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Breaking down public transit travel time for more accurate transport equity policies: A trip component approach

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A R T I C L E I N F O

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A B S T R A C T

In the Northern hemisphere, low-income transit users typically take shorter trips and use buses in a greater proportion, but there is limited knowledge on inequalities in the detailed characteristics of public transit trips.

In this paper, we seek to understand and explain differences in segment components of transit trips across socio-economic groups. Trip components include access time, wait time, total travel time, overall trip speed and percent of trip time spent in access and wait (off-vehicle time).

Using the Montreal metropolitan region travel survey (2013), we focus on the 46,186 transit trips made by 20,138 individuals for which household income was available. This data is augmented by time estimations of the aforementioned trip components, and combined with trips specific transit service measures calculated using General Transit Feed Specification (GTFS). We first assess the relationship between trip components and income using descriptive statistics. OLS regressions are then conducted to identify which individual and transport-based factors contribute to variations in trip component outcomes.

Low-income transit users take more transit trips (especially bus and Metro) than their higher income counterparts and combine multiple transit modes through more frequent transfers. While average access and wait time are individually lower than those for trips of wealthier respondents, low-income total trip time is similar but trip speed is considerably lower. Lower-income populations also spend a greater share of their trips in access and wait time due to service and trip discrepancies including trip timing, proximity to metro stations and requirement for transfers. When controlling for other factors, the conditions under which trips by low-income individuals are taken mainly drive income differences.

1. Introduction

Existing research shows that lower-income population are less likely to own a car and are thus more frequently transit dependent (Deka, 2002; Lachapelle, 2015; Lubitow et al., 2017). As captive users, lower-income populations generally have higher rates of public transit use. Service providers are increasingly interested in ensuring an equitable distribution of transit service across territories and population groups but rarely have clear and detailed metrics to do so (Manaugh et al., 2015). While research has shown that low-income riders in the northern hemisphere travel shorter distances on transit (Martens and Di Ciommo, 2017), the level of details of

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study on the quality of transit trips is still incomplete. The existing research does not provide us with a detailed understanding of how well low-income populations are served by public transit when considering separate components of transit trips. Metrics of travel distance, accessibility or access time are often studied separately.

In order to plan appropriately for a transit system that enables those most in need to use it and conduct satisfactory trips, the various features that make up a good transit trip must be taken into account. This includes short access and egress components to a frequent service regardless of the timing of trips, with minimal need for transfers, on transit lines with high operational speeds, and that serve various trip purposes and destinations. The paper seeks to: (a) propose a methodology and set of metrics for segment components (b) understand differences in segment components of public transit trips across socioeconomic groups, and (c) assess the additional determinants of the various trip components. Trip components include access time, wait time, total travel time, overall trip speed and percent of trip time spent in access and wait (off-vehicle time). These segment outcomes are operationalized using trip planner style data produced using a trip calculator. We first evaluate how the different segments of an entire transit journey are related to categories of income. We then conduct multivariate analyses, which includes individual, trip and public transport service variables, to identify which characteristics contribute to longer access, wait and travel times as well as lower trip speed and lower share of off-vehicle time. In doing so, we identify the specific factors that contribute to potentially putting low-income populations at a disadvantage. This study provides researchers, planners and policy-makers with component specific evidence and a methodological approach to inform decision-making and future research avenues.

We first present existing research on transit use and low-income populations especially focusing on socio-economic distribution of transit users, disparities in access to transit use by mode (bus, metro, commuter train) and the characteristics of transit trips. This presentation focuses on the equity implications of existing knowledge and serves to justify our study. We then turn to a presentation of our methodology using the Montreal Origin-Destination (OD) travel survey augmented by General Transit Feed Specification (GTFS) derived components of transit trips. After presenting our results that focus on the individual components of transit trips across socioeconomic groups, we discuss the implications of this research for the development of equitable and efficient transit networks in Montreal and elsewhere.

2. Literature

2.1. Socioeconomic distribution and characteristics of transit users

It is generally found that lower-income population use transit at a higher rate than higher-income groups (Glaeser et al., 2008; Nuworsoo et al., 2009). Car ownership also tends to be lower in low-income individuals (Deka, 2002; Potoglou and Kanaroglou, 2008), which partly explains this higher rate of use. Without access to a car, individuals can become dependent upon public transit to access the labor market and conduct daily activities. Even when the household owns a car, this vehicle may be shared between household members and not available at the time of the trip for a given member (Lachapelle, 2015).

Dependence on transit has thus become an important factor in ensuring appropriate service to populations most in need of using transit. Beyond income and car access, gender characteristics and the presence of children in a household may make some trip components such as access to the system and transfers more complicated (Lubitow et al., 2017). Large differences remain between men and women in travel time and travel distances (Crane, 2007), with further variations depending on the presence of children within households (Fan, 2017).

An individual's age may also influence his use of a car. Under driving age, young people must make longer distance trips either by public transit or by getting a ride from a family member or friend. Purchasing a car is sought out to allow individuals to take part in the labor market and enjoy discretionary and non-discretionary activities, but it comes at the cost of a significant financial burden on individuals or households, something often referred to as forced car ownership (Curl et al., 2018; Currie et al., 2018; Mattioli, 2017).

2.2. Trip time and distance traveled: The smaller activity space of low-income populations

In similar population, disadvantaged groups often have smaller activity spaces considering both work and discretionary destinations (Tao et al., 2020) and travel shorter distances on average (Morency et al., 2011). As a result, they also often experience shorter transit travel times (Deboosere and El-Geneidy, 2018).

However, this travel time advantage varies depending on the time of day, an important feature for access to low-income jobs (Boisjoly and El-Geneidy, 2016). Because low-income populations are more likely to work shift schedules outside of regular nine to five schedules where transit is more prevalent, considering the scheduling of transit trips in service level available to low-income riders is important (Vermesch et al., 2021). Indeed, transit service frequency may vary considerably depending on the time of day, with morning and evening peak travel periods receiving far more service. Hence researchers have pointed to the importance of fit between scheduling and users' needs (Benenson et al., 2017).

Further, while shorter trip durations are perceived as more desirable, little is known on whether this is simply the result of shorter distances traveled by low-income individuals, or whether this reflects advantageous public transport services, such as greater speeds for example. Studies typically focus on commercial speeds, the average in-vehicle operating speed for one specific route, or between two points, including any delay at stops. This measurement unfortunately does not reflect the experience and perceptions of individuals during their entire journey (that includes access and wait time). As indicated by Meng et al. (2018), the perceived travel time has an important influence on travel satisfaction. Therefore, assessing not only in-vehicle time but also the overall trip time and speed is warranted.

Finally, it should be noted that studies referenced here reflect the experience of Montreal and more broadly northern hemisphere regions. Experience in the Global South may vary considerably with respect to the travel times of lower income groups of the population and South American countries can serve a case in point. In Bogota, Colombia, spatial segregation of low-income population and slower feeder lines result in lengthier travel times for this group (Guzman et al. 2018). Santiago de Chile (Tiznado-Aitken et al. 2021) and Belo Horizonte, Brazil (Rudke et al. 2021) experience similar inequities due to low-income populations living more frequently on the outskirts of the city and perhaps, as Rudke et al. (2021) suggests it, because of the invisibility of these communities to decision-makers. In contrast, Montreal's low-income population is spread in across the territory in neighborhoods at varying distances from the center.

