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

Ahmed El-Geneidy*
E-mail: ahmed.elgeneidy@mcgill.ca

David Levinson**
E-mail: dlevinson@umn.edu

Ehab Diab*
E-mail: ehab.diab@mail.mcgill.ca

Genevieve Boisjoly*
E-mail: genevieve.boisjoly@mail.mcgill.ca

David Verbich*
E-mail: david.verbich@mail.mcgill.ca

Charis Loong *
E-mail: charis.loong@mail.mcgill.ca

*McGill University: School of Urban Planning
Suite 400, 815 Sherbrooke St. W.
Montréal, Québec, H3A 0C2
Canada
Tel.: 1-514-398-4058

** University of Minnesota: Department of Civil, Environmental, and Geo-Engineering
138 Civil Engineering
Minneapolis, Minnesota.
United States
Tel: 612-625-6354

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ABSTRACT

Social equity is increasingly incorporated as a long-term objective into urban transportation plans. Researchers used 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 fares, 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.

Keywords: Equity, Job accessibility, Transit fare, Travel time. Cost

1 **INTRODUCTION**

2 Increasingly, social equity is incorporated as a long-term objective into urban transportation plans,
3 although what is meant by 'equity' varies widely (Manaugh, Badami, & El-Geneidy, 2015). Access
4 to opportunities such jobs and services is one of the main benefits of transportation service such
5 public transit (Grengs, 2010; Jones & Lucas, 2012). Due to the nature of cities having centers and
6 peripheries, not all residents benefit from similar levels of accessibility (Martens, 2012).
7 Nevertheless, a fair distribution of transportation resources should provide a variety of options to
8 commuters with various travel options to increase their access to opportunities, particularly jobs;
9 this is often not the case despite stated transport goals. Low-income and socially disadvantaged
10 individuals are the most likely to be transit-dependent (Denmark, 1998; Dodson, Gleeson, Evans,
11 & Sipe, 2007), often face barriers to access their desired destinations (Lucas, 2012). To determine
12 the level of opportunities residents in a region can reach, as well as to assess the spatial distribution
13 of public transit provisions, typical research employs accessibility measures, which are measures
14 of land use and transportation interaction (El-Geneidy et al., 2015; Foth, Manaugh, & El-Geneidy,
15 2013). The simplest measure of accessibility that used is known as cumulative opportunities, where
16 within a given time thresholds (usually 45 or 60 minutes) the number of opportunities that can be
17 access is counted. By revealing the level of accessibility of socially disadvantaged neighborhoods,
18 transport planners can evaluate the vertical or horizontal equity of transport benefits spatially.

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

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

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

38 **LITERATURE REVIEW**

39 **What is Accessibility?**
40 Accessibility is a measure of potential opportunities (Hansen, 1959). A simple measure of
41 accessibility is the cumulative opportunity measure, which counts the number of opportunities that
42 are reachable from a given location within a specified travel duration or travel distance when using
43 a particular travel mode (Geurs & van Wee, 2004; Vickerman, 1974). While this measure is simple
44 to calculate and understand, it evaluates all destinations equally, does not differentiate travel times

1 except that they are above or below a threshold, and does not account for traveler perceptions of
2 time (Ben-Akiva & Lerman, 1979). The gravity-based measure of accessibility, on the other hand,
3 discounts the attractiveness of the destinations by the cost of travelling. Typically, these costs are
4 defined by the time or distance a person has to travel (Geurs & van Wee, 2004; Handy, 1994;
5 Hansen, 1959; Owen & Levinson, 2014; Vickerman, 1974). The main disadvantage that the
6 gravity-based measure has, however, is that its results are harder to communicate and interpret
7 (Geurs & van Wee, 2004; Owen & Levinson, 2014). Importantly, gravity and cumulative
8 accessibility measures are highly correlated, allowing their interchangeable use as necessary (El-
9 Geneidy, Cerdá, Fischler, & Luka, 2011; El-Geneidy & Levinson, 2006). Hence, cumulative
10 opportunity is used in this study.
11
12 **Accessibility and Equity**
13 Measuring accessibility for public transportation is important to evaluate the distribution of
14 services in a region based on equity (Foth et al., 2013). However, what constitutes an equitable
15 distribution is difficult to define due to varying social norms and moral judgments (van Wee &
16 Geurs, 2011). Two main types of equity are generally evaluated in transportation planning:
17 horizontal equity and vertical equity. Horizontal equity refers to the uniform distribution of benefits
18 and costs among individuals within a group. Based on egalitarian theories, it avoids favoring one
19 individual or group over another. Most studies of horizontal equity look into spatial distribution of
20 transportation impacts. However, with regard to public transit, some groups are more likely require
21 such service, like low-income groups that are transit-dependent (Pucher & Renne, 2003; Sanchez,
22 Shen, & Peng, 2004) as they cannot afford owning a car. According to Krumholz and Forester
23 (1990), a fair distribution of resources provides a greater variety of options to those with the least.
24 This relates to vertical equity, which considers the distribution of benefits between groups, and this
25 compares, e.g. the well-off with marginalized and vulnerable populations. In the case of
26 transportation, potentially disadvantaged populations include low-income and unemployed people
27 as well as minorities (Denmark, 1998; Dodson et al., 2007).
28 One way to investigate vertical equity issues in transportation is to assess the effectiveness
29 of the service provided by transit agencies among different stratified socioeconomic groups by
30 using accessibility as an indicator of the equity levels in the land use and transportation system in
31 a region. Recently, Riccardi, Xia, and Currie (2015) studied transit accessibility in Perth, Australia,
32 and found that socially disadvantaged groups comprising of elderly people, low-income
33 households and no-car households suffered from inequitable distribution of accessibility using
34 transit services. In contrast the transit distribution in Toronto is such that residents living in areas
35 of lower socioeconomic status benefit from higher accessibility to jobs and have shorter travel
36 times than those living in areas of higher socioeconomic status (Foth et al., 2013). Yet, the level of
37 equity of accessibility varied throughout the day (El-Geneidy et al., 2015). As such, measuring
38 accessibility to important destinations, like employment, provides a useful tool to evaluate equity
39 issues in a region.
40
41 **Accessibility by Cost**
42 In the studies discussed above, accessibility is typically measured based on travel duration and/or
43 distance (Geurs & van Wee, 2004; Handy, 1994; Hansen, 1959; Owen & Levinson, 2014;
44 Vickerman, 1974). However, travel duration and/or distance is only one of the limiting components
45 of accessibility. As indicated by Lucas (2012), the cost of transit also constrains individuals in
46 reaching their desired destinations. Using three American case studies, Nadeau (2015) shows a
47 practical example of budgetary constraints, where low-wage employees working at airports cannot

