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The cost of equity: Assessing transit accessibility and social disparity using total travel cost

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ABSTRACT

Social equity is increasingly incorporated as a long-term objective into urban transportation plans. Researchers use accessibility measures to assess equity issues, such as determining the amount of jobs reachable by marginalized groups within a defined travel time threshold and compare these measures across socioeconomic categories. However, allocating public transit resources in an equitable manner is not only related to travel time, but also related to the out-of-pocket cost of transit, which can represent a major barrier to accessibility for many disadvantaged groups. Therefore, this research proposes a set of new accessibility measures that incorporates both travel time and transit fares. It then applies those measures to determine whether people residing in socially disadvantaged neighborhoods in Montreal, Canada experience the same levels of transit accessibility as those living in other neighborhoods. Results are presented in terms of regional accessibility and trends by social indicator decile. Travel time accessibility measures estimate a higher number of jobs that can be reached compared to combined travel time and cost measures. However, the degree and impact of these measures varies across the social deciles. Compared to other groups in the region, residents of socially disadvantaged areas have more equitable accessibility to jobs using transit; this is reflected in smaller decreases in accessibility when fare costs are included. Generating new measures of accessibility combining travel time and transit fares provides more accurate measures that can be easily communicated by transportation planners and engineers to policy makers and the public since it translates accessibility measures to a dollar value.

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1. Introduction

Increasingly, social equity is incorporated as a long-term objective into urban transportation plans, although what is meant by 'equity' varies widely (Manaugh et al., 2015). Access to opportunities such as jobs and services is one of the main benefits of a transportation service such as public transit (Grengs, 2010; Jones and Lucas, 2012). Due to the central and peripheral nature of cities, not all residents benefit from similar levels of accessibility (Martens, 2012). Nevertheless, a fair distribution of transportation resources should provide commuters with various travel options to increase their access to

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opportunities, particularly to jobs; this is often not the case despite stated transport goals. Low-income and socially disadvantaged individuals are the most likely to be transit-dependent (Denmark, 1998; Dodson et al., 2007), and often face greater barriers to access their desired destinations (Lucas, 2012). To determine the level of opportunities residents in a region can reach, as well as to assess the spatial distribution of public transit service, typical research employs accessibility measures, which are measures of land use and transportation interaction (El-Geneidy et al., 2015; Foth et al., 2013). The simplest measure of accessibility and most commonly used is known as cumulative opportunities, where within a given time thresholds (usually 45 or 60 min) the number of opportunities that can be accessed using a specified mode is counted. By revealing the level of accessibility of socially disadvantaged neighborhoods, transport planners can evaluate the vertical or horizontal equity of transport benefits spatially.

To date, transportation equity studies have focused on travel time as a constraint on accessibility. However, financial access to transit is also crucial. For low-income populations, transit fares present a barrier to accessibility, since fares can consume a large share of individuals' budget (Carruthers et al., 2005). Job accessibility research that ignores transit fares may overestimate job accessibility, particularly for low-income riders. It is accordingly important to take the monetary aspect of commuting into account when examining accessibility.

The present study assesses the level of accessibility to jobs using public transit for people residing in socially disadvantaged neighborhoods in Montreal region compared to those living in other neighborhoods. In particular, we account for hourly wages and transit fares as important constraints on accessibility, in the context of a complex fare structure involving 14 different schemes. This methodology can benefit transportation planning agencies aiming to promote transit equity based on transit service supply and fare structure. Also the generated measure can be communicated easily to policy makers and the public as it will be either in a dollar value or travel time.

This paper is organized in five sections. The first section provides an overview of the literature on accessibility and equity issues in transportation. Next, the Montreal study context is presented, followed by a description of the data and methodology used to generate and assess the accessibility measures in relation to social equity. Results are analyzed spatially for the different accessibility measures. Finally, the results are discussed and the recommendations and conclusions of the study are presented.

2. Literature review

2.1. What is accessibility?

Accessibility is a measure of potential opportunities (Hansen, 1959). A simple measure of accessibility is the cumulative opportunity measure, which counts the number of opportunities that are reachable from a given location within a specified travel duration or travel distance when using a particular travel mode (Geurs and van Wee, 2004; Vickerman, 1974). While this measure is simple to calculate and understand, it evaluates all destinations equally, does not differentiate travel times except that they are above or below a threshold, and does not account for travelers' perceptions of time (Ben-Akiva and Lerman, 1979). The gravity-based measure of accessibility, on the other hand, discounts the attractiveness of the destinations by the cost of travelling. Typically, these costs are defined by the time or distance a person has to travel (Geurs and van Wee, 2004; Handy, 1994; Hansen, 1959; Owen and Levinson, 2014; Vickerman, 1974). The main disadvantage of the gravity-based measure, however is that its results are harder to communicate and interpret (Geurs and van Wee, 2004; Owen and Levinson, 2014). Importantly, gravity and cumulative accessibility measures are highly correlated, allowing their interchangeable use as necessary (El-Geneidy et al., 2011; El-Geneidy and Levinson, 2006). Hence, cumulative opportunity is used in this study.

2.2. Accessibility and equity

Measuring accessibility by public transportation is important to evaluate the distribution of services in a region based on equity (Foth et al., 2013). However, what constitutes an equitable distribution is difficult to define due to varying social norms and moral judgments (van Wee and Geurs, 2011). Two main types of equity are generally evaluated in transportation planning: horizontal equity and vertical equity. Horizontal equity refers to the uniform distribution of benefits and costs among individuals within a group. Based on egalitarian theories, it avoids favoring one individual or group over another. Most studies of horizontal equity look into spatial distribution of transportation impacts. However, with regard to public transit, some groups are more likely require such service, namely low-income populations that are transit-dependent (Pucher and Renne, 2003; Sanchez et al., 2004) as they cannot afford owning a car. According to Krumholz and Forester (1990), a fair distribution of resources provides a greater variety of options to those with the least. This relates to vertical equity, which considers the distribution of benefits between groups, and compares the benefits across socio-economic groups, e.g. the well-off with marginalized and vulnerable populations. In the case of transportation, potentially disadvantaged populations include low-income and unemployed people as well as minorities (Denmark, 1998; Dodson et al., 2007).

One way to investigate vertical equity issues in transportation is to assess the effectiveness of the service provided by transit agencies among different stratified socioeconomic groups by using accessibility as an indicator of the benefits provided by the land use and transportation system in a region. Recently, Riccardi et al. (2015) studied transit accessibility in Perth, Australia, and found that socially disadvantaged groups comprising of elderly people, low-income households and no-car households suffered from inequitable distribution of accessibility using transit services. In contrast the transit distribution in Toronto is such that residents living in areas of lower socioeconomic status benefit from higher accessibility to jobs and have shorter travel times than those living in areas of higher socioeconomic status (Foth et al., 2013). Yet, the level of equity of accessibility varied throughout the day (El-Geneidy et al., 2015). As such, measuring accessibility to important destinations, like employment, provides a useful tool to evaluate equity issues in a region.

2.3. Accessibility by cost

In the studies discussed above, accessibility is typically measured based on travel duration and/or distance (Geurs and van Wee, 2004; Handy, 1994; Hansen, 1959; Owen and Levinson, 2014; Vickerman, 1974). However, travel duration and/or distance is only one of the limiting components of accessibility. As indicated by Lucas (2012), the cost of transit also constrains individuals in reaching their desired destinations. Using three American case studies, Nadeau (2015) shows a practical example of budgetary constraints, where low-wage employees working at airports cannot afford transit services developed by the municipalities to connect employees to airports. In another study, the Utah Transit Authority partnered with Farber et al. (2014) to assess the effects that distance-based fares would have on vulnerable populations. In general, they found that riders with lower socioeconomic statuses traveled shorter distances than average. Subsequently, they concluded that changing their fare structure from flat fares to distance-based fares would reduce travel costs of low-income households and the elderly. However, their results also indicated that distance-based fares would increase the travel costs for certain minority populations living far away from the city center. In these studies, affordability is understood as the fare of travel.