2.3. Distance to public transit, access time, wait time and transfers

The transit experience goes beyond in-vehicle time and extends to the entire journey, which requires accessing the transit system (by active modes or by car), waiting for public transit to arrive and completing any transfers when required. Access to public transit influence the use, the frequency of use, as well as the satisfaction with public transit service (Lachapelle, 2010; Wasfi et al., 2013). The distance that individuals are willing to walk to access public transit is fairly well established: studies typically use 500 m for bus transit and 1000 m for subway and commuter train transit, although some research have observed considerable shares of longer access distances (Hoback et al., 2008; Lachapelle, 2010; van Soest et al., 2020; Wasfi et al., 2013). While health research has focused on increasing walking at the population level, public transport research theoretically and empirically demonstrates that there is a limit to how far people are willing to walk to access transit (Lachapelle, 2009). Stations and stops that are too far away will discourage use, but those with fewer travel options, the transit dependent, may be forced to take on longer access distances.

Wait time impedance at a transit stop can reduce the quality of the transit journey's experience (Ben-Akiva and Morikawa, 2002) and increase the overall door-to-door travel time of a trip. But more importantly, idle time generally feels more like lost time: people hate to wait (Yoh et al., 2011). Just as wait time, transfer impedances will increase a trip's overall length, require additional effort, wayfinding, and sometimes additional fares (Ben-Akiva and Morikawa, 2002). Depending on the mode used (bus, trains, or subways), access and wait time, as well as need for transfers are likely to vary. One stated preference study (Ben-Akiva and Morikawa, 2002) suggests that mode preference is largely based on those underlying differences. When developing an accessibility measure that takes into account access and wait time, Benenson et al. (2017) notice that the benefits of transit improvements mainly accrue for longer trips.

While studies on making the distribution of transit service more equitable have blossomed in recent years, there is still limited guidance on the most appropriate method. Researchers have proposed multiple conceptual as well as empirical approaches (Golub and Martens, 2014; Lucas, 2012; Pereira et al., 2017). In Canada, researchers found that residents of socially disadvantaged areas tend to experience better transit accessibility to jobs than more advantaged groups (El-Geneidy et al., 2015). Yet, little is known on whether this greater accessibility leads to more desirable trips, as the approach does not capture trips that were actually made. In line with this, Karner and Golub (2015) point to the weaknesses of only using aggregated census data to assess equity in the distribution of transit service and recommend ensuring the collection and analysis of ridership data. By using the Montreal travel survey in the following study, we heed this call. While some have attempted to identify what should be measured (Pereira et al., 2017), we take the view that understanding the multiple metrics that define the entire transit journey provides an essential complement to other indicators such as accessibility or participation rate.

3. Methods

3.1. Survey data

This paper draws transit trip information from the 2013 Montréal metropolitan area Origin Destination (OD) survey. This one-weekday travel survey of 410,741 trips made by 188,746 individuals from 78,731 households in the metropolitan region is designed to be spatially representative of the populations of eight sectors comprising over 80 municipalities.

Socio-demographic characteristics of the population and households (age, sex, household structure, having children, car ownership, drivers' license and employment status) are used to describe the sample and as control variables in regressions. A categorical variable identifies car availability per licensed drivers within household for more clarity. The OD survey also provides trip characteristics (travel mode, hours of departure, purpose of trips, transfers and trip origin zone) that serve to compare trips and are used as control variables in models.

A key additional restricted access data file transferred by the Autorité Régionale de Transport Métropolitain (ARTM) for the purpose of this project includes household income of respondents, which is subject to high non-response. While individual income may be preferable, including household structure as an independent variable in multivariate analyses attenuates this shortcoming.

3.2. GTFS and trip calculator information

A second set of data, produced by the ARTM was also transferred to researchers as part of a broader mandate. Using GTFS data for the period of the survey, the ARTM produced information specific to transit trips conducted during the survey day in a geographic information system (GIS) system. For each OD pairs of a transit trip (complete with slightly shifted x,y coordinates to preserve anonymity), a trip calculator tool computed the most plausible transit line, home to transit stop walk time, destination transit stop to final trip destination walk time, wait time based on the hour of departure and transit schedule, travel time based on transit schedule and total trip time (from departure to estimated arrival). Access time here includes both access and egress side times. Wait times here includes transfer time.

Based on these measures and on the network distance from origins to destinations, we are able to compute an average speed for the entire trip (which is arguably more important than in-vehicle commercial speed from the transit users standpoint). We also compute a metric of the percentage share of the total trip time spent accessing the system and waiting. A proportionally larger size of these segments of the trip reduces the overall efficiency of the trip.

Cases were excluded if travel distance was above 100 km (1 case removed), if calculated overall trip speeds were above the 99th percentile (55 km/hour, 427 cases removed) and if percent of trips spent accessing or waiting were above the 99th percentile (92%, 569 cases removed).

Once these values and those without data on income were removed, 46,186 trips taken by 20,138 individuals were used in regression analyses. Survey weights were provided by the producing agency and were applied to descriptive statistics and regression analyses.

3.3. Transit service

Using the same set of GTFS data, we computed measures of access to transit in the form of distance from both points of origin and destination to bus, subway and train stations, and in terms of average service frequency depending on time of departure. Network distances to the closest subway, train and bus stop were calculated and binary measures were computed: 1 if distance is 500 m or less (bus) or 1000 m or less (subway and train), 0 otherwise.

For bus frequency, the indicators were first calculated at the dissemination area block level, the smallest geographical unit of the Canadian census. All unique trips stopping within 500 m of the dissemination block centroid were counted and the results were segmented into five time periods (midnight to 6 am, 6 am to 9 am, 9 am to 3:30 pm, 3:30 pm to 6:30 pm, 6:30 pm to midnight). Hourly averages were then computed for each time period and were assigned to individual trip origins based on the time when the trip was taken.

3.4. Analyses

Descriptive analyses are presented to understand the use of transit based on income groups and to characterize populations and trips. Trip components are then compared across socio-economic groups. Bivariate ANOVA tests are conducted on the studied outcomes against categories of income and presented graphically.

A set of regression analyses then assesses the relationship between trip components, public transport service variables and income and other individual characteristics. The objective is to identify when trip components and service features are advantageous or disadvantageous to low-income populations once all other confounding factors are considered. For example, the availability of a vehicle or the frequency and proximity of the transit service may confound the association between income and trip speed. Household composition must be inserted in the regression to account for the potentially varying relationship between household income on actual travel restrictions and disadvantages. Trip specific control variables isolate the relationship between income and the trip component and show what remains explainable by income. Variables were included based on their expected relationships either with the dependent variable or with income. Some variables are thus considered not relevant in a specific regression and were not included, others were theoretically required in the model but failed to provide significant results.