1   afford transit services developed by the municipalities to connect employees to airports. In another
2   study, the Utah Transit Authority partnered with Farber, Bartholomew, Li, Páez, and Habib (2014)
3   to assess the effects distance-based fares would have on vulnerable populations. In general, they
4   found that riders with lower socioeconomic statuses traveled shorter distances than average.
5   Subsequently, they concluded that changing their fare structure from flat fares to distance-based
6   fares would reduce travel costs of low-income households and the elderly. However, their results
7   also indicated that distance-based fares would increase the travel costs for certain minority
8   populations living far away from the city center. In these studies, affordability is understood as the
9   fare of travel. Travel time can also be included in terms of monetary cost. Using a log-sum benefit
10   measure, Niemeier (1997) translated job accessibility into units of dollars per morning trip to work.
11   However, the results did not include the cost of a transit fare. Incorporating monetary travel costs
12   as a factor in accessibility measures has the benefit of being more wide-ranging, though log-sum
13   measures are hard to communicate and have no physical interpretation. Although monetary issues
14   are central for accessibility, and such factors have appeared together in accessibility measures (such
15   as log-sums) derived from regional travel demand *models*, to the authors' knowledge, no study thus
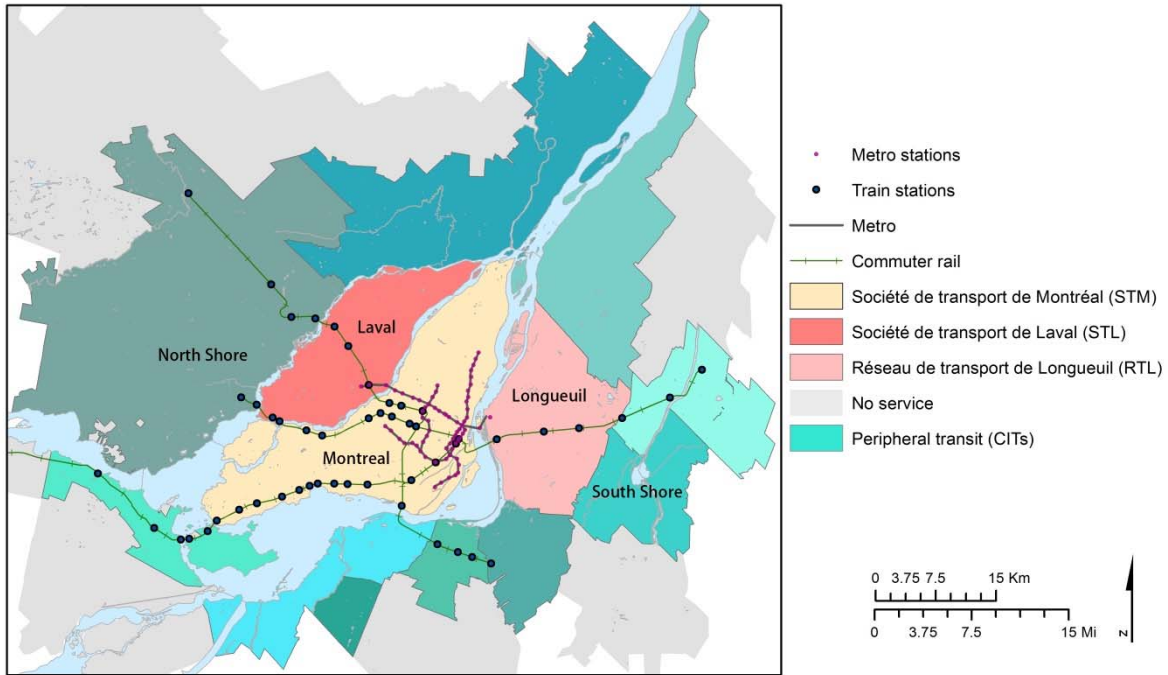16   far has *measured* accessibility through including the observed cost of travel time together with the
17   fare.
18
19   **STUDY CONTEXT**
20
21   The Greater Montreal Area, also known as and hereafter referred to as the Communauté
22   Métropolitaine de Montréal (CMM), is the second largest metropolitan region in Canada, with a
23   current population of nearly 4 million residents. While almost half of the residents reside on the
24   Island of Montreal, the population of off-island suburbs (yellow, green and orange regions in Figure
25   1) is increasing. Montreal's major employment centers remain in the central business district and
26   other on-island centers that are accessible by transit (El-Geneidy et al., 2011; Shearmur, Coffey,
27   Dube, & Barbonne, 2007).
28   Transit in the CMM is coordinated by the Agence Métropolitaine de Transport (AMT), with
29   local agencies operating local bus service with separate fare schemes. The Société de Transport de
30   Montréal (STM), the transit agency of the City of Montreal and the largest transit agency in the
31   region (red in Figure 1), operates the metro and bus services on the Island of Montréal with more
32   than 759 metro cars and 200 bus routes, allowing for over a million trips per weekday. The AMT
33   is responsible for the commuter rail with the goal of transporting commuters from various suburbs
34   to downtown Montreal. As such, commuter train frequency is highest during weekday morning
35   and afternoon peaks, with little service off-peak weekdays and weekends. The two other major
36   transport agencies in the region are the Réseau de Transport de Longueuil (RTL) and the Société
37   de Transport de Laval (STL), with a total ridership of 200,000 per day. Several other small inter-
38   municipal transit agencies operate the in peripheral areas of the region (Figure 1).
39   With 14 separate fare schemes, transport within the Montreal region represents an
40   interesting case study. It is not unusual for transit users to have to purchase more than one transit
41   fare to travel within the region. For example, a single trip will cost $3.25 (CAD), regardless of
42   mode (bus or metro), transferring, time of day, or distance for travelling on the Island of Montreal
43   (red in Figure 1). However, travelling to Laval, the island north of Montreal, will cost $3.25 to
44   arrive there from Montreal, plus another fare of $3.25 to travel on the Laval transit agency's
45   network. Moreover, residents living in one of the municipalities on the South Shore wishing to
46   travel to Laval, depending on proximity to commuter rail or the metro station in Longueuil, may
47   need to buy one fare for their local bus ($3, for instance) which travels to Montreal, then a fare to