While there is an extensive literature on the impacts of unaffordable public transit, few studies have incorporated transit fares into accessibility measures. Using travel-demand models, logsum accessibility measures have been generated, which account for generalized travel costs (Geurs et al., 2010; Niemeier, 1997). While logsum measures have the benefit of including a wide range of travel costs, these measures are hard to communicate and have no physical interpretation.

Using an Origin-Destination travel survey, Bocarejo and Oviedo (2012) developed a methodology to measures changes in accessibility by transit based on generalized travel costs, which include the travel time cost (expressed in time), and an affordability component. The affordability component represents the proportion of income spent on commuting, and is derived from the average transport expenditures and income for each zone. Using the travel time and affordability for each pair of origin-destination zones, the authors derive a zone-specific impedance function, which is then used to measure accessibility based on standard parameters of time and affordability, and on desired parameters. Developing a zone-specific impedance function allows assessing the changes in accessibility resulting from time and cost savings, as done by the authors for selected zones of Bogotà. Yet, expanding the methodology to all zones of a large metropolitan area is challenging and requires a lot of resources that might not be available to planners. Additionally, the approach, based on reported affordability and travel times, does not measure accessibility using specific transportation modes, e.g., using transit.

Few studies have incorporated travel time and transit travel fares into accessibility-by-transit measures based on the actual network characteristics. The UK Department for Transport developed a software to measure accessibility based on the travel time, the monetary travel cost, or both. Yet, due to the lack of data, national indicators have been developed based solely on travel times (Department for Transport, 2004). Nevertheless, the Department for Transport recommends that local agencies include the travel time. In this regard, Currie (2004) measured accessibility by transit in Hobart, a small Australian town, based on estimated generalized travel costs, including travel time and travel fare. Travel times were converted into monetary values based on a wage of $Aust 8.69/h, and travel fares were estimated through an analysis of boarding and revenue data. Currie (2010) conducted a similar "need-gaps" analysis in Melbourne, Australia, but simplification was required due to the scale of the study area. As a result, travel fares were not included in the cost of travel. Working with large metropolitan regions that include multiple transit agencies is a significant challenge for including travel fares in generalized travel costs. Ford et al. (2015) developed accessibility measures based on generalized costs including time and fares of travel for London. The fare of travel was based on a flat rate for a bus trip, and on an average price/km for heavy and light rail services. This approach allows calculating fares based on readily available data, but is not applicable to all large metropolitan areas. In many North-American cities, fare structures, involving multiple agencies, are more complex and cannot be approximated with simple indicators.

In sum, although travel fares are central for accessibility, and such factors have appeared together in accessibility measures derived from regional travel-demand models or travel surveys, few studies thus far have *measured* accessibility by including the observed cost of travel time together with the actual transit fare in large metropolitan areas. Such measures, developed in the present study, allow measuring the performance of the transit and land use system, independently from the characteristics of the users, and can then be used to conduct socio-spatial equity analyses. Additionally, as few studies have used generalized travel costs, this study compares various accessibility measures, including travel time and/or travel fare, and discusses the implications of integrating different travel fares into the cost of travel. To our knowledge, no study has assessed the loss in accessibility resulting from including transit fares or the difference in accessibility by accounting for monthly or single fares.

3. Study context

The Greater Montreal Area, also known and hereafter referred to as the Communauté Métropolitaine de Montréal (CMM), is the second largest metropolitan region in Canada, with a current population of nearly 4 million residents. While almost half of the residents reside on the Island of Montreal, the population of off-island suburbs (yellow, green and orange regions in Fig. 1) is increasing. Montreal's major employment centers remain in the central business district and other on-island centers that are accessible by transit (El-Geneidy et al., 2011; Shearmur et al., 2007).

Transit in the CMM is coordinated by the Agence Métropolitaine de Transport (AMT), with local agencies operating local bus service with separate fare schemes. The Société de Transport de Montréal (STM), the transit agency of the City of Montreal and the largest transit agency in the region (red[1] in Fig. 1), operates the metro and bus services on the Island of Montréal with more than 759 metro cars and 200 bus routes, allowing for over a million trips per weekday. The AMT is responsible for the commuter rail with the goal of transporting commuters from various suburbs to downtown Montreal. As such, commuter train frequency is highest during weekday morning and afternoon peaks, with little service off-peak weekdays, and weekends. The two other major transport agencies in the region are the Réseau de Transport de Longueuil (RTL) and the Société de Transport de Laval (STL), with a total ridership of 200,000 per day. Several other small inter-municipal transit agencies operate the in peripheral areas of the region (Fig. 1).

With 14 separate fare schemes, transport within the Montreal region represents an interesting case study. It is not unusual for transit users to have to purchase more than one transit fare to travel within the region. For example, a single trip will cost $3.25 (CAD), regardless of mode (bus or metro), transferring, time of day, or distance for travelling on the Island of Montreal (red in Fig. 1). However, travelling to Laval, the island north of Montreal, will cost $3.25 to arrive there from Montreal, plus another fare of $3.25 to travel on the Laval transit agency's network. Moreover, residents living in one of the municipalities on the South Shore wishing to travel to Laval, depending on proximity to commuter rail or the metro station in Longueuil, may need to buy one fare for their local bus ($3, for instance) which travels to Montreal, then a fare to use the Montreal metro ($3.25), and then another fare to use the local transit network in Laval ($3.25). All previous examples do not include travelling using the commuter rail system. This system has different zones and fares than the explained above, which adds more complexity to the context. Our calculations include all these complexities to capture zonal and fare network differences in the CMM.

4. Data and methodology

To determine how equitable job accessibility is among socially disadvantaged groups compared to the rest of the population in the CMM, we studied accessibility at 7 am during a weekday, either based solely on travel time, solely on travel fare or on a combination of travel time and fare. When combining travel time and fare, measures are reported both as a monetary value (converting travel time to cost) and in time (converting cost to time).

Four main data sources are used in the analysis at the census tract (CT)-level, with a total of 921 CTs in the CMM. The first is the demographic census tract information and comes from the Statistics Canada National Household Survey (NHS) collected in 2011 (Statistics Canada, 2011). This data includes household median income, unemployment rates, percentage of immigrants, and educational achievement and is used to determine social and economic deprivation. The second dataset provides data regarding the total number of jobs by CT in the CMM and is also obtained from the 2011 NHS (Statistics Canada, 2011). The third dataset is a cost matrix of daily and monthly fare costs obtained from the AMT website for travel between all 14 transit agencies in the region at 7 am and 12 pm. The final dataset is a transit travel time matrix based on May-June 2014 General Transit Feed Specification (GTFS) data for all 14 transit agencies. This dataset is used to determine the travel times between CT origin and destination centroids using the OpenTripPlanner Analyst developed by Conveyal (OpenTripPlanner, 2014).

