respectively) and Vancouver ($77,606 and $86,412 respectively).

4. Discussion

In this study, we present a four-step methodology to select priority areas for accessibility-improving investments and identify appropriate transport and land-use interventions and apply it to older adults across three large metropolitan areas in Canada. Building off the accessibility framework by Geurs and van Wee (2004), we bridge accessibility theory and practice with the literature on FRT and DRT's geographical and populational requirements (Archetti et al., 2018; Djavadian & Chow, 2017; Institute of Transportation Engineers, 1998; Kittelson & Associates et al., 2003). In doing so, we provide a policy-oriented tool to facilitate the elaboration of accessibility-based intervention plans. This framework was developed with the hopes of helping to guide policy, rather than offering a strict procedure to follow to directly increase accessibility or ridership among older adults.

4.1. Scenario analysis: discussion

Our analysis shows that the prioritization of urban areas for land-use and transport interventions based on accessibility to jobs is not highly sensitive to the types of jobs being considered. For the three Canadian cities analyzed, there are no major differences in focusing on healthcare, retail, or total number of jobs. In this sense, public policies that focus on improving transit accessibility to healthcare will also likely improve transit accessibility to retail, and vice versa. However, the same might not be true for other desired destinations for older adults or other social groups which are not captured in jobs data (i.e., parks, visiting family or friends), thus requiring additional research comparing more closely a large array of destinations. On the other hand, our analysis showed that priority area identification is more strongly dependent on the measures used to assess the targeted sociodemographic group – older adults in this study. We found that considering number, proportion, and density of older adults yields significantly different results in terms of priority areas selected. Thus, we conclude that a composite measure is required to simultaneously account for multiple measures of older-adult prevalence. These findings complement recent research suggesting that more thorough analysis and justification of methodological decisions are necessary when assessing accessibility for older adults (Ravensbergen et al., 2022). While it is important to note that these observations are specific to this research's case study, similar findings may be expected for analyses focusing on other sociodemographic groups. This is because areas with higher land use diversity tend to be spatially concentrated, whereas total population, share of the population, and population density present larger spatial variation within a city.

4.2. Policy identification: discussion

When analysing geographical patterns of the different intervention classifications, it was observed that areas classified as requiring on-demand transit service and land-use changes were significantly further from the CBD which is coherent with general urban geographical patterns and past research on DRT (Archetti et al., 2018; Djavadian & Chow, 2017; Ma et al., 2021). However, geographical distribution of the priority areas as a whole and of each of the types of intervention was generally dispersed. Indeed, some geographical clusters are present but for the most part, priority areas are scattered around the regions which would make the provision of transit to all these areas, whether FRT or DRT, difficult. This can be attributed to the fact that contiguity, which refers to the adjacency of geographical units, and is a crucial consideration in geographical optimization (Tong & Murray, 2012; Wu & Murray, 2008), was not integrated as a requirement. While this could, in theory, limit the applicability of the policy recommendation, it is important to emphasize that the framework presented in this paper does not focus on service provision (e.g., area served by a given line, route, frequency) but rather provides recommendations of geographical areas to consider before deriving new transit services.

Through our analysis of the different type of interventions we propose, important equity considerations were highlighted. While DRT – of which on-demand transit is part – is becoming an increasingly more popular solution to provide public transit in lower-density areas (Archetti et al., 2018; Djavadian & Chow, 2017; Ma et al., 2021), areas where such interventions would be warranted to promote improvements in accessibility by transit are notably wealthier than those where FRT would be beneficial or even than the regional median values. As a result, focusing primarily on DRT as a mean to efficiently improve accessibility by transit for older adults could likely result in increased inequalities in accessibility levels between socio-economic groups. This reality comes back to the individual component of the Geurs and van Wee (2004) framework as the sociodemographic characteristics of interest have to be identified before final policy recommendations can be formulated. To promote increased equity in accessibility levels, priority areas with lower income levels, which in the case study considered are areas recommended for FRT (with and without land-use changes), should be highlighted as being the first interventions to be implemented. Still, given that the selection process for priority areas was conducted with the perspective of promoting healthy aging as driving abilities decrease with age, older adults living in car-oriented areas, which tend to be wealthier suburban and rural areas, are still likely to require transit alternatives if they are to be able to age in place. Lastly, while a distinction was made earlier between accessibility as the ease of reaching destinations and universal accessibility, the later is still important to consider when devising transport and land-use policies. Indeed, for the proposed interventions to have the fullest possible benefit on older adults' well-being and health, it is crucial that these be disability inclusive. New destinations should be universally accessible and the same applies for transit services. Therefore, while this paper does not focus on the provision of service in itself, it is important to note that para-transit – which is a form of on-demand service (Nguyen-Hoang & Yeung, 2010) – could be warranted both as part of the novel service offered in the areas highlighted for DRT and in those highlighted for FRT as a complimentary measure.

It is important to consider potential externalities of the policies being recommended. First, CTs that were identified to best fit DRT might be spatially close to other areas with lower concentrations of older adults, but who might benefit from an increase in transit provision, making FRT for the larger area worth considering. Similarly, densification or diversification in land use in one CT where it is recommended will have impacts on other CTs' level of accessibility. This is also the case for any transit service being provided – FRT or DRT – for a specific CT as it will necessarily allow for people previously too far to reach opportunities in the area to do so. In the case of encouraging aging in place, transit investments – mainly FRT – could potentially promote gentrification and displacement which would go against the formulated goal of the suggested interventions. While policy implementations are context specific and remain under the jurisdiction of decision makers and transit providers, it remains important to integrate potential externalities in the planning process to ensure a maximization of the societal benefits.