1 use the Montreal metro ($3.25), and then another fare to use the local transit network in Laval
2 ($3.25). All previous examples do not include travelling using the commuter rail system. This
3 system has different zones and fares than the explained above, which adds more complexity to the
4 context. Our calculations include all these complexities to capture zonal and fare network
5 differences in the CMM.

Data sources: AMT, DMTI

Projection: NAD 1983 MTM 8

7 **Figure 1: Transport Agency Zones in the Montreal Metropolitan Region**

8 **DATA AND METHODOLOGY**

9 To determine how equitable job accessibility is among socially disadvantaged groups compared to
10 the rest of the population in the CMM, we studied accessibility at 7 am during a weekday, either
11 based solely on travel time, solely on travel fare or on a combination of travel time and fare. When
12 combining travel time and fare, measures are reported both as a monetary value (converting travel
13 time to cost) and in time (converting cost to time).
14   Four main data sources are used in the analysis at the census tract (CT)-level, with a total
15 of 921 CTs in the CMM. The first is the demographic census tract information and comes from the
16 Statistics Canada National Household Survey (NHS) collected in 2011 (Statistics Canada, 2011).
17 This data includes household median income, unemployment rates, percentage of immigrants, and
18 educational achievement and is used to determine social and economic deprivation. The second
19 dataset provides data regarding the total number of jobs by CT in the CMM and is also obtained
20 from the 2011 NHS (Statistics Canada, 2011). The third dataset is a cost matrix of daily and
21 monthly fare costs obtained from the AMT website for travel between all 14 transit agencies in the
22 region at 7 am and 12 pm. The final dataset is a transit travel time matrix based on May-June 2014
23 General Transit Feed Specification (GTFS) data for all 14 transit agencies. This dataset is used to
24 determine the travel times between CT origin and destination centroids using the OpenTripPlanner
25 Analyst developed by Conveyal (OpenTripPlanner, Accessed Jule 30, 2014).

1
2
3
4

5   **Accessibility Measures**

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

12
13   $A_i = \Sigma_{j=1}^{n} O_j f(C_{ij})$ (1)
14

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

16
17   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
18   $f(C_{ij})$ is the weighting function with C_{ij} being the time or cost of travel from i to j, and t is the travel
19   time or cost threshold. For cumulative accessibility, if travel time or cost is greater than a specified
20   threshold, jobs reachable beyond those thresholds are not counted (Equation 2).
21
22   Accessibility based on time
23   Initially, cumulative accessibility based solely on travel duration was generated. In this case, one-
24   way travel cost is expressed in minutes (Equation 3) with the following thresholds: 30, 45, 60, 75
25   and 90 minutes.
26
27   $C_{ij} = t_{ij}$ (3)
28
29   Accessibility based on fare cost
30   Second, accessibility based solely on fare cost was generated. The one-way travel cost is equal to
31   the cost of the fare (Equation 4) and thresholds are expressed in terms of minimum hourly wage in
32   Quebec ($10.35) as follows: 1 hourly wage, 1.5 hourly wages, 2 hourly wages, 2.5 hourly wages,
33   3 hourly wages and 4 hourly wages. Equation 1 is used as above, but substituting the following:
34
35   $C_{ij} = F_{ij}$ (4)
36
37   where F_{ij} is the cost of transit fare to travel from zone i to zone j.
38
39   Accessibility based on travel time and fare cost, expressed in monetary term
40   Third, we calculated accessibility based on both travel time and fare cost. Travel cost was
41   determined by multiplying minimum hourly wage in Quebec ($10.35) by the travel time, so one
42   hour of travel costs $10.35. In this way, we were able to determine the number of jobs accessible

1   by transit based on hourly wage (1, 1.5, 2, 2.5, 3 and 4 wages) and the transit fare used (discussed
2   further in the proceeding section). Equation 1 is used as above, but substituting cost with the
3   following formula:
4
5   $C_{ij} = t_{ij}w + F_{ij}$ (5)
6
7   where C_{ij} is the time cost of travel, t_{ij} is the travel time in hours, w is the minimum wage per hour
8   ($10.35), and F_{ij} is the transit fare (either for a single trip or a monthly pass) to travel from zone i
9   to zone j.
10
11   <u>Accessibility based on travel time and fare cost, expressed in time</u>
12   Finally, cumulative accessibility was calculated including travel time and fare cost, but this time
13   expressed in terms of time. Cost was calculated with the following formula:
14
15   $C_{ij} = t_{ij} + \dfrac{F_{ij}}{w}$ (6)
16
17   where C_{ij} is the time cost of travel, t_{ij} is the travel time in hours, w is the minimum wage per hour
18   ($10.35), and F_{ij} is the transit fare (either for a single trip or a monthly pass) to travel from zone i
19   to zone j.
20
21   Finally, to simplify comparisons throughout the region among social deciles and by
22   different fares, accessibility values are converted to normalized z-scores (El-Geneidy et al., 2015;
23   Foth et al., 2013).
24