For each model, we use Ordinary Least Square (OLS) regression with variance–covariance matrix estimators accounting for the clustering of individuals making multiple trips. Models generally perform well in terms of explanatory power, save for the Access time model, which has a lower R-squared value.

All analyses use appropriate (individual and trip level) weights provided by the data producer. Breusch Pagan heteroskedasticity test can thus not be estimated with weighted and clustered data but clustered standard errors account for potential heteroskedasticity. Variance Inflation Factor (VIF) tests were all below 3, suggesting no strong collinearity (James et al. 2013 suggest moderate collinearity above 5 and strong collinearity above 10) in any of the regressions' independent variables.

3.5. Study area information

As per the 2016 Canadian census, the Montreal Metropolitan Region was home to 4.447 million residents living on an inland island and on both of its north and south shores.[1] The same census states that 46.1% of residents had household incomes below 30,000$. In comparison, 18.4% of the travel survey respondents that declared household incomes had household incomes below 30,000$.[2]

[1] https://www.artm.quebec/faits-saillants-eod-2018/#territoire-eod-2018.

[2] Statistics Canada. Census Profile, 2016 Census.https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/details/page.cfm?Lang=E&Geo1=CMACA&Code1=462&Geo2=PR&Code2=01&SearchText=montreal&SearchType=Begins&SearchPR=01&B1=Income&TABID=1&type=1 .

Table 1
Base sample description by income, trips by all modes.

	Less than $30000	Between $30000 and $59999	Between $60000 and $119999	$120000 or more	Total
Total trips recorded	44,041	94,130	145,906	62,965	347,042
Moved during survey day (% by column)	84.5	90.39	92.94	94.7	91.39
Public transit trips	9,565	13,630	18,713	8,258	50,166
Public transit trips (% by column)	21.72	14.48	12.83	13.12	14.46
	% by column	**% by column**	**% by column**	**% by column**	**% by column**
Bus (%)	17.22	10.52	8.43	7.65	9.97
Metro (%)	10.86	8.38	7.61	7.33	8.18
Train (%)	0.25	0.66	1.32	2.22	1.17
Transfer (%)	11.18	7.78	6.52	6	7.36
Park-and-ride (%)	0.53	1.06	2	2.86	1.71

Note: Trips can include more than one transit mode, percentages are independent of each other.

The Montreal area transit system includes 220 daytime bus lines and thousands of stops (across four major service providers), four subway lines (68 stations over 71 km) and five commuter rail lines (52 stations over 235 km). Most park-and-ride facilities are located at commuter rail stations, but all three transit modes are sometimes served by park-and-ride facilities (including 5 subway stations).[3]

4. Results

4.1. Descriptive statistics of individuals and trips

There are important differences in individual level characteristics and mobility depending on income. In Table 1**,** based on all 347,042 trips for which income is available in the database, low-income populations travel (at all) at a lower rate and use public transit at a higher rate. Low-income population use buses and metro at a higher rate than the commuter rail. When higher income groups use transit, comparatively higher shares of them use the Montreal metro system or the commuter rail as compared with the low-income population. Low-income individuals make more transfers than their wealthier counterparts, and use Park-and-Ride facilities at a lower rate than their higher income counter parts.

Turning to the study sample of those making transit trips, Table 2 describes the sample used in this study based on individuals, not trips. We find a higher share of women in all income groups with slightly higher shares in the two lowest income groups. Lower income groups are generally older than the rest of the sample, and more often live alone or head a single parent household. Lower-income households more frequently either have no cars or one car per person. Fewer higher income individuals have no cars, but more of them share vehicles. Possession of a driver's license is the lowest for low-income groups.

In Table 3, descriptive statistics are presented for the transit trip level data used in models based on income levels. It can be seen that low-income groups make fewer trips for the purpose of accessing or coming back from work. More than 50% of transit trips are made by metro, a rate lower than any other income group. Rates are also lower for suburban trains (1% vs. 17% for high income groups) but much higher for buses (76% vs. 58% for high income groups). Low-income groups use park-and-ride far less (2% vs. 22% for the highest income group), and differences in the use of transfers across income for individual trips (ranging from 48% to 55%) are considerably less distinct than those presented for individuals (in Table1). Trips of low-income groups are noticeably less frequent during the morning and afternoon peak period. Finally, proximity to bus stops (within 500 m) is similar across all income groups both at origins and destination (overall share of 94,8%); the Metro is situated within 1000 m for about 51 % both near home and workplace for all income groups. Fewer low-income groups have trains nearby (11% vs. 22% for the highest income group). The lowest income group begins more trips in the core (62%) than the highest income group (38%). As income increases, more trips begin outside of the central area suggesting that more people from these groups also live or work outside the central areas.

4.2. The trip components

The five studied outcomes of transit trips also vary depending on income in singular ways. Using violin plots, the following figures show differences in mean and median values by income groups, while also presenting the distribution of variables. All ANOVA tests are reported in figure caption and show that at least two income levels have statistically significant differences. Graphs further help interpret this and provide a distributional analysis (Bills and Walker, 2017).

In Fig. 1, access and wait times are shown to be on average lower for low-income populations with all income groups facing positive skewed distribution (hinging towards lower values). Wait time has a much wider distribution, which seems to disadvantage higher income individuals, likely representing the higher shares of commuter rail trips described earlier for this group.

But as income increases, travel times and distances increase (Figs. 2 and 3) as was shown elsewhere in literature on Montreal

[3] https://www.stm.info/fr/a-propos/informations-entreprise-et-financieres/rapport-annuel-2021.

Table 2
Sample description of public transit users by income (individual level).

	Less than $30 000	Between $30 000 and $59 999	Between $60 000 and $119 999	$120 000 or more	Total
Sample size (individuals)	3,715	5,551	7,559	3,313	20,138
	% by column	% by column	% by column	% by column	% by column
Sex					
Men	44.19	43.12	47.66	49.54	45.94
Women	55.81	56.88	52.34	50.46	54.06
Age groups (years old)					
0 to 17	9.77	12.27	14.32	18.19	13.4
18 to 29	33.75	33.26	33.35	32.85	33.33
30 to 39	17.04	18.29	18.27	14.86	17.52
40 to 49	12.22	13.9	15.37	16.85	14.54
50 to 59	8.85	11.9	13.44	14.22	12.19
60 to 69	8.67	6.62	4.23	2.52	5.55
70 and over	9.7	3.75	1.02	0.5	3.47
Household type					
Single person household	34.52	22.78	7.17	1.22	16.25
Couple, no kids	18.7	20.14	22.47	15.9	20.06
Couple, with kids	16	22.11	35.32	47.31	29.44
Single parent	10.03	8.62	4.89	2.04	6.57
Enlarged/multi generational/adult children	18.97	22.88	25.59	29.54	24.07
Other	1.79	3.46	4.57	3.97	3.61
Car ownership					
Without car	30.01	23.17	11.16	3.91	17.31
Shared cars	13.42	30.48	46.56	53.69	36.35
One car per household driver	56.57	46.35	42.28	42.39	46.34
Driver license					
No	58.93	42.31	31.78	26.74	39.51
Yes	41.07	57.69	68.22	73.26	60.49

(Deboosere and El-Geneidy, 2018; Morency et al., 2011). If these components seem to show more favorable conditions for low-income riders, they do not reveal the entire story of the transit journey.