4.1. Accessibility measures

In this study, we used a cumulative accessibility measure to determine how residents throughout the region have access to jobs (Geurs and van Wee, 2004). Specifically, we calculated cumulative accessibility to jobs with transit at 7 am. In other words, we determined the number of jobs reachable with transit (within a defined travel time and/or cost threshold) from every CT, to all jobs in all CTs (including the CT of interest). Cumulative accessibility was calculated using the formulas below:

$$A_i = \sum_{j=1}^{n} O_j f(C_{ij}) \tag{1}$$

$$f(C_{ij}) = \begin{cases} 1 & \text{if } C_{ij} \leqslant t_{ij} \\ 0 & \text{if } C_{ij} > t_{ij} \end{cases} \tag{2}$$

[1] For interpretation of color in Figs. 1, 2, and 5, the reader is referred to the web version of this article.

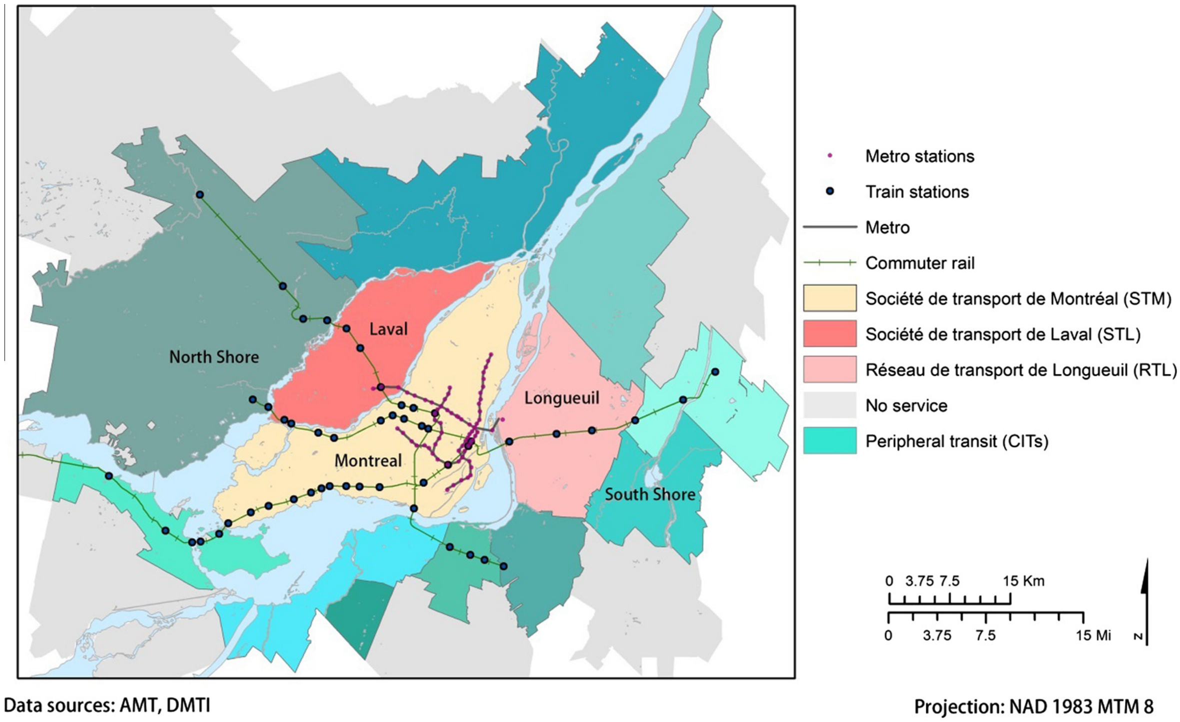

Fig. 1. Transport agency zones in the Montreal metropolitan region.

where A_i is the accessibility from zone i to all jobs in zone j, O_j is the number of jobs in zone j and $f(C_{ij})$ is the weighting function with C_{ij} being the time or cost of travel from i to j, and t is the travel time or cost threshold. For cumulative accessibility, if travel time or cost is greater than a specified threshold, jobs reachable beyond those thresholds are not counted (Eq. (2)).

4.1.1. Accessibility based on time

Initially, cumulative accessibility based solely on travel duration was generated. In this case, one-way travel cost is expressed in minutes (Eq. (3)) with the following thresholds: 30, 45, 60, 75 and 90 min. The average commuting time by transit in the Montreal metropolitan region is 43.1 min, with 27% of the commuting trips by transit lasting more than 60 min, and 22% lasting between 45 min and 60 min (Statistics Canada, 2011). Similar patterns are found throughout Canada, with an average commuting time by transit of 42.9 min, and 28% of the commuting trips lasting more than 60 min (19% between 45 and 60 min) (Statistics Canada, 2011).

$$C_{ij} = t_{ij} \tag{3}$$

4.1.2. Accessibility based on fare cost

Second, accessibility based solely on fare cost was generated. The one-way travel cost is equal to the cost of the fare (Eq. (4)) and thresholds are expressed in terms of minimum hourly wage in Quebec ($10.35) as follows: 1 hourly wage, 1.5 hourly wages, 2 hourly wages, 2.5 hourly wages, 3 hourly wages and 4 hourly wages. Eq. (1) is used as above, but substituting the following:

$$C_{ij} = F_{ij} \tag{4}$$

where F_{ij} is the cost of transit fare to travel from zone i to zone j.

4.1.3. Accessibility based on travel time and fare cost, expressed in monetary term

Third, we calculated accessibility based on both travel time and fare cost. Travel cost was determined by multiplying minimum hourly wage in Quebec ($10.35) by the travel time, so one hour of travel costs $10.35. In this way, we were able to determine the number of jobs accessible by transit based on hourly wage (1, 1.5, 2, 2.5, 3 and 4 wages) and the transit fare used (discussed further in the proceeding section). Eq. (1) is used as above, but substituting cost with the following formula:

$$C_{ij} = t_{ij}w + F_{ij} \tag{5}$$

where C_{ij} is the time cost of travel, t_{ij} is the travel time in hours, w is the minimum wage per hour ($10.35), and F_{ij} is the transit fare (either for a single trip or a monthly pass) to travel from zone i to zone j.

4.1.4. Accessibility based on travel time and fare cost, expressed in time

Finally, cumulative accessibility was calculated including travel time and fare cost, but this time expressed in terms of time. Cost was calculated with the following formula:

$$C_{ij} = t_{ij} + \frac{F_{ij}}{w} \tag{6}$$

where C_{ij} is the time cost of travel, t_{ij} is the travel time in hours, w is the minimum wage per hour ($10.35), and F_{ij} is the transit fare (either for a single trip or a monthly pass) to travel from zone i to zone j.

Finally, to simplify comparisons throughout the region among social deciles and by different fares, accessibility values are converted to normalized z-scores (El-Geneidy et al., 2015; Foth et al., 2013).

4.2. Travel time and transit fares

To determine travel times between census tracts, we generated a transit travel time matrix based on GTFS database for all Montreal regional transit agencies. The used data was for the period from May to June 2014. The region includes three major transit agencies as well as 11 inter-municipal transit agencies that provide transit service for certain municipalities and connects them to various regional destinations. The travel time from each CT centroid to every other CT centroid is measured for a departure time of 7 am, and are organized to produce an OD travel time matrix. The commute times include access and egress time, waiting time, time-in-vehicle, and transfer time. These calculations were done using the OpenTripPlanner Analyst provided by Conveyal (OpenTripPlanner, 2014). OpenTripPlanner provides the fastest transit route for a defined departure time, and we matched this travel time to the transit fare described below.