25   **Travel Time and Transit Fares**
26   To determine travel times between census tracts, we generated a transit travel time matrix based
27   on GTFS database for all Montreal regional transit agencies. The used data was for the period from
28   May to June 2014. The region includes three major transit agencies as well as 11 inter-municipal
29   transit agencies that provide transit service for certain municipalities and connects them to various
30   regional destinations. The travel time from each CT centroid to every other CT centroid is measured
31   for a departure time of 7 am, and are organized to produce an OD travel time matrix. The commute
32   times include access and egress time, waiting time, time-in-vehicle, and transfer time. These
33   calculations were done using the OpenTripPlanner Analyst provided by Conveyal
34   (OpenTripPlanner, 2014). OpenTripPlanner provides the fastest transit route for a defined
35   departure time, and we matched this travel time to the transit fare described below.
36   While OpenTripPlanner provides an accurate transit itinerary many regions do not include
37   the fare costs in their GTFS data and just include a link to their websites. This was the case for the
38   CMM. Therefore, we used the fare calculator tool on the website of the regional public transport
39   coordinator in the CMM, AMT, to calculate the transit fare (AMT, 2015a). This was done manually
40   through querying origin and destination centroid coordinates of every CT that yielded different trip
41   and fare options, using trips leaving closest to 7 am and 12 pm regardless of mode were selected,
42   and with the earliest arrival times (consistent with OpenTripPlanner routes). The prices for a single
43   fare and a monthly pass for that trip were recorded. Single fares varied more than monthly fares
44   because of the zonal nature of the territory (AMT, 2015b). Then, based on the monthly fare, we
45   calculated a single trip fare by dividing the total monthly cost by 44, which corresponds to returns
46   trips to and from a destination a total of 22 working days per month. Note that purchasing monthly