Transforming these variables to speed of the entire trip and share of the trip in access and wait time (off-vehicle time), two known impedances to transit use, reverses the portrait drawn previously (Figs. 4 and 5). As income increases, the share of the trip in access and wait time decreases consistently. As for trip speed, lower-income individuals have lower mean and median trip speed, and very few of them travel at high speed (distribution skewed to the left). Hence while they spend less time off-vehicle, the shorter distances they cover using slower local transit services produces trips that cumulate less pleasant features.

4.3. Determinants of trip components in a multivariate approach

In this next section, five OLS regression models are estimated, one for each trip component considered in this study (the sixth, trip distance, is used as a control variable in each model). Public transport service characteristics are included in addition to individual and trip characteristics to identify which factors are associated with the five outcomes (Tables 4). The models preform well, with R-Squared values generally between 0.45 and 0.79, with the exception of the access model (0.16).

We start by commenting on relationships with the income variable for each trip component outcome and then discuss the socio-demographic, trips and service characteristics separately. The reference case is a low-income male, 30 to 39 years old, in a couple without kids, with no car, no license and making a peak morning non-work trip leaving from the region center.

When compared to the lowest income group (reference category), the other income groups are not always significantly associated with the six trip component outcomes. As in the bivariate analyses, low-income groups spend less time accessing transit stops, less time waiting for transit, and less overall travel time, even when controlling for other trip characteristics. This last association occurs even when considering the fact that low-income transit users also have shorter trip distances (an explanatory variable in models).

Contrary to bivariate analyses, share of trip spent accessing and waiting, as well as overall trip speed are not significantly different between high and low-income groups and overall, income groups have modest differences. This is likely due to the distinctive characteristics of the transit trips of low-income individuals, which are controlled for in these analyses and captured by other variables. In other words, the disadvantages observed for low-income are not directly the results of their income, but rather of the characteristics of the trips low-income riders make (with longer wait times, off peak trips, more transfers, less metro, more buses, and less commuter rail and park and ride trips) which is indirectly related to their income and spatial location. We now turn to exploring the other independent variables component-by-component, starting with access time.

Access time is negatively associated with being a woman, being older, not having a car, taking the bus, park-and-ride and transfers, and having any form of transit within close proximity to home. Near suburbs of Montreal also have shorter access time. Driving access

Table 3
Transit trip characteristics by trip purpose (trip level).

	Less than $30 000	Between $30 000 and $59 999	Between $60 000 and $119 999	$120 000 or more	Total
Sample size (trips)	8,836 % by column	12,606 % by column	17,176 % by column	7,568 % by column	46,186 % by column
Work trip					
Yes	14.51	24.98	27.9	26.93	24.12
Work trip (return)					
Yes	12.87	22.33	24.88	23.76	21.48
Mode used					
Metro					
Yes	54.39	61.55	62.05	58.05	59.71
Bus					
Yes	76.01	70.22	64.45	57.56	67.49
Commuter train					
Yes	1.06	4.34	10.43	17.43	7.78
Use of Park-and-Ride					
Yes	2.14	6.86	14.74	21.7	10.9
Transfer					
Yes	53.23	55.16	52.72	47.92	52.81
Departure time					
4 h to 5 h59	1.35	1.86	1.83	1.26	1.65
6 h to 8 h59 (AM peak)	21.3	29.7	34.54	37.15	30.78
9 h to 11 h59	14.88	10.79	7.91	7.16	10.07
12 h to 15 h29	22.84	15.23	12.99	11.09	15.41
15 h30 to 18 h29 (PM peak)	26.1	30.85	33.62	35.06	31.47
18 h30 to 23 h59	12.73	10.92	8.69	7.93	10.05
24 h to 28 h (4am)	0.8	0.65	0.42	0.36	0.56
Bus within 500 m of origin					
Yes	96.11	95.94	94.25	92.67	94.88
Bus within 500 m of destination					
Yes	96.02	95.99	94.05	92.77	94.82
Subway within 1000 m of origin					
Yes	50.9	51.82	51.49	51.33	51.44
Subway within 1000 m of destination					
Yes	51.2	52.55	51.87	52.05	51.95
Train within 1000 m of origin					
Yes	11.77	14.98	18.59	22.12	16.66
Train within 1000 m of destination					
Yes	11.85	15.1	18.65	22.85	16.84
Trip origin zone					
Montreal Central neighbourhoods and Downtown	62.46	53.99	42.19	37.67	49.11
Inner suburbs	34.88	39.28	43.52	45.74	40.84
Outer suburbs	2.66	6.73	14.3	16.59	10.06

times upwards are couples with children (reference category is a couple without children), trips going to or coming back from work, having at least a car and a driver's license and trip distance.

Having children, a driver's license, using the metro and park-and-ride, as well as evening trips and proximity to metro station and higher frequency of service reduces **wait time**. Wait times are increased for younger people, living alone, using the bus or commuter rail (the latter adding nearly 15 min to wait), making transfers, taking early morning trips, and taking trips over longer distances. Compared to residents and trip beginning in the center, wait times are greater for those with trip origins in the near and outer suburbs.

Women, the youngest and oldest age groups, as well as those with driver's license tend to have shorter **overall trip time**. Those making trips by metro, with park-and-ride, and mid-day or in evening trips also are shorter in duration, likely by avoiding traffic when in buses. Greater service frequency and proximity to the metro also drives trip time downwards. Having kids, work trips, bus and commuter rail trips, taking transfers over a longer distance trip with origins in the near suburbs each individually drive overall travel time higher.

As for the **percent off-vehicle**, it tends to be lower when children are present and a person owns a car, for work trips, for trips that include metro or bus legs, when trips include park-and-ride and when trips cover a longer distance. Access to any form of nearby transit near home and destination also reduces that share, as well as greater service frequency. On the other hand, older riders, commuter rail user and midday and PM peak riders will face greater shares of the trip off-vehicle. Respondents with trip origins in near and outer suburbs will also have greater share of trips off-vehicle.