While OpenTripPlanner provides an accurate transit itinerary many regions do not include the fare costs in their GTFS data and just include a link to their websites. This was the case for the CMM. Therefore, we used the fare calculator tool on the website of the regional public transport coordinator in the CMM, AMT, to calculate the transit fare (AMT, 2015a). This was done manually through querying origin and destination centroid coordinates of every CT that yielded different trip and fare options, using trips leaving closest to 7 am and 12 pm regardless of mode were selected, and with the earliest arrival times (consistent with OpenTripPlanner routes). The prices for a single fare and a monthly pass for that trip were recorded. Single fares varied more than monthly fares because of the zonal nature of the territory (AMT, 2015b). Then, based on the monthly fare, we calculated a single trip fare by dividing the total monthly cost by 44, which corresponds to returns trips to and from a destination a total of 22 working days per month. Note that purchasing monthly fares is the most cost-effective manner to access transit, but involves larger up-front costs than single fares (Carruthers et al., 2005).

4.3. Social vulnerability indicator

To ascertain the social vulnerability of neighborhoods in the Montreal region, we used census tract-level data from Statistics Canada's 2011 NHS and Census (Statistics Canada, 2011). With the assumption that socially disadvantaged groups are spatially concentrated (Ades et al., 2012), we derived an indicator from four equally-weighted variables to identify socially vulnerable neighborhoods at the CT-level. In addition to median household income, we also used percentage of recent immigrants (since 2006), the percentage of the workforce that is unemployed, and percentage of residents with education at the level of only a high school diploma (25–64 years old). The current social indicator is a modification of previous work sensitive to the Canadian context (Foth et al., 2013; Manaugh and El-Geneidy, 2012), but more specific to Montreal. Briefly, immigrant status is relevant to the Canadian context because recent immigrants tend to be well educated due to the Canadian immigration laws, yet they work for lower-wages and be employed in lower skill trades, and have a greater likelihood to be unemployed compared to Canadian-born workers (Canada, 2004). Nevertheless, we also included education levels to account for non-immigrants with low educational achievement. Although previous work in Toronto included households that spend more than 30% of their income on rent (El-Geneidy et al., 2015), in the Montreal area, this value was not significantly correlated with the other variables. All variables in the indicator were correlated with a Pearson correlation coefficient above 0.5, in order to make sure that they are explaining the same population. The indicator is in line with previous studies, identifying low-income and unemployed people as well as ethnic minorities as potentially disadvantaged groups (Dodson, 2005).

Each variable was then normalized as a z-score to determine how each tract compares to the regional average, and all variables were then summed to give an overall score of social disadvantage (for details of this measure see Foth et al. (2013)). By grouping census tracts into deciles based on the social deprivation indicator score, we identify the least disadvantaged census tracts (top 10%, or 10th decile) ranging to the most disadvantaged census tracts (bottom 10%, or 1st decile). It is important to note the statistical analyses presented in this study compare the most socially disadvantaged census tracts (the first decile) to the other deciles.

Fig. 2 shows the spatial distribution social deciles. As seen in the figure, the redder colors demonstrate the more socially deprived areas. Most of the socially disadvantaged CTs (the first three deciles) are located on the Island of Montreal (85%),

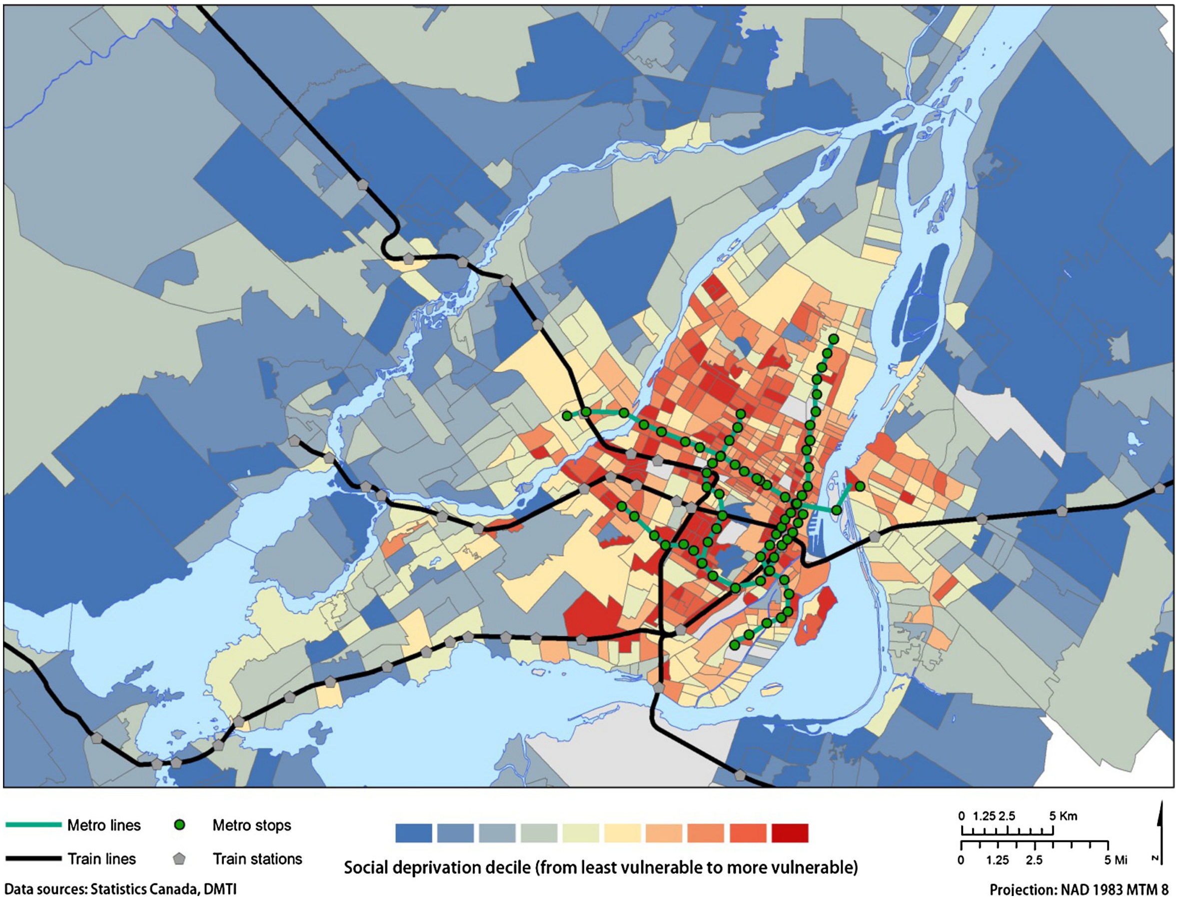

Fig. 2. Census tracts of the Montreal metropolitan region based on social vulnerability.

while only about 15% are located off the island. Also, generally speaking, socially disadvantaged CTs are mainly located around metro lines, with the exception of one zone in the north of the Island. This area is known as a district concentrating many socio-economic issues.

5. Results and analysis

5.1. Regional accessibility trends

First, we measured the cumulative opportunities job accessibility by transit using travel duration throughout the region. This corresponds to the literature that normally calculates accessibility based only on travel time (van Wee and Geurs, 2011). As seen in Fig. 3, most of central Montreal, with some off-Island locations near metro stations have medium accessibility to jobs by transit within 45 min of travel time (Fig. 3A). Within 60 min of travel time, a large proportion of CTs on most of the island, particularly around the metro lines and on the northeastern side of the Island, saw an increase in accessibility to jobs. A similar surge in accessibility can be observed off the Island, especially on the South Shore and Longueuil, as well as in Laval (Fig. 3B). This is attributable to the greater amount of available transit in terms of suburban commuter rail and suburban buses at these locations and their usefulness for linking South Shore and Laval residents with job centers on the Island of Montreal.