1 fares is the most cost-effective manner to access transit, but involves larger up-front costs than
2 single fares (Carruthers et al., 2005).
3
4 **Social Vulnerability Indicator**
5 To ascertain the social vulnerability of neighborhoods in the Montreal region, we used census tract-
6 level data from Statistics Canada's 2011 NHS and Census (Statistics Canada, 2011). With the
7 assumption that socially disadvantaged groups are spatially concentrated (Ades, Apparicio, &
8 Séguin, 2012), we derived an indicator from four equally-weighted variables to identify socially
9 vulnerable neighborhoods at the CT-level. In addition to median household income, we also used
10 percentage of recent immigrants (since 2006), the percentage of the workforce that is unemployed,
11 and percentage of residents with education at the level of only a high school diploma (25–64 years
12 old). The current social indicator is a modification of previous work sensitive to the Canadian
13 context (Foth et al., 2013; Manaugh & El-Geneidy, 2012), but more specific to Montreal. Briefly,
14 immigrant status is relevant to the Canadian context because recent immigrants tend to be well
15 educated due to the Canadian immigration laws, yet they work for lower-wages and be employed
16 in lower skill trades, and have a greater likelihood to be unemployed compared to Canadian-born
17 workers (Canada, 2004). Nevertheless, we also included education levels to account for non-
18 immigrants with low educational achievement. Although previous work in Toronto included
19 households that spend more than 30% of their income on rent (El-Geneidy et al., 2015), in the
20 Montreal area, this value was not significantly correlated with the other variables. All variables in
21 the indicator were correlated with a Pearson correlation coefficient above 0.5, in order to make sure
22 that they are explaining the same population. The indicator is in line with previous studies,
23 identifying low-income and unemployed people as well as ethnic minorities as potentially
24 disadvantaged groups (Dodson, 2005).
25   Each variable was then normalized as a z-score to determine how each tract compares to
26 the regional average, and all variables were then summed to give an overall score of social
27 disadvantage (for details of this measure see Foth et al. (Foth et al., 2013)). By grouping census
28 tracts into deciles based on the social deprivation indicator score, we identify the least
29 disadvantaged census tracts (top 10%, or 10th decile) ranging to the most disadvantaged census
30 tracts (bottom 10%, or 1st decile). It is important to note the statistical analyses presented in this
31 study compare the most socially disadvantaged census tracts (the first decile) to the other deciles.
32   Figure 2 shows the spatial distribution social deciles. As seen in the figure, the redder colors
33 demonstrate the more socially deprived areas. Most of the socially disadvantaged CTs (the first
34 three deciles) are located on the Island of Montreal (85%), while only about 15% are located off
35 the island. Also, generally speaking, socially disadvantaged CTs are mainly located around metro
36 lines, with the exception of one zone in the north of the Island. This area is known as a district
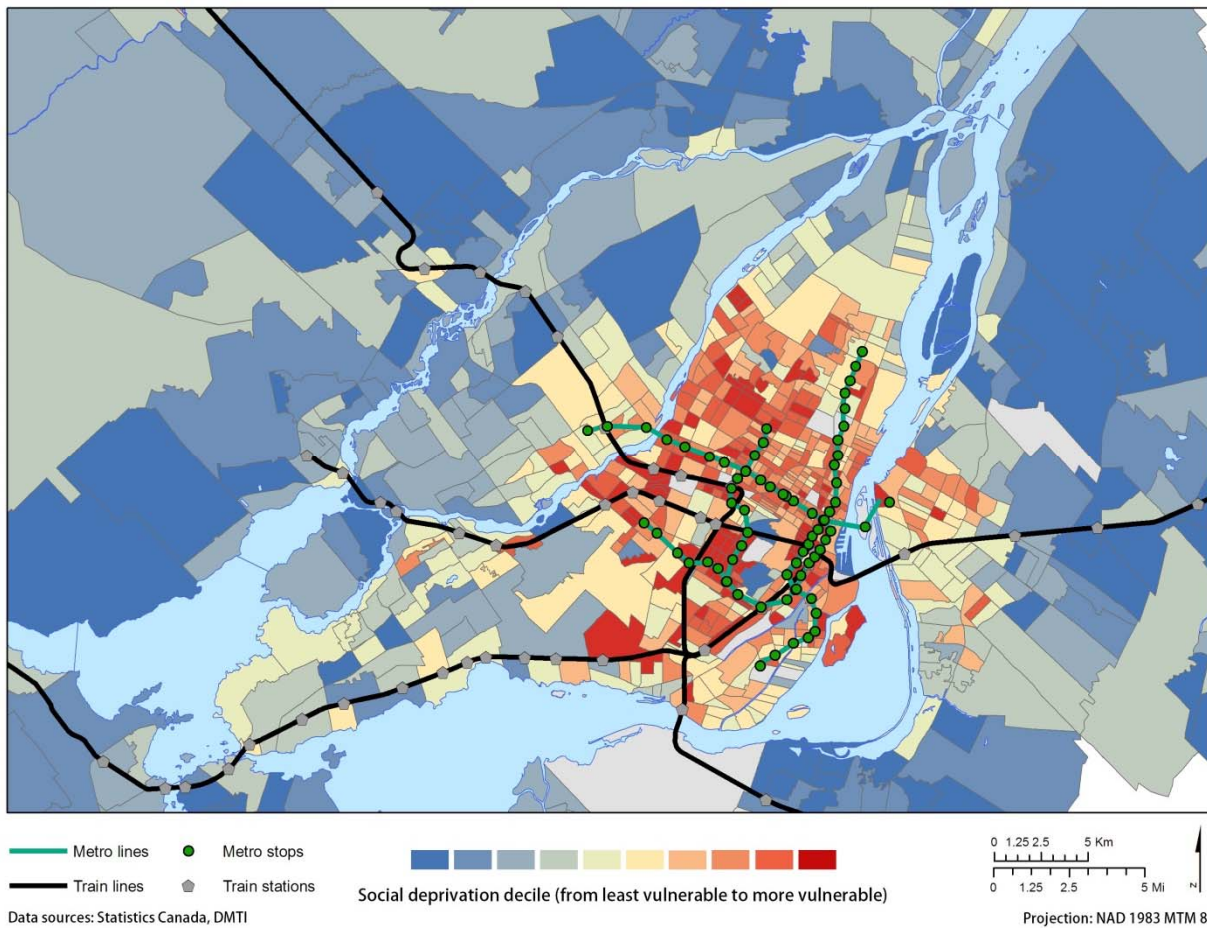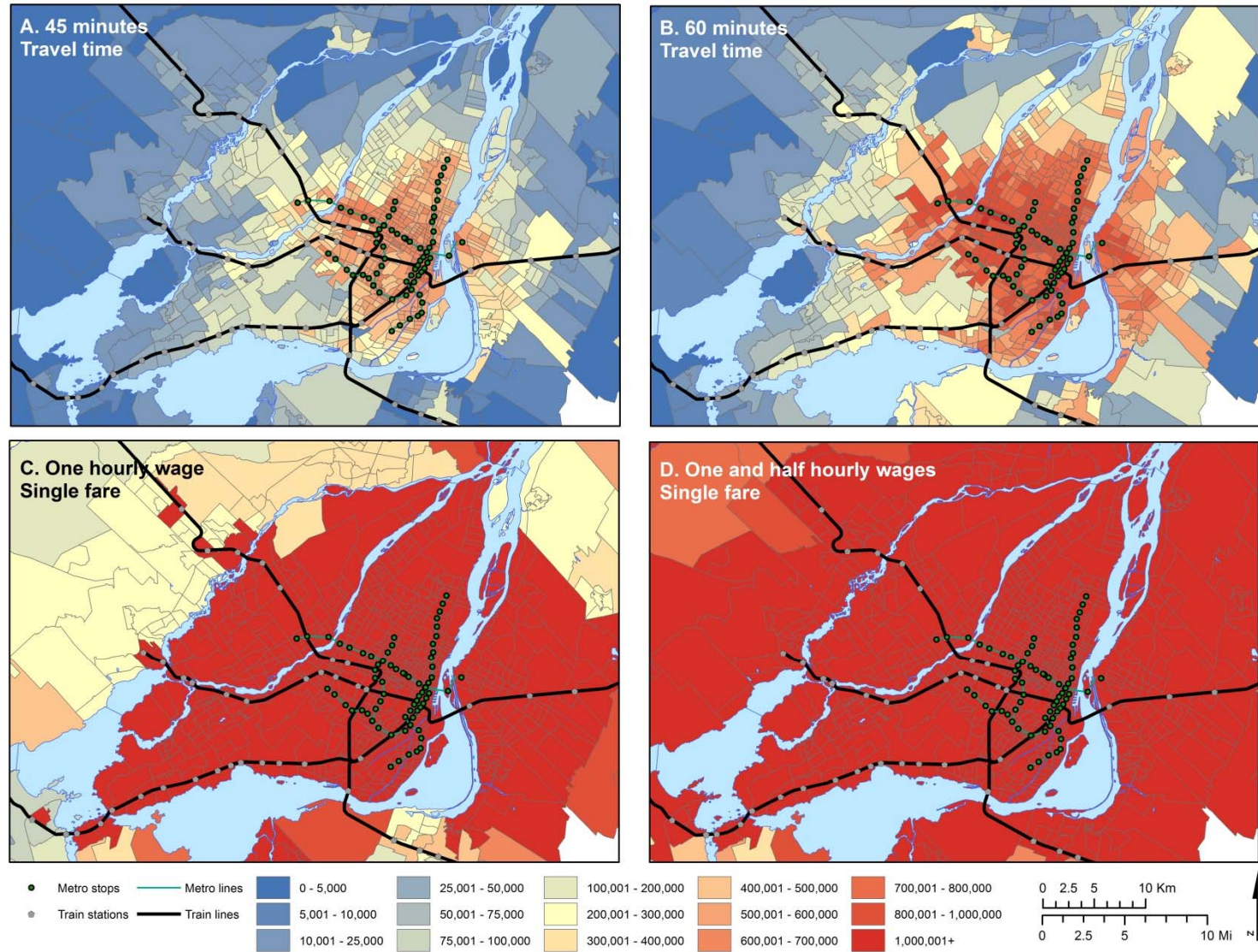37 concentrating many socio-economic issues.
38