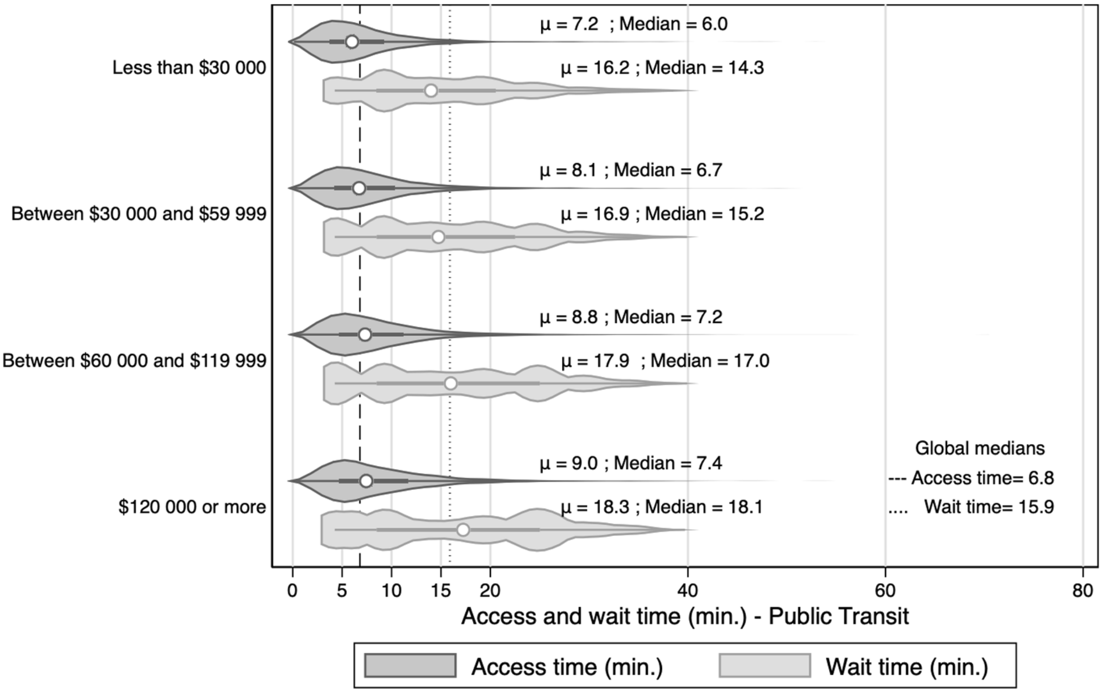

Fig. 1. Access and wait time by income (ANOVA: Access F 182.96; Prob > F: 0.000; Wait F 63.22; Prob > F: 0.000).

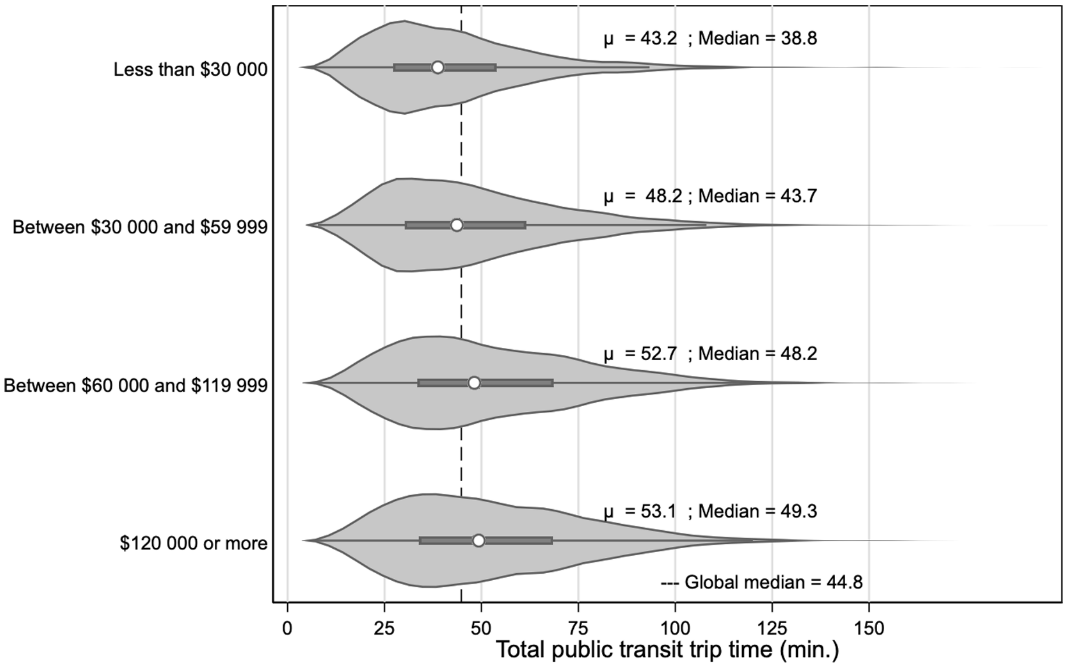

Fig. 2. Overall trip time by income (ANOVA: F 385.63; Prob > F: 0.000).

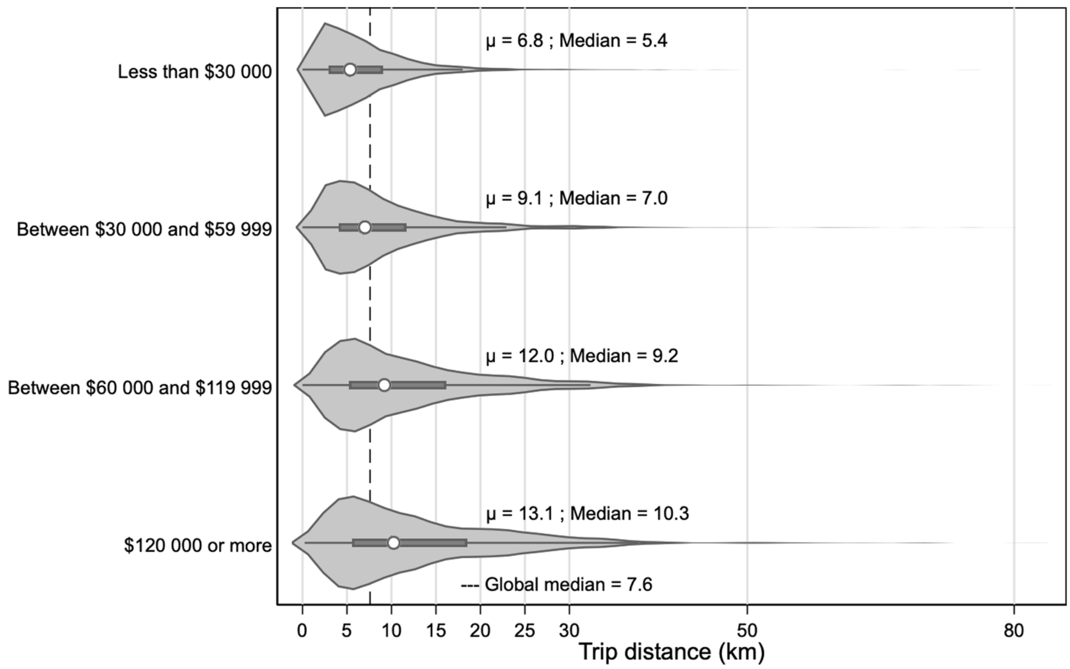

Fig. 3. Distance travelled by income (ANOVA: F 1123.31; Prob > F: 0.000).