Next, we asked how job accessibility throughout the region would depend on the out-of-pocket cost of a transit fare based on hourly wage. Put another way, how many jobs can a resident reach for a given wage with a single or monthly fare? Interestingly, one hour's wage will buy access to most jobs on the Island of Montreal and the shores surrounding it (Fig. 3C), and one-and-a-half hour's wage will buy access to all the jobs throughout the CMM, based on the cost a single fare to the appropriate census tracts (Fig. 3D). These results seem to indicate that the entire region is highly accessible with transit given the current hourly minimum wage in Quebec. Nevertheless, travelling is based not only on out-of-pocket costs, like transit fares, but also on travel time cost. So using transit fare as the only cost in an accessibility measure is likely misleading. It should be noted that for all of the previous four maps, the same scales were used allowing us to compare across maps.

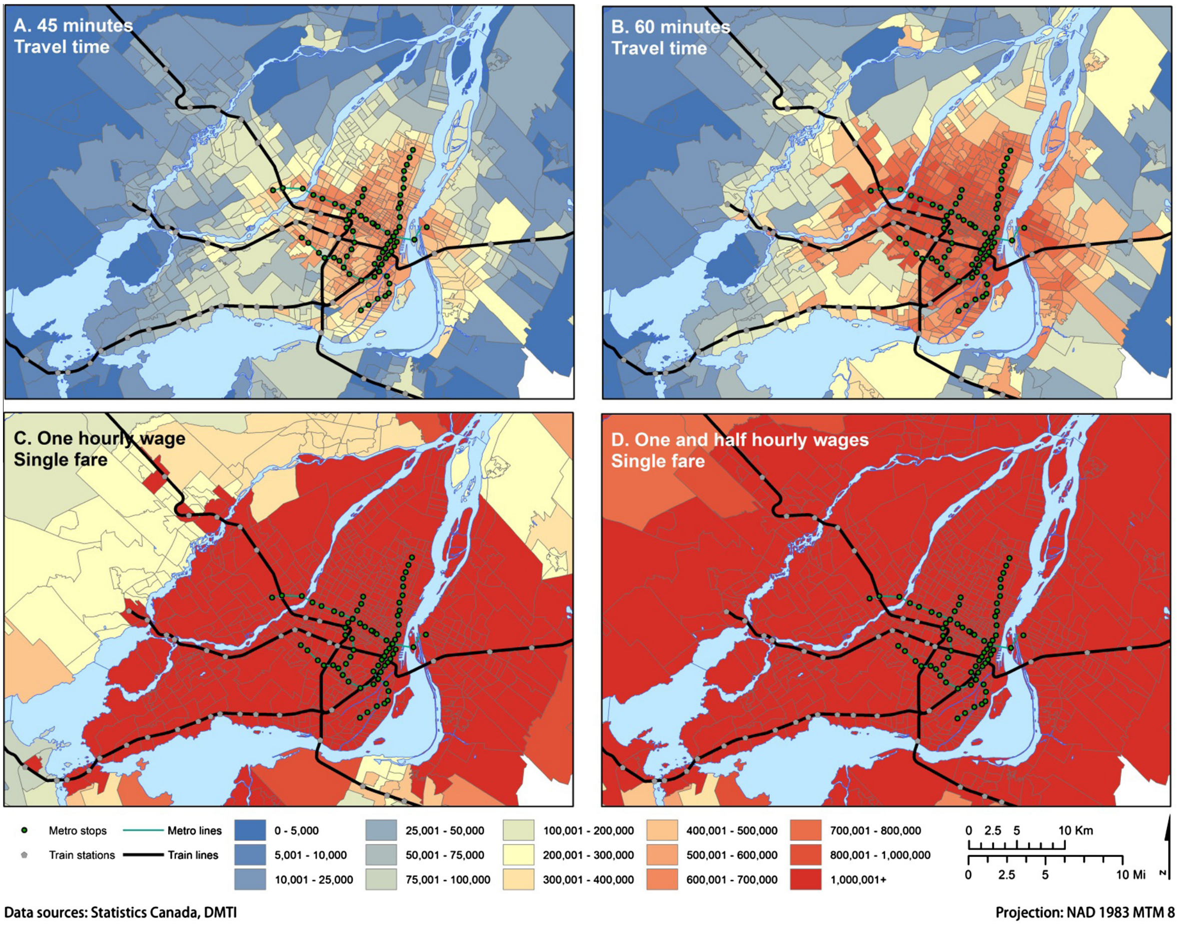

Fig. 3. Number of jobs accessible by transit based solely on travel time and solely on fare.

To gain a more realistic picture of accessibility based on fare cost and travel time, we used two methods illustrated in Fig. 4. The first is based on using the travel cost as a combination of transit fares and travel time converted to monetary value (based on hourly wage), and then calculating the number of jobs reachable within given thresholds of defined wages (the threshold values are discussed in the previous section). As an example of the results, Fig. 4A to D shows the total number of jobs that are accessible by transit within one minimum wage and one-and-a-half minimum wages. While Fig. 4E-F is based on calculating travel time as combination of both transit fares converted to travel time (based on hourly wage) and travel time. Then, cumulative accessibility is measured based on travel time thresholds as normally done in the literature.

For the time value of an hourly wage and the cost of a single transit fare, at a departure time of 7 am, the CTs nearest to metro stations and some off-Island areas near commuter stations have high job accessibility (Fig. 4A). The picture changes dramatically, as an outward spread from the center of accessibility for a larger travel cost of one-and-a-half hour's wage and a single fare. Most of the CTs on the Island and on the North and South Shore suburbs have excellent job accessibility. In addition, more areas have greater accessibility in the western portion of the Island near the commuter rail (Fig. 4B). This is likely due to the number of offered train trips during the morning peak hours.

While analyzing cost based on a single fare is a good approximation for accessibility by cost, commuters travelling on a daily basis likely purchase monthly fares, since these are cost-effective and usually cheapest per ride (Carruthers et al., 2005). Therefore, we also mapped job accessibility based on monthly fares calculated per ride. Importantly, we found that more CTs in the CMM had greater accessibility for both an hour and one hour-and-a-half's wages' time cost based on a monthly fare (Fig. 4C and D) compared to job accessibility with a single fare. This result indicates that buying a monthly pass enables greater job accessibility for larger share of residents than the price of a single ticket for the same travel cost. These findings reveal that including both the cost of a fare and the cost of travel time is an important consideration when studying accessibility.

Fig. 4E and F shows the other accessibility measure results that are based on converting monthly fare cost to time. Very similar trends can be found across these two maps and the previously discussed maps that are based on the monthly fares. In fact, Fig. 4C and F are almost identical. This is expected since in both figures, the accessibility measures were calculated based