Figure 2: Census tracts of the Montreal metropolitan region based on social vulnerability

RESULTS AND ANALYSIS

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 & Geurs, 2011). As seen in Figure 3, most of central Montreal, with some off-Island locations near metro stations have medium accessibility to jobs by transit within 45 minutes of travel time (Figure 3- A). Within 60 minutes 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 (Figure 3- B). 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.

Data sources: Statistics Canada, DMTI

Projection: NAD 1983 MTM 8

1
2 **Figure 3: Number of jobs accessible by transit based solely on travel time and solely on fare**

1   Next, we asked how job accessibility throughout the region would depend on the out-of-
2   pocket cost of a transit fare based on hourly wage. Put another way, how many jobs can a
3   resident reach for a given wage with a single or monthly fare? Interestingly, one hour's wage will
4   buy access to most jobs on the Island of Montreal and the shores surrounding it (Figure 3- C), and
5   one-and-a-half hour's wage will buy access to all the jobs throughout the CMM, based on the
6   cost a single fare to the appropriate census tracts (Figure 3- D). These results seem to indicate
7   that the entire region is highly accessible with transit given the current hourly minimum wage in
8   Quebec. Nevertheless, travelling is based not only on out-of-pocket costs, like transit fares, but
9   also on travel time cost. So using transit fare as the only cost in an accessibility measure is likely
10   misleading. It should be noted that for all of the previous four maps, the same scales were used
11   allowing us to compare across maps.
12   To gain a more realistic picture of accessibility based on fare cost and travel time, we used
13   two methods illustrated on Figure 4. The first is based on using the travel cost as a combination
14   of transit fares and travel time converted to monetary value (based on hourly wage), and then
15   calculating the number of jobs reachable within given thresholds of defined wages (the threshold
16   values are discussed in the previous section). As an example of the results, Figure 4 – A to D
17   shows the total number of jobs that are accessible by transit within one minimum wage and one-
18   and-a-half minimum wages. While Figure 4 E-F is based on calculating travel time as
19   combination of both transit fares converted to travel time (based on hourly wage) and travel time.
20   Then, cumulative accessibility is measured based on travel time thresholds as normally done in
21   the literature.
22   For the time value of an hourly wage and the cost of a single transit fare, at a departure
23   time of 7 am, the CTs nearest to metro stations and some off-Island areas near commuter stations
24   have high job accessibility (Fig. 4- A). The picture changes dramatically, as an outward spread
25   from the center of accessibility for a larger travel cost of one-and-a-half hour's wage and a single
26   fare. Most of the CTs on the Island and on the North and South Shore suburbs have excellent job
27   accessibility. In addition, more areas have greater accessibility in the western portion of the
28   Island near the commuter rail (Fig. 4- B). This is likely due to the number of offered train trips
29   during the morning peak hours.
30   While analyzing cost based on a single fare is a good approximation for accessibility by
31   cost, commuters travelling on a daily basis likely purchase monthly fares, since these are cost-
32   effective and usually cheapest per ride (Carruthers et al., 2005). Therefore, we also mapped job
33   accessibility based on monthly fares calculated per ride. Importantly, we found that more CTs in
34   the CMM had greater accessibility for both an hour and one hour-and-a-half's wages' time cost
35   based on a monthly fare (Fig. 4 - C and D) compared to job accessibility with a single fare. This
36   result indicates that buying a monthly pass enables greater job accessibility for larger share of
37   residents than the price of a single ticket for the same travel cost. These findings reveal that
38   including both the cost of a fare and the cost of travel time is an important consideration when
39   studying accessibility.
40   Figures 4 – E and F show the other accessibility measure results that are based on
41   converting monthly fare cost to time. Very similar trends can be found across these two maps and
42   the previously discussed maps that are based on the monthly fares. In fact, Figure 4 - C and F
43   are almost identical. This is expected since in both figures, the accessibility measures were
44   calculated based on an hour threshold: 60 minutes (Figure 4 – C) and one hour of minimum wage
45   (Figure 4 - C). Thus, both accessibility measures can be used interchangeably while evaluating
46   the regional accessibility, while keeping in mind which one could be easier to interpret and to