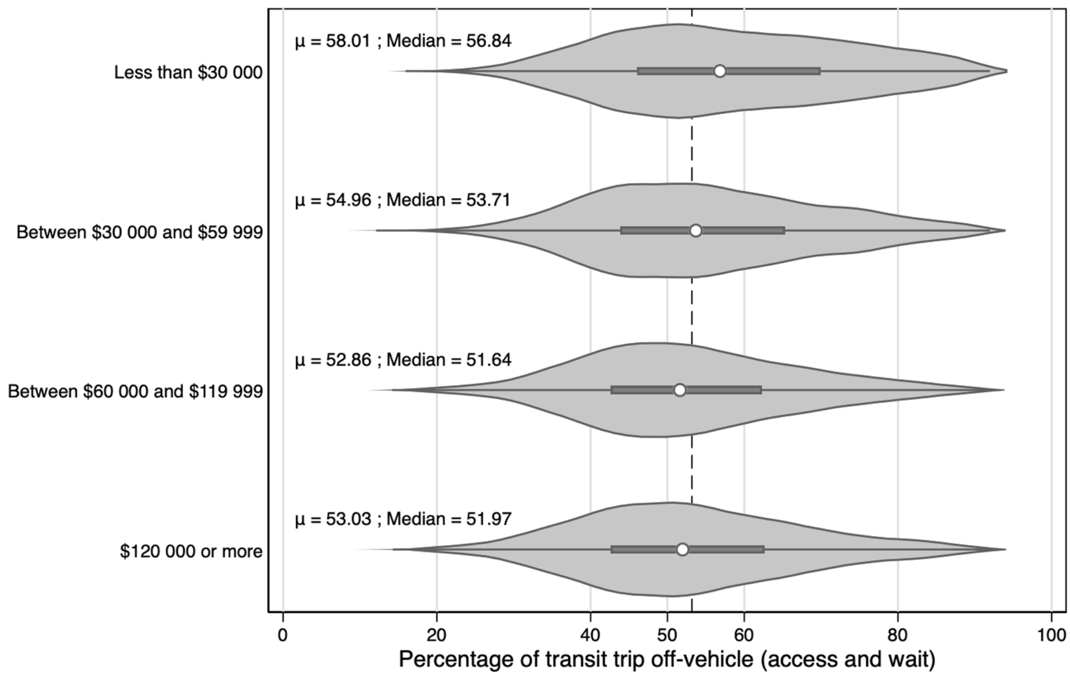

Fig. 4. Share of entire trip spent in access and wait time (off-vehicle) by income (ANOVA: F 272.21; Prob > F: 0.000).

Finally, the model on **the trip's overall speeds** presents very few associations with individual level variables. Having a car and a driver's license is associated with higher speeds. Bus trips, commuter rail and transfer reduce the overall speed of trips, so does afternoon peak trips (likely due to congestion). Living in outer suburbs also tends to be associated with reduced trip speeds. On the other hand, work trips, subway trips, use of park-and-ride and evening trips tend to be made at higher speeds. Increase in service frequency and presence of metro and train stations nearby increases trip speeds. The greater share of park-and-ride use and metro trips by higher

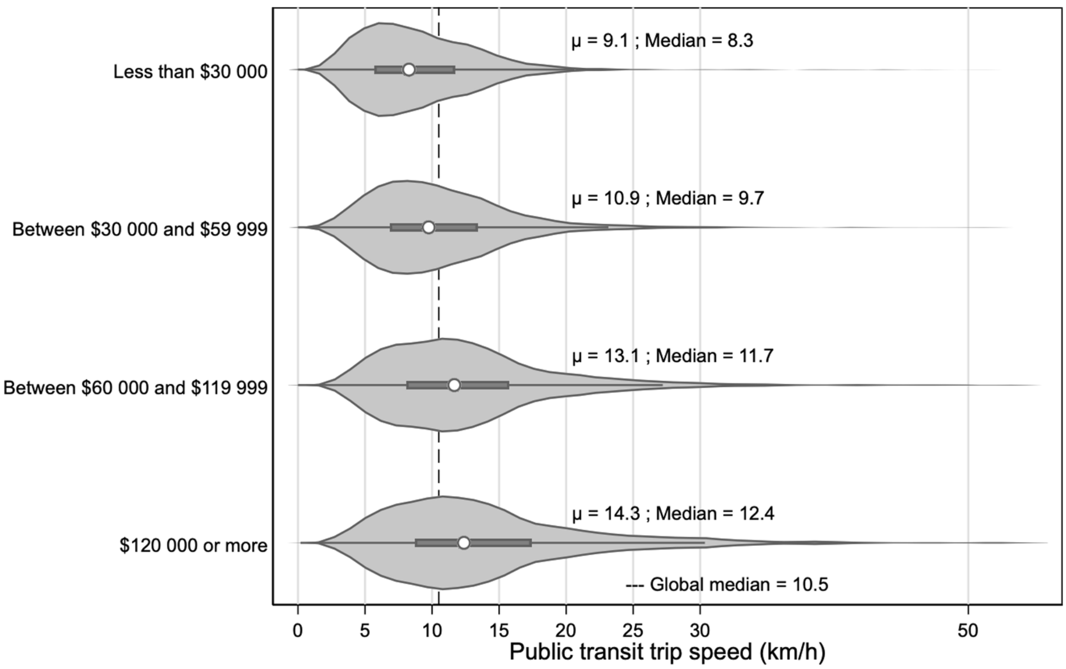

Fig. 5. Overall trip speed by income (ANOVA: F 1130.33; Prob > F: 0.000).

income individuals (which makes the overall trip faster) and bus trips outside of peak hours by lower income riders (which reduces exposure to traffic) largely absorbs the association attributed to income in bivariate analyses.

During the analytical phase of the research, we estimated the same models restricted to the low–income subsample to assess whether specific individual, trip or service features were more salient for this specific group. Because associations were consistent with our full sample, we do not present these results here.

5. Discussion

Taken together, these analyses suggest that household income *per se* is not necessarily always directly related to reduced quality of trips overall and on average, but that the types of trips taken by low-income riders, as well as their home and work location characteristics, tend to contribute to disadvantages in some important components of the trips. While low-income rider trips were seemingly shorter in distance and duration, and required shorter access and wait times, they tended to be overall slower and required a greater share of less desirable out-of-vehicle time.

Trips for the purpose of accessing or coming back from work tend to be better served by transit. Two potential explanations can be suggested for this relationship. First, commuters seek living and working locations that are better served by transit since the commute is frequent and structuring in a person's life. While low-income populations are more constrained in both their housing and their work location choices, they still likely invest efforts in improving the quality of this structuring trip. Second, the transit network is designed particularly to access locations with high employment. Since non-work trips are proportionally more frequently done by low-income residents (Table 3), equity implications arise from a commuter centric network design. These equity implications not only impact low-income riders but also women, children and the elderly, who all take more non-work transit trips. Further, not only is the network designed around commute trips, but it also largely favors trips converging from the suburban areas to downtown. Yet, a high proportion of low-income individuals work in decentralized areas (Vermesch et al., 2021).