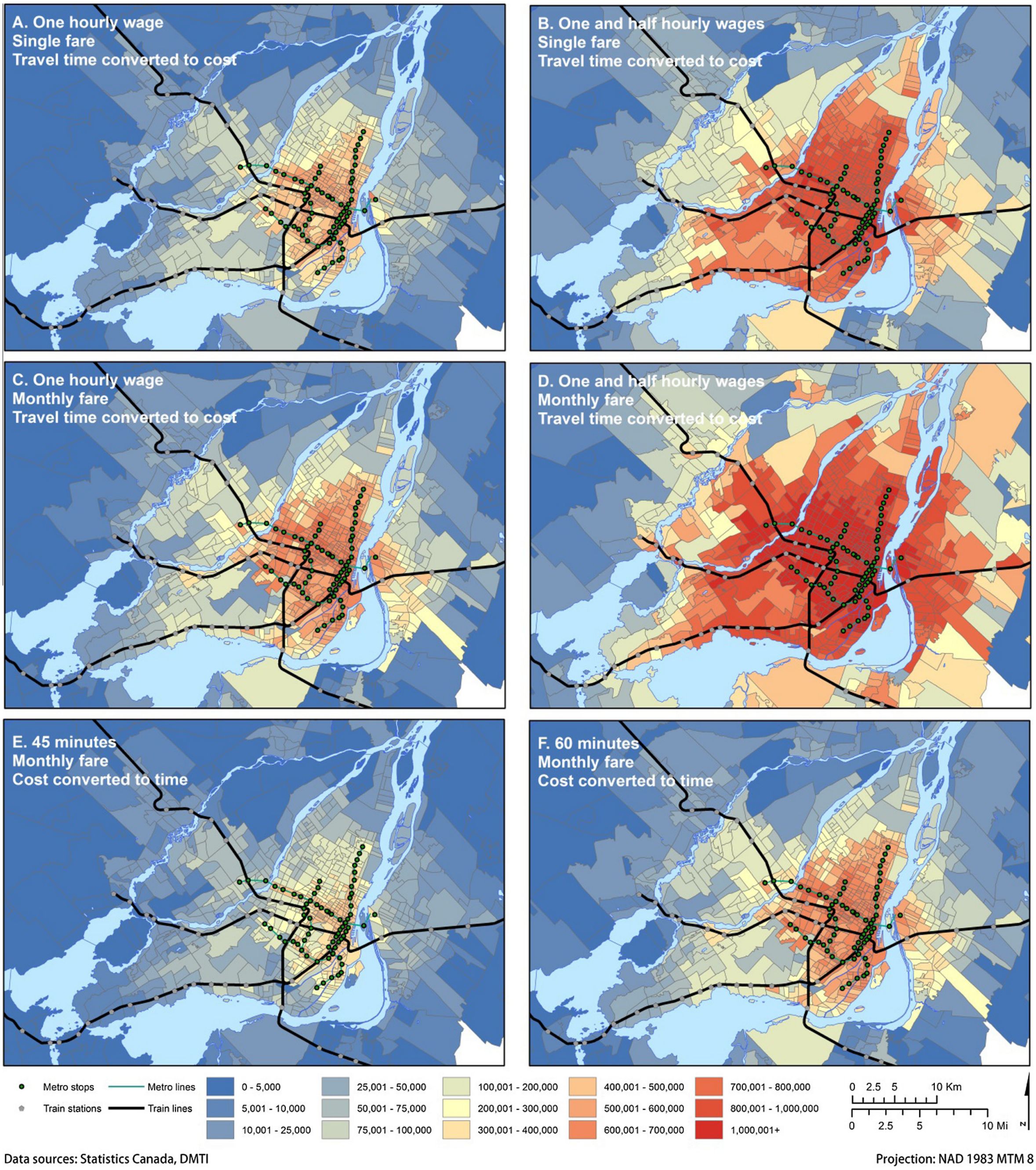

Fig. 4. Number of jobs accessible by transit based on travel time and cost fare (single and monthly fare).

on an hour threshold: 60 min (Fig. 4C) and one hour of minimum wage (Fig. 4C). Thus, both accessibility measures can be used interchangeably while evaluating the regional accessibility, while keeping in mind which one could be easier to interpret and to communicate to the public according to the context. It should be noted that for all of the previous maps, the same scale was used allowing us to compare across maps.

Since little variability was noticed between 7 am and 12 pm in term of travel time and travel time by cost, we only reported 7 am calculations in this paper.

Table 1
Correlation matrix between accessibility measures*.

	Travel time					Monthly fare with travel cost					Single fare with travel cost				
	Within 30 min	Within 45 min	Within 60 min	Within 75 min	Within 90 min	One hourly wage	One and half hourly wages	Two hourly wages	Two and half hourly wages	Three hourly wages	One hourly wage	One and half hourly wages	Two hourly wages	Two and half hourly wages	Three hourly wages
Travel time															
Within 30 min	1.00														
Within 45 min	0.82	1.00													
Within 60 min	0.71	0.92	1.00												
Within 75 min	0.64	0.85	0.95	1.00											
Within 90 min	0.57	0.77	0.89	0.96	1.00										
Monthly pass with travel cost															
One hourly wage	**0.80**	**0.99**	0.93	0.85	0.77	1.00									
One and half hourly wages	0.64	0.86	**0.96**	**0.98**	0.94	0.87	1.00								
Two hourly wages	0.51	0.70	0.83	**0.93**	**0.98**	0.71	0.91	1.00							
Two and half hourly wages	0.37	0.54	0.67	0.78	**0.88**	0.55	0.75	0.92	1.00						
Three hourly wages	0.26	0.38	0.49	0.60	**0.72**	0.39	0.57	0.76	0.93	1.00					
Single fare purchase with travel cost															
One hourly wage	**0.86**	**0.95**	0.84	0.76	0.69	**0.95**	0.78	0.62	0.47	0.33	1.00				
One and half hourly wages	0.69	0.90	**0.94**	0.90	0.83	0.93	**0.93**	0.79	0.62	0.46	0.85	1.00			
Two hourly wages	0.57	0.79	0.90	**0.93**	0.91	0.81	**0.96**	0.91	0.76	0.59	0.72	0.91	1.00		
Two and half hourly wages	0.48	0.68	0.81	0.90	**0.94**	0.70	0.90	**0.97**	0.88	0.73	0.61	0.80	0.94	1.00	
Three hourly wages	0.39	0.57	0.70	0.81	**0.89**	0.58	0.79	0.93	**0.95**	0.87	0.49	0.67	0.83	0.94	1.00

Number of jobs within different travel time and cost thresholds by transit at 7 am.
* Using Pearson correlation test: All correlations are significant at the 0.01 level.

5.1.1. Correlations between measures

Several correlation matrices are used to understand the relationship between accessibility measures. Table 1 shows the correlation between the total number of jobs that can be reached within different travel time and cost thresholds by transit. Generally, the table shows that for the number of jobs that can be reached within a cost of one hour of minimum wage (using a single transit fare), there is very high correlation at 95% with 45 min travel time. This indicates that the two variables tend to increase (or decrease) together. This correlation value increases to 99% by using accessibility based on monthly fares. This indicates that the number of jobs that can be reached within one hour of minimum wage and based on monthly fare is almost connected to the number of jobs that can be reached within 45 min, with an almost perfect linear relationship. Using monthly fare causes less variation compared to using single fare while accounting for the changes in accessibility based on time versus cost. A very similar tends can be found in the table between accessibility measures using monthly fares and travel time. One-and-a-half hour's wage accessibility using a single transit fare is highly correlated at 94% with using 60 min accessibility threshold. However, when we consider a monthly fare, the one-and-a-half hour's wage accessibility correlation increases to 96%. While these correlations do not imply the difference between the measures, they rather show the extent to that they are changing together. The following section investigates the differences between accessibility measures that are based on the monthly fare and travel time.

5.1.2. Loss in accessibility

This section investigates potential differences between the proposed accessibility measures that are based on the travel cost as a combination of transit fares and travel time and the measures that have been traditionally used in the literature, which are based only on travel duration. Fig. 5 shows the results of these comparisons. The difference was calculated based on the total number of jobs that can be reached within an hour of time minus the number of jobs that can be reached within an hour of minimum wage. As seen in the figure, there is a difference in the number of jobs that can be reached by transit all over the region. Using a monthly fare, a large proportion of CTs on most of the island, particularly around the metro lines and on the northeastern side of the island, experience a small decrease in the number of jobs. However, this loss in accessibility surges in the northeastern area of the Island of Montreal and the shores surrounding it. This is attributable to users who will have to pay different fare to move from or to the Island from the surrounding shores.