4.3. Limitations

Regarding the limitations of this work, firstly, while job data are used as proxies for the destinations older adults would want to reach, they are for the majority not interested in reaching the job positions in themselves, but rather the retail, healthcare, and/or other opportunities to which these jobs are related. To have more precise accessibility measures that are tailored to specific sociodemographic groups, it would be important in further research to directly ask people of a pre-determined sociodemographic group about the destinations they want and/or need to reach. Such data could help further tailor the proposed methodology to each sociodemographic group. Secondly, using accessibility to select priority areas in this framework supposes that travel time is the most important factor when choosing a travel mode, and more specifically public transit. This is likely not the case, as mode choice is dependent on a plurality of factors including other sociodemographic characteristics and individual preferences (De Vos, Mokhtarian, Schwanen, Van Acker, & Witlox, 2016). In the specific case of older adults, factors such as affordability and comfort could play a significant role when choosing to use public transit, which are considerations that cannot be considered in the calculation of regular accessibility measures. Older adults might also be choosing to live in remote areas to suit their lifestyle and travel preferences. As such, providing them with public transit would not necessarily result in an increase in their health or wellbeing. Overall, to address these limitations that are applicable to the broader field of accessibility research, future work can aim to study accessibility more holistically, moving beyond considering it as a solely quantitative measure but more as a complex concept that changes its meaning depending on the studied group. Asking people directly about the destinations they want and need to reach as well as their willingness to spend time in transit could allow to better fill the accessibility gaps for a specific demographic – in this case older adults. Still, in the case of this paper and the practice-ready aim of the methodology developed, making use of a simpler measure such as the cumulative opportunity count to all jobs allows for an easier translation of research findings to policy makers (El-Geneidy & Levinson, 2022). Of course, testing of the implementability of the tool in practice, which was not conducted here, will need to be done in future studies to make sure proper.

Overall, the framework presented in this study offers practitioners and researchers with a flexible methodology that allows them to identify priority areas for interventions and classifies interventions, to promote increased accessibility for a sociodemographic group of interest. As such, this paper contributes to the literature both through the methodology developed and its applicability to promote the integration of accessibility in policy making (El-Geneidy & Levinson, 2022), as well as through the evaluation of methodological choices made when generating accessibility measures for older adults (Ravensbergen et al., 2022).

5. Conclusion

In the context of increased efforts to promote a sustainable transport transition across Western countries, prioritization of new public-transit investments has become even more important to maximize benefits of new service and infrastructure. In this study, we developed a methodological approach to help inform policies aimed at promoting an increase in accessibility by public transit where it is low in an equitable way and apply it to older adults in three Canadian metropolitan areas. The focus on promoting accessibility by public transit for a specific underserved group is key to our study as it provides a pathway to address widening inequities in public-transit provision that have been highlighted in past research (Taylor & Morris, 2015) by orienting policy. Our study also builds upon the state-of-the-art accessibility framework by Geurs and van Wee (2004) by providing a way to select priority areas based on accessibility levels and sociodemographic characteristics while concurrently differentiating between suitable type of interventions. This later differentiation is novel, as previous studies looking at promoting accessibility by transit usually stopped at identifying the areas of interest (Deboosere & El-Geneidy, 2018; Jomehpour & Smith-Colin, 2020; Mamun, Lownes, Osleeb, & Bertolaccini, 2013; Mamun & Lownes, 2011; Yan-Yan et al., 2016). The framework and methodology developed in this study can be easily adapted and applied across other regions and sociodemographic groups, as long as the necessary data (GTFS, jobs, census and road network data) is available.

Future research should aim to test the usability of the proposed methodology in practice for urban areas of different scales as well as situated in different regions. Indeed, the value of the methodology presented in this study is likely to be higher in regions with more mature transit systems as transit investments there will have lower marginal impact on overall accessibility levels, thus requiring more precision when elaborating new service to maximize benefits. On the contrary, regions with underdeveloped transit systems might not benefit from the proposed methodology given that any new infrastructure and service is likely to have very high benefits across the region. Lastly, it is important to note that we do not propose particularities of the needed transit service, nor should the application of the framework be considered as a failsafe way to increase accessibility levels for the targeted sociodemographic group. Future research should combine the methods developed in this study with modelling approaches to simulate the effect of the proposed transit service implementation or land-use modifications on accessibility allowing for optimization of the policy recommendations. We also suggest that more grounded data on accessibility needs specific to sociodemographic groups be gathered through surveys and interviews and that this data be combined with the proposed framework to refine the analysis.

Authors contribution

The authors confirm contribution to the paper as follows: Study conception and design: Rodrigue, Alousi-Jones, Negm, Victoriano-Habit, El-Geneidy; Data collection: Rodrigue, Alousi-Jones, Negm, Victoriano-Habit, El-Geneidy; Analysis and interpretation of results: Rodrigue, Alousi-Jones, Negm, Victoriano-Habit, Zhang, Jimenez, El-Geneidy; Draft manuscript preparation: Rodrigue, Alousi-Jones, Negm, Victoriano-Habit, Zhang, Jimenez, El-Geneidy. All authors reviewed the results and approved the final version of the manuscript.

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