Our study found that nearly 40% of low-income transit riders begin their trips (and this may be a trip departing from work) in the inner (36.2%) and, to a lesser extent, outer suburbs (2.8%) of the region, exposing these two subgroup to more distant and less frequent service even if it is considerably faster (Table 5). This may be particularly inconvenient when riders depend on transit for most trips for lack of a car. The broad and frequent availability of fast and efficient public transit and other non-motorized modes for all sought destinations enables low-income riders foregoing the expenses of owning a car.

We also found that low-income riders take more transit trips outside of peak periods where fewer lines operate, often at reduced frequency. The regression analyses demonstrated that service frequency was significantly and negatively associated with wait time, trip time and off-vehicle time, but was positively associated with trip speed. Whether the trip was conducted for unconventionally scheduled shift work or for other purposes, it is likely that riders facing low frequencies will be disadvantaged for most trip components. This relates to the equity implications of network designed mainly around typical commutes, where a lower consideration is given to travel outside of peak periods.

Living or working within 1000 m of a metro station also appeared to be significantly associated with almost all trip components.

Table 4
Ordinary least square regression models of trip components.

	Access time		Wait time		Total trip time		Percent off-vehicle		Overall trip speed (km/h)	
	Coef.	**S.E.**	**Coef.**	**S.E.**	**Coef.**	**S.E.**	**Coef.**	**S.E.**	**Coef.**	**S.E.**
Less than $30 000	[REF.]	.		.		.		.		.
Between $30 000 and $59 999	0.36***	0.11	0.36**	0.13	1.06***	0.23	−0.09	0.24	−0.13*	0.06
Between $60 000 and $119 999	0.52***	0.11	0.65***	0.13	1.22***	0.24	0.35	0.24	−0.05	0.06
$120 000 or more	0.56***	0.14	0.75***	0.15	1.21***	0.29	0.78**	0.29	0.02	0.08
Men	[REF.]	.		.		.		.		.
Women	−0.29***	0.07	−0.04	0.08	−0.60***	0.15	0.07	0.15	0.07	0.04
Age: 0 to 17	−0.14	0.16	0.43*	0.18	−1.23***	0.34	1.85***	0.33	−0.05	0.08
18 to 29	0.14	0.12	0.21	0.13	0.22	0.25	−0.03	0.26	0.07	0.07
30 to 39	[REF.]	.		.		.		.		.
40 to 49	−0.40**	0.12	−0.03	0.14	−0.4	0.26	−0.24	0.26	0.14	0.08
50 to 59	−0.15	0.13	0.13	0.14	−0.13	0.27	0.22	0.26	0.04	0.08
60 to 69	−0.60***	0.15	0.26	0.18	−0.65*	0.33	0.32	0.33	−0.05	0.09
70 and over	−1.05***	0.18	0.1	0.24	−1.54***	0.42	0.95*	0.47	−0.08	0.1
Single person household	0.01	0.13	0.32*	0.14	0.49	0.26	−0.04	0.29	0.02	0.07
Couple, no kids	[REF.]	.		.		.		.		.
Couple, with kids	0.34**	0.11	−0.24*	0.12	0.59*	0.23	−0.78**	0.24	0.02	0.07
Single parent	0.21	0.17	−0.08	0.19	0.58	0.36	−0.07	0.34	−0.12	0.09
Enlarged/multi generational/adult children	0.04	0.12	−0.06	0.13	0.45	0.23	−0.81**	0.25	0.1	0.07
Other	−0.2	0.21	−0.29	0.24	−0.17	0.45	−1.06*	0.44	0.05	0.12
At least one car in household (vs. none)	0.64***	0.09	−0.1	0.11	0.78***	0.2	−0.57**	0.22	0.18***	0.05
Driver license (vs. none)	0.27**	0.09	−0.44***	0.1	−0.42*	0.19	−0.34	0.19	0.24***	0.04
Trip purpose										
Work trip	0.20*	0.1	0.19	0.11	0.87***	0.21	−0.94***	0.21	0.17**	0.05
Work trip return	0.56***	0.1	0.41***	0.11	1.27***	0.2	−0.44*	0.21	0.15**	0.06
Other trip purposes	[REF.]	.		.		.		.		.
Trip mode (more than one possible)										
Mode: Metro	−0.16	0.12	−2.51***	0.17	−1.31***	0.31	−2.58***	0.26	1.41***	0.07
Mode: Bus	−3.60***	0.12	7.87***	0.14	10.40***	0.25	−0.49*	0.24	−3.87***	0.07
Mode: Commuter train	1.08***	0.21	14.52***	0.24	10.60***	0.55	19.14***	0.43	−5.51***	0.16
Park-and-Ride	−6.48***	0.15	−4.07***	0.15	−18.89***	0.36	−3.34***	0.32	7.13***	0.15
Transfer	−1.39***	0.09	8.50***	0.12	11.17***	0.21	−0.24	0.21	−2.08***	0.06
Trip distance (km)	0.15***	0.01	0.18***	0.01	2.04***	0.03	−1.33***	0.03	0.54***	0.01
Trip timing										
4 h to 5 h59	−0.31	0.23	0.96**	0.34	1.11	0.66	−0.11	0.45	−0.32	0.17
6 h to 8 h59 (AM peak)	[REF.]	.	0.00	.	0.00	.	0.00	.	0.00	.
9 h to 11 h59	−0.08	0.11	−0.04	0.12	−0.64**	0.22	0.47*	0.22	−0.08	0.06
12 h to 15 h29	−0.08	0.09	−0.07	0.1	−0.63***	0.18	0.39*	0.19	−0.03	0.05
15 h30 to 18 h29 (PM peak)	−0.06	0.08	0.02	0.09	0.04	0.16	0.52**	0.17	−0.13**	0.04
18 h30 to 23 h59	0.05	0.12	−0.74***	0.13	−1.18***	0.25	−0.48	0.27	0.17*	0.07
24 h to 28 h (4am)	0.17	0.39	−0.35	0.44	−0.98	0.79	−1.26	0.88	0.31	0.24
Service frequency at trip time (origin)	N.R.		−0.01***	0.00	−0.02***	0.00	−0.02***	0.00	4.58e-3***	0.00
Service frequency at trip time (dest.)	N.R.		−0.01***	0.00	−0.02***	0.00	−0.02***	0.00	3.99e-3***	0.00
Bus within 500 m of origin	−1.42***	0.17	−0.01	0.16	0.03	0.35	−2.31***	0.28	0.18	0.1
Bus within 500 m of destination	−1.26***	0.16	−0.15	0.17	−0.53	0.35	−1.68***	0.27	0.14	0.1
Subway within 1000 m of origin	−1.36***	0.08	−1.36***	0.09	−3.59***	0.16	−1.01***	0.16	0.06	0.04
Subway within 1000 m of destination	−1.44***	0.08	−1.80***	0.09	−3.83***	0.16	−1.72***	0.16	0.14***	0.04
Train within 1000 m of origin	−0.69***	0.08	−0.14	0.1	−0.2	0.18	−0.69***	0.19	0.30***	0.05
Train within 1000 m of destination	−0.73***	0.08	−0.18	0.1	−0.26	0.18	−1.04***	0.19	0.33***	0.06
Montreal Center	[REF.]	.	0.00	.	0.00	.	0.00	.	0.00	.
Montreal near suburbs	−0.34***	0.09	2.38***	0.1	2.96***	0.2	0.44*	0.2	0.35***	0.05
Outer suburbs	0.34	0.21	4.55***	0.23	−0.94	0.51	11.23***	0.41	−0.60***	0.13
Constant	14.04***	0.37	7.48***	0.38	21.42***	0.75	75.61***	0.68	7.47***	0.2
Observations	46,186		46,186		46,186		46,186		46,186	
Chi square significance	0.000		0.000		0.000		0.000		0.000	
R-Squared	0.167		0.67		0.781		0.454		0.79	
AIC	288329.8		298108.2		355852.1		353630.8		237931.5	