When considering a single fare, similar trends of losses in accessibility can be observed, with darker colors indicating larger loses compared to a monthly fare. This is attributable to the difference in cost between the monthly and single fares. This indicates that monthly vs single fare has an impact on the total number of jobs that can be reached within a threshold of time. Thus, decreasing the difference in cost between both will increase the total number of jobs that can be reached. Furthermore, this confirms that accessibility is sensitive to transit fare. In addition, it is important to understand if the socially disadvantaged areas in the Montreal region actually suffer more or less losses in the number of jobs they can access within a certain threshold than other areas in the regions, which we have done in the following section.

5.2. Trends by social decile

This section assesses the distribution of transit benefits across all CTs based on the social disadvantage decile. It compares the transit benefits, in terms of accessibility, of the most socially disadvantaged CTs to the rest of the CTs in the CMM. Table 2 presents summary statistics of accessibility by cost for each decile. Note that the results are consistent with the accessibility by time. Table 2 uses ANOVA tests to compare each decile's accessibility by cost and travel time to the first decile.

Generally speaking, socially vulnerable CTs enjoy higher levels of accessibility, both in terms of travel cost and travel time, while socially advantaged tracts enjoy lower levels. Deciles 5–10 (in bold in Table 2) show significantly lower accessibility than decile 1. These findings suggest that public transit supply and fares provide equitable benefits in terms of vertical equity. The provision of public transit generally favors vulnerable populations in Montreal. This is also consistent with the social indicator map (Fig. 2) showing that low-income and immigrant populations generally reside in central Montreal, relatively near metro stations. Inversely, high-income, non-immigrant populations are concentrated in suburban areas. Socially vulnerable populations may decide to locate near major transit lines, as they are more likely to be transit-dependent.

Fig. 6 presents the proportion of jobs that are accessible within one hour's wage (including travel time and cost fare expressed in monetary terms) compared to the number of jobs calculated with the traditional measure of accessibility based on travel duration (within 60 min). Results show for decile 1, based on a monthly pass, only 70% of the jobs (measured with travel time duration) are accessible when including fare cost. Accordingly, 30% of the jobs calculated with the measure based on travel time duration are not accessible when including fare cost. The decrease is more pronounced when looking at a single fare (50% for decile 1). This confirms that accessibility is sensitive to transit fare. Nevertheless, results show that socially advantaged deciles experience bigger decreases in accessibility, when including fare cost. This is likely due to the fact that they are mainly located in suburban areas, where travel fares are significantly more expensive (up to $21 of cost).

While the results suggest that socially disadvantaged decile have higher accessibility to jobs by transit, they do not account for the individual characteristics that might affect their ease of reaching their desired work destination. Firstly, the analysis does not account for the types of jobs that can be reached (as has been done by, for example, El-Geneidy et al. (2015)). As low-income jobs are increasingly located in the suburbs in many North-American cities, accounting for low-income jobs only could yield different results. Namely, our results suggests that residents living in suburban areas will experience greater loss in accessibility when including the travel costs. Similar results are to be expected for workers com-

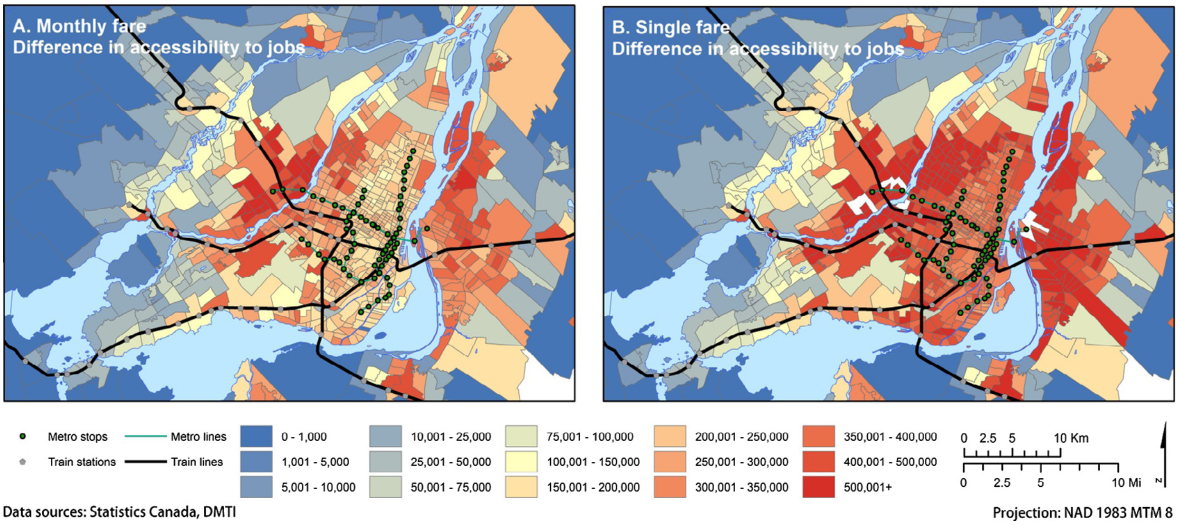

Fig. 5. Difference in accessibility to jobs including fare cost (single fare and monthly fare) compared to accessibility based on travel time only.

Table 2
Standardized accessibility measures by CT decile on the social deprivation scale.

Deciles	Mean[a]	Min.	Max.	Range	Std. dev.	Mean[a]	Min.	Max.	Range	Std. dev.
	Monthly pass with travel cost within one hourly wage					Monthly pass with travel cost within one and half hourly wages				
Decile one	0.94	−0.89	1.76	2.65	0.57	0.81	−0.01	1.18	1.19	0.26
Decile two	0.96	−0.89	1.79	2.68	0.55	0.82	−0.11	1.20	1.31	0.26
Decile three	0.77	−0.86	1.75	2.62	0.66	0.74	−0.56	1.22	1.78	0.31
Decile four	0.70	−1.09	1.84	2.94	0.70	0.65	−1.75	1.20	2.95	0.47
Decile five	**0.28**	**−1.13**	**1.58**	**2.72**	**0.88**	**0.43**	**−1.78**	**1.18**	**2.96**	**0.62**
Decile six	**−0.28**	**−1.18**	**1.21**	**2.39**	**0.70**	**0.05**	**−1.84**	**0.93**	**2.77**	**0.71**
Decile seven	**−0.74**	**−1.18**	**1.18**	**2.36**	**0.55**	**−0.62**	**−1.90**	**0.86**	**2.76**	**0.87**
Decile eight	**−0.91**	**−1.18**	**1.01**	**2.19**	**0.47**	**−0.96**	**−1.90**	**0.74**	**2.64**	**0.83**
Decile nine	**−1.03**	**−1.18**	**0.62**	**1.80**	**0.25**	**−1.13**	**−1.90**	**0.62**	**2.52**	**0.72**
Decile ten	**−1.00**	**−1.18**	**0.76**	**1.94**	**0.42**	**−1.14**	**−1.90**	**0.84**	**2.74**	**0.76**
	Single fare with travel cost within one hourly wage					Single fare with travel cost within one and half hourly wages				
Decile one	0.88	−0.79	1.94	2.73	0.81	0.93	0.14	1.35	1.21	0.27
Decile two	0.94	−0.73	1.98	2.71	0.76	0.88	−0.94	1.37	2.31	0.32
Decile three	0.70	−0.88	1.93	2.81	0.88	0.77	−0.87	1.38	2.25	0.40
Decile four	0.61	−0.90	2.00	2.90	0.89	0.68	−1.37	1.40	2.77	0.53
Decile five	**0.19**	**−0.96**	**1.74**	**2.70**	**0.96**	**0.42**	**−1.37**	**1.33**	**2.70**	**0.71**
Decile six	**−0.38**	**−0.97**	**1.38**	**2.35**	**0.65**	**−0.03**	**−1.46**	**1.10**	**2.56**	**0.75**
Decile seven	**−0.71**	**−0.97**	**1.48**	**2.45**	**0.46**	**−0.72**	**−1.46**	**0.96**	**2.42**	**0.71**
Decile eight	**−0.80**	**−0.97**	**1.15**	**2.12**	**0.38**	**−0.98**	**−1.46**	**0.95**	**2.41**	**0.63**
Decile nine	**−0.88**	**−0.97**	**−0.18**	**0.79**	**0.14**	**−1.16**	**−1.46**	**0.82**	**2.28**	**0.45**
Decile ten	**−0.83**	**−0.97**	**0.82**	**1.79**	**0.37**	**−1.14**	**−1.46**	**0.90**	**2.35**	**0.61**