1 communicate to the public according to the context. It should be noted that for all of the previous
2 maps, the same scale was used allowing us to compare across maps.
3   Since little variability was noticed between 7 am and 12 pm in term of travel time and
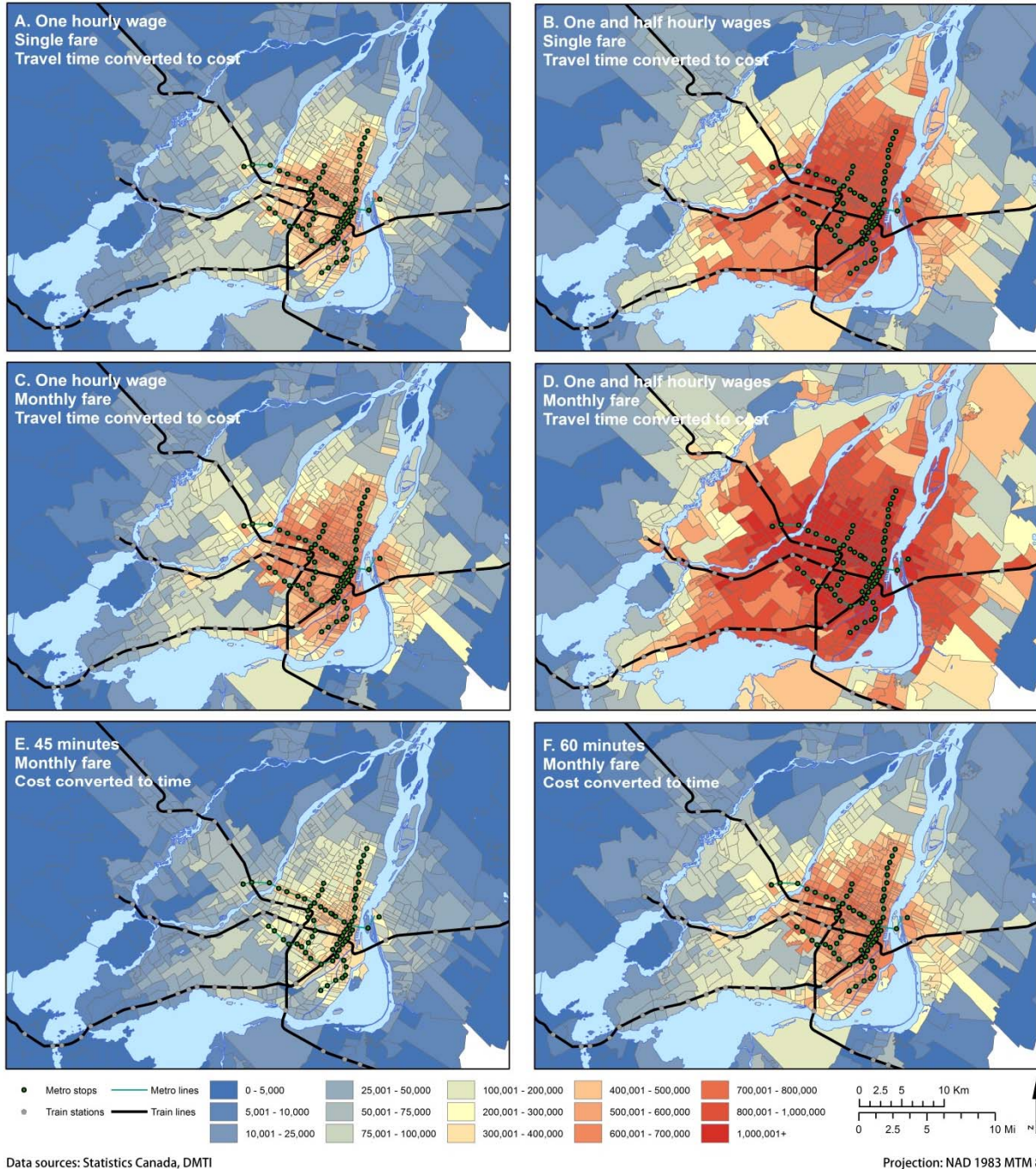4 travel time by cost, we only reported 7 am calculations in this paper.
5

6
7
8 **Figure 4: Number of jobs accessible by transit based on travel time and cost fare (single and**
9 **monthly fare)**
10

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 minutes 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 minutes, 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 minutes 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.

Loss in accessibility

This section investigates potential differences between the proposed accessibility measures that are based on using 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. Figure 5 show 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.