Note: Coef. = Coefficient; S.E. = Standard Error; REF. = Reference Category; N.R. = Not relevant (variable was not used in models for lack of theoretical or logical justification); AIC: Akaike information criterion; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

While lower-income households in large part locate in central areas that are better served by public transport (El-Geneidy et al., 2016), they do not reside or work in greater proportion than other groups in close proximity of metro stations. For each income category, approximately 50% of households with transit users were within 1000 m of a metro station both for place of residence and place of work, even though low-income populations use transit in greater proportions.

In the present study, breaking down trips into their components provides a more nuanced portrait of low-income riders' situation. Once characteristics of trips and riders were taken into account, income ceased to be significant in many models estimating the

Table 5
Mean transit trip component values depending on trip departure location for low-income riders (Less than $30 000).

	Percent of trips by departure zone	Access time	Wait time	Total trip time	Percent off-vehicle	Overall trip speed (km/h)	Distance (km)
Trip origin zone							
Montreal Central neighbourhoods and Downtown	60.9	6.99	14.41	38.31	59.11	8.61	5.58
Inner suburbs	36.2	7.06	19.62	49.78	57.71	9.10	7.95
Outer suburbs	2.8	9.67	27.66	70.49	56.37	14.23	17.48
Overall mean	100	7.09	16.68	43.37	58.52	8.94	6.78

components. The observed bivariate income effect was thus largely a product of the underlying variables (of service and trip features such as transfers and departure times) that were included in multivariate models. Future research should aim at further understanding what other factors if any contribute to the remaining income-related gaps that were identified. Given the aforementioned realities of the Global South, it would be equally important to explore these metrics in other locations around the world and in countries and cities with different spatial and socioeconomic distribution. Finally, studies assessing the experience of low-income riders based on matched housing and work locations would provide additional evidence on the employment benefits of specific network configurations.

6. Limitations

Four main limitations should be mentioned here. As the Montreal OD survey only surveys weekdays, any travel performed during the weekend is not accounted for in this paper. Given that many service sector jobs tended by low-income populations also occur during the weekend, and given that many transit lines operate at reduced frequency during the weekend, the estimates presented here likely overestimate the quality of trip components that low-income workers experience when working during weekend shifts. The income discrepancies might be even greater.

Second, within the OD survey, income is reported at the household level and not the individual level. While this make sense from an opportunities perspective – households share most expenses including cars – this measure does not enable a clear identification of the income of individual respondents. The impact of earning less than $30,000 CAD is likely different for individuals living alone as compared to households with multiple members. We were able to improve estimates by including household structure (e.g. singles, couples, kids) as a supplementary independent variable. For a solo household, $17,500 CAD is considered in Montreal as the low-income threshold (Institut de la Statistique du Québec, 2019). Income group classification in the OD survey, however, did not enable this level of detail. The survey provided limited categories of income and a low response rate on the income question. A report comparing this data to census income levels per areas did show that it was both consistent with area averages and internally consistent with area distributions (Lachapelle et al., 2020).

Third, readers may wonder if associations between key variables like car ownership, trip timing and trip origin location might have distinctive associations depending on levels of income. While we've explored some of these associations through interactions and stratification, it was impossible to provide a clear discussion within the space allowed in this paper. We thus hope this issue may stimulate further studies.

Finally, this analysis focuses on completed transit trip and does not include trips that low-income riders would have rather taken by transit, but were not able to because of the low or non-existent service between required trips' origins and destinations. Other tools must be developed to assess these properly.

7. Conclusion

While low-income populations are important users of public transportation, numerous studies have identified that they are underserved by the transit systems of the cities they live in. Based on our analyses, in Montreal, some features of the city configuration, system design and trip departure location of low-income populations actually favors them while others do not. It seems that for most trips, low income riders have shorter access times, shorter wait times, they travel over shorter distances and thus also have overall shorter trip times. However, because of the shorter distances of their trips, in many cases they spend a greater proportion of their trip time accessing and waiting for transit, and a smaller one in moving vehicles. Thus the entire trip's speed tends to be lower. In multivariable models controlling for many other features of individuals, locations, trips and service, we find that low-income populations are not necessarily disadvantaged directly, but the types of trips taken and circumstances of these trips are what disadvantages them. Off peak trips, on lower frequency bus lines, with transfers, that do not involve park-and-ride are for example considerably slower and include less in-vehicle time.

Focusing on providing access to low-income riders in cities goes beyond physical access to stops, stations and transit lines, and can encompass a better understanding of all components of trips, including access, waiting, overall travel time, in and out-of-vehicle time, and travel speed. This paper demonstrates how this can be assessed, and provides evidence that inequities can be identified in specific components of trips while others are favorable. Ensuring the entire travel experience favors those most likely to use transit would support consideration of equity in transit provision and likely increase both ridership and existing rider experience.

Networks designed for commutes (both in terms of convergence to centers and in terms of higher service frequency and coverage during peaks) may be revised to address the more diverse trip types taken by low-income riders including in inner suburbs less well covered by transit service. Furthermore, the implementation of express lines through low-income neighborhoods and along commercial streets with fewer stops (to increase speeds), while maintaining existing comprehensive lines, and the development of bus priority measures to increase travel speeds (timed streetlights, priority departures at intersections, dedicated right of way for buses) would likely improve the travel conditions of low-income riders. Low-income populations also stand to gain from more robust nighttime transit service. Because we find that even though low-income population use transit at a higher rate, they are no better located to use it than wealthier populations, housing policies should be considered to improve access. This namely includes subsidized housing near transit as well as provision of smaller rental units in close proximity to transit.

Cost-Benefit analyses of transportation project are often focussed on in-vehicle travel times. We suggest here that the important additional metrics we presented here vary across income group and space and can inform transport planning and provide more detailed and accurate results.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contribution statement

Ugo Lachapelle and Geneviève Boisjoly contributed to this paper as follows: study conception and design: Ugo Lachapelle and Geneviève Boisjoly; data collection: Ugo Lachapelle and Geneviève Boisjoly; analysis: Ugo Lachapelle; interpretation of results: Ugo Lachapelle and Geneviève Boisjoly; draft manuscript preparation: Ugo Lachapelle; draft manuscript revision: Geneviève Boisjoly. Both authors confirm to have reviewed the results and to have approved the final manuscript.

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