[a] Bold indicates that the mean difference is significant at the 0.05 level compared to decile one.

muting to suburban areas. Using this paper methodology, the results from this social decile analysis could be augmented by investigating differentiated travel needs of low-income households with respect to their desired destinations. Atypical working hour could also be further investigated, as low-income households are likely to travel outside the peak-hour, which might require higher or shorter travel times.

Secondly, low-income households are expected to have higher budget constraints, which can limit their accessibility to jobs, more than for higher income households. Also, as suggested in the literature, low-income individuals may be willing to travel more time to save travel costs (Bocarejo and Oviedo, 2012) or to purchase more expensive fares (single tickets and weekly passes rather than monthly passes) (Hickey et al., 2010; Verbich and El-Geneidy, 2016). Thus, using fixed time or monetary thresholds does not account for the differences in wages, and available time budget and cost constrain. Nevertheless, by using different time and cost thresholds, it is possible to account for some levels of variations. Building on this methodology, further studies could measure the accessibility of different socio-economic groups in terms of the percentage

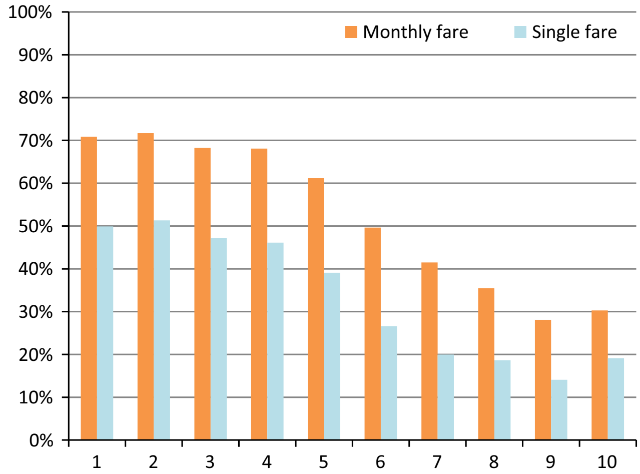

Fig. 6. Proportion of jobs accessible within one hour minimum wage based on travel time and cost compared to the number of jobs accessible within 60 min of travel time.

of the household budgets spent on transportation, whenever data is available. Additionally, different values of time could be used to account for different travel preferences.

6. Discussion and conclusion

A large body of transportation research uses travel time to assess accessibility to jobs in a region. In the present work, we expand on this idea to include monetary cost (or transit fare) as a constraint to job accessibility. Specifically, we tackled this issue in two ways. The first is by using the travel cost as a combination of transit fares and travel time converted to monetary value (based on hourly wage), and then calculating the number of jobs reachable at different departure times within given thresholds of defined wages. The second is by calculating travel time as combination of travel time and transit fares converted to time (based on hourly wage). By incorporating the monetary cost of travel with the transit fare an individual will actually pay has the advantage of addressing wider equity issues. The current paper expands the literature on accessibility measures by providing an important practical advance. The number of jobs accessible is measured based on the travel time and the travel fares of the network, for a large metropolitan area including multiple transit agencies. The suggested method provides a simple, replicable accessibility measure that can be used to assess the performance of the land use and transportation system. If planners can explain to policy makers the number of jobs a resident can reach for a given cost, then fare structures and hourly wages can be judged against the cost of commuting. Additionally, this research shows that excluding transit fares from accessibility assessments overestimates accessibility, and this is even more significant when comparing to single fares.

Beyond presenting new ways of measuring the spatial distribution of accessibility specifically, or transit benefits more generally, our study also reveals that job accessibility in the Montreal region is equitable from a vertical standpoint. Indeed, residents in the most disadvantaged neighborhoods in Montreal have the best job accessibility, regardless of whether it was examined by travel time or cost. This finding corroborates previous work in Toronto (Foth et al., 2013). Future work could refine these findings by studying if low-income earners can efficiently reach low-income jobs with transit, as this may not be a given (El-Geneidy et al., 2015), using a similar methodology that is based on combining both transit fare and actual departure times. The results suggest that including transit fares has greater impacts for residents in suburban areas, which could also mean greater impacts for accessing low-income jobs. Regardless, our methodology shows how these accessibility measures can identify neighborhoods combining low levels of accessibility and high levels of social deprivation, which according to vertical equity requirements, need transportation benefits the most. Other future research can investigate the travel habit of residents of socially disadvantaged areas and other areas that are not considered socially disadvantaged. Results may show differences in movement patterns between different areas.

Considering both the cost of travel and the cost of transit fares, we gain a more accurate view of jobs available to residents. For the most socially disadvantaged residents, travel time only was found to estimate job accessibility as 30% higher when a monthly pass is factored in, and 50% higher when a single fare is added. For the least socially disadvantaged residents, this overestimation is even greater, likely because of their suburban locations and higher cost of travel.

This finding has important social implications regarding transit fare structures. Exploratory work in New York City has shown that entries into subway stations in low-income and minority neighborhoods are mostly from weekly and single fares, while in high-income neighborhoods, most entries are from monthly fares; weekly and single fares cost more per ride compared to monthly fares (Hickey et al., 2010). A similar situation occurs in Montreal (Verbich and El-Geneidy, 2016), which is together with our findings showing that single fare use decreases job accessibility more than monthly fare use, our results strongly suggest that socially vulnerable residents bear a large burden when buying transit fares. Thus, job accessibility is sensitive to transit fares, and policies should consider ways of enabling socially disadvantaged individuals to acquire passes rather than paying by the trip. Finally, findings of this research can be of interest to transportation planners, engineers and policy makers in diverse regions as they highlight issues related to current practice and provide insight into how combined measures of accessibility can be used to better understand the impact of transport planning decisions. More specifically, policy-makers can use these measures to assess the impacts of various fare structures on accessibility to jobs by transit for different areas in the city, based on their level of socio-deprivation. The socio-spatial implications of proposed fare structures can thus be accounted for, through a comparative accessibility analysis of different fare schemes (such as distance-based fares, constant fares, zone-based fares, mode-specific fares). In this specific paper, we have demonstrated how to conduct such comparative assessment, by comparing monthly and single fares. Further studies could investigate the impact of an integrated fare system in the Greater Montreal Area.

Other future research includes segmentation by job type and income to better capture the level of accessibility experienced by various socio-economic groups. In addition, further accessibility assessment based on generalized costs as done in this study should take into account the affordability of transit, rather than the cost. This can be included by looking at the average daily expenditure on commuting by transit, or at the proportion of a household's budget spent on commuting by transit.

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