14

1
2
3 **Table 1: Correlation matrix between accessibility measures**

		Travel time					Monthly fare with travel cost					Single fare with travel cost				
		Within 30 minutes	Within 45 minutes	Within 60 minutes	Within 75 minutes	Within 90 minutes	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 minutes	1.00														
	Within 45 minutes	0.82	1.00													
	Within 60 minutes	0.71	0.92	1.00												
	Within 75 minutes	0.64	0.85	0.95	1.00											
	Within 90 minutes	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
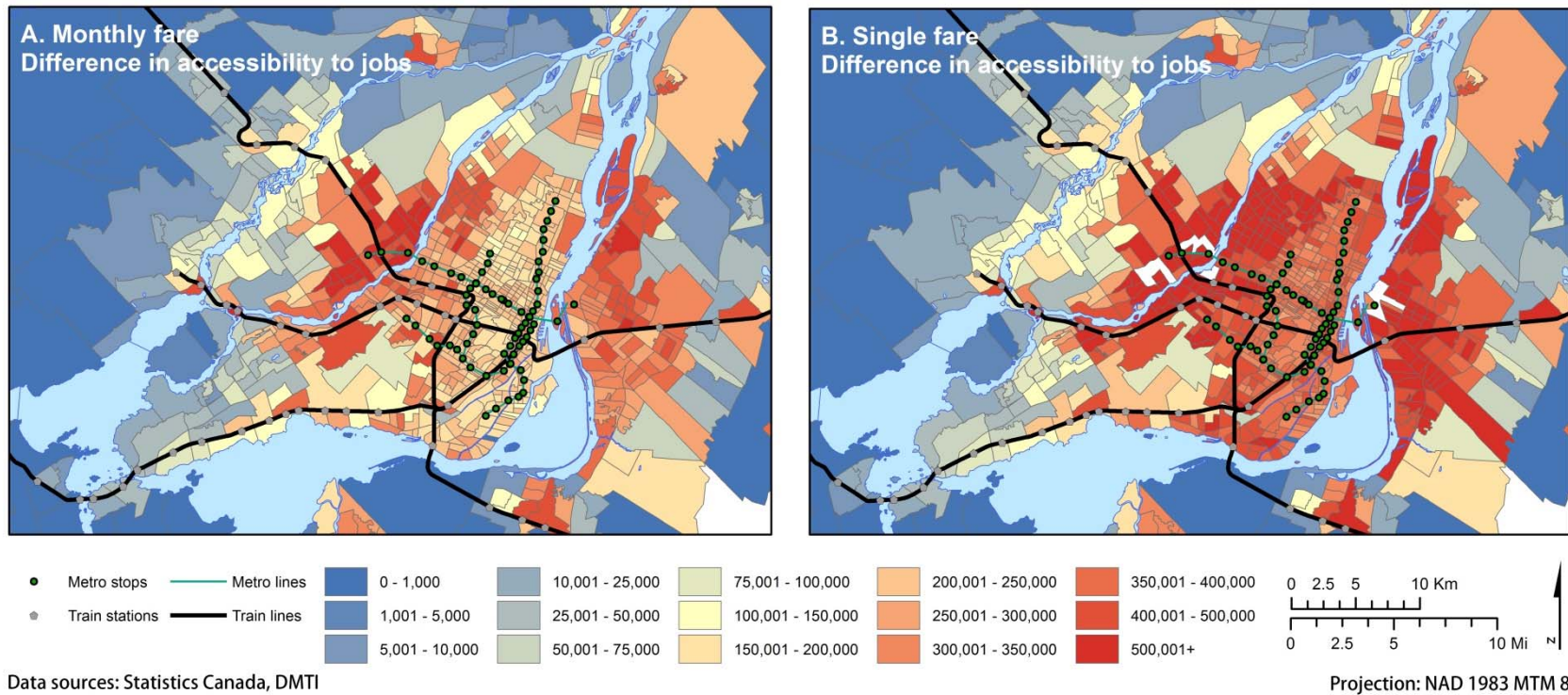*****Using Pearson correlation test: All correlations are significant at the 0.01 level.**

4
5

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

1 **TRENDS BY SOCIAL DECILE**
2 This section assesses the distribution of transit benefits across all CTs based on the social
3 disadvantage decile. It compares the transit benefits, in terms of accessibility, of the most socially
4 disadvantaged CTs to the rest of the CTs in the CMM. Table 2 presents summary statistics of
5 accessibility by cost for each decile. Note that the results are consistent with the accessibility by
6 time. Table 2 uses ANOVA tests to compare each decile's accessibility by cost and travel time to
7 the first decile.
8 Generally speaking, socially vulnerable CTs enjoy higher levels of accessibility, both in
9 terms of travel cost and travel time, while socially advantaged tracts enjoy lower levels. Deciles 5
10 to 10 (in bold in Table 2) show significantly lower accessibility than decile 1. These findings
11 suggest that public transit supply and fares provide equitable benefits in terms of vertical equity.
12 The provision of public transit generally favors vulnerable populations in Montreal. This is also
13 consistent with the social indicator map (Figure 2) showing that low-income and immigrant
14 populations generally reside in central Montreal, relatively near metro stations. Inversely, high-
15 income, non-immigrant populations are concentrated in suburban areas. Socially vulnerable
16 populations may decide to locate near major transit lines, as they are more likely to be transit-
17 dependent.
18
19 **Table 2: Standardized accessibility measures by CT decile on the social deprivation scale**

Deciles	Mean*	Min.	Max.	Range	Std. Dev.	Mean*	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**

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

20
21 Figure 6 presents the proportion of jobs that are accessible within one hour's wage
22 (including travel time and cost fare expressed in monetary terms) compared to the number of jobs
23 calculated with the traditional measure of accessibility based on travel duration (within 60

1 minutes). Results show for decile 1, based on a monthly pass, only 70% of the jobs (measured with
2 travel time duration) are accessible when including fare cost. Accordingly, 30% of the jobs
3 calculated with the measure based on travel time duration are not accessible when including fare
4 cost. The decrease is more pronounced when looking at a single fare (50% for decile 1). This
5 confirms that accessibility is sensitive to transit fare. Nevertheless, results show that socially
6 advantaged deciles experience bigger decreases in accessibility, when including fare cost. This is
7 likely due to the fact that they are mainly located in suburban areas, where travel fares are
8 significantly more expensive (up to $21 of cost).
9

10
11 **Figure 6: Proportion of jobs accessible within one hour minimum wage based on travel time**
12 **and cost compared to the number of jobs accessible within 60 minutes of travel time**
13
14 **DISCUSSION AND CONCLUSION**
15
16 A large body of transportation research uses travel time to assess accessibility to jobs in a region.
17 In the present work, we expand on this idea to include monetary cost (or transit fare) as a
18 constraint to job accessibility. Specifically, we tackled this issue in two ways. The first is by
19 using the travel cost as a combination of transit fares and travel time converted to monetary value
20 (based on hourly wage), and then calculated the number of jobs reachable at different departure
21 times within given thresholds of defined wages. The second is by calculating travel time as
22 combination of travel time and transit fares converted to time (based on hourly wage). By
23 incorporating the monetary cost of travel with the transit fare an individual will actually pay has
24 the advantage of addressing equity issues. Therefore, the current paper expands the literature on
25 accessibility measures by providing an important practical advance. If planners can explain to
26 policy makers the number of jobs a resident can reach for a given cost, then fare structures and
27 hourly wages can be judged against the cost of commuting.
28   Beyond presenting new ways of measuring the spatial distribution of accessibility
29 specifically, or transit benefits more generally, our study also reveals that job accessibility in the
30 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. 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, Lu, & Reddy, 2010). If a similar situation occurs in Montreal, together with our findings showing that single fare use decreases job accessibility more than monthly fare use, then 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.

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