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# Resolving the accessibility dilemma: Comparing cumulative and gravity-based measures of accessibility in eight Canadian cities

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ABSTRACT

There is a lack of agreement regarding the theoretical framework that practitioners should use for accessibility assessment – a measure of transport and land-use systems performance. Cumulative measures are simple and easy to interpret, while gravity-based measures are more sophisticated, resourceful, and less intuitive approaches. As such, this study aims to investigate whether the estimates of a simple cumulative opportunity measure are significantly different from those made using advanced gravity-based measures to understand if the former can be a substitute for the latter in practice and if a certain threshold of travel time can be recommended for different regions. We estimated cumulative and gravity-based accessibility using decay-probability density functions, decay-cumulative density functions, Gaussian, and a Log-Logistic decay-cumulative density functions using census commuting flows, car congested travel time and public transit schedules from eight metropolitan regions across Canada – Toronto, Montreal, Vancouver, Edmonton, Quebec City, Winnipeg, London, and Halifax. These measures of accessibility were tested for correlation, and we found that a coefficient of approximately 0.90 is reached when the threshold to calculate cumulative opportunities accessibility is set to the average commute time for both low- and non-low-wage jobs accessibility analyses by transit and motor vehicles. The paper provides evidence to support the reliability of cumulative accessibility, facilitates its broader adoption for evaluation of transport and land use interactions in North American cities, as well as opens opportunities to advance the equitable distribution of transport system benefits.

## 1. Introduction

Accessibility, the ease of reaching destinations, has been part of the land use and transport academic discourse for over six decades. The theory and methods for accessibility assessment have been constantly evolving (Deboosere and El-Geneidy, 2018). Despite the acknowledgment of its ability to comprehensively assess transport and land-use systems performance, there is a lack of agreement regarding the theoretical framework that practitioners should use in its application. An argument to keep accessibility measures simple and easy to interpret is often challenged with the call for more sophisticated and resourceful approaches that are in turn harder to communicate to the public.

This study focuses on comparing the two most frequently used approaches to measuring accessibility – cumulative and gravity-based. The former is an example of a straightforward concept that only opportunities reached within a certain travel time threshold by a certain mode of transport should be considered accessible, while those over it should not (El-Geneidy and Levinson, 2021). While easy to quantify and grasp, it is believed to be a poor approximation to the way opportunities are perceived, thus oftentimes criticized for its shortcomings and argued against and in favor of gravity-based measures (Geurs and van Wee, 2004; Siddiq and Taylor, 2021). Selecting the most appropriate threshold of travel time to be used is also a subject of debate (Páez et al., 2012). The latter family of accessibility measures incorporates the distance-decay factor into the evaluation and results in lower estimates of opportunity for the places that are harder to reach. It better represents the original Hansen's idea of the concept (Hansen, 1959) that the traveler's appeal of the opportunity goes down with the increase in travel time or distance, as well as incorporates Cochrane's (Cochrane, 1975) logic that the negative exponential decay of accessibility reflects the decrease in the attractiveness of the trips that are made to achieve maximum consumer surplus. However, this advantage comes at a cost of

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less straightforward explanations of opportunity discounting, higher data requirements, and the need for more sophisticated analytical skills, which together become a barrier for some decision-makers and the general public when such measures are communicated (Siddiq and Taylor, 2021; Boisjoly and El-Geneidy, 2017).

More cities should include accessibility in their planning toolkit, as, for example, London in the UK, Paris in France, Sydney in Australia, and Atlanta in the USA employ accessibility in their assessment of transport systems (Deboosere and El-Geneidy, 2018). To support the broader adoption of accessibility assessment by practitioners, this study uses information on travel times by automobile and public transport as well as the location of jobs by income group in eight metropolitan regions across Canada (Toronto, Montreal, Vancouver, Edmonton, Quebec City, Winnipeg, London, and Halifax) to estimate four different gravity-based accessibility measures and compare them to cumulative opportunities accessibility measures calculated at various thresholds of travel time for those respective regions. The goal of this comparison is to better understand if cumulative opportunity measures, which are simpler and easier to interpret, can replace gravity-based measures in practice and if a certain threshold of travel time can be recommended to be used when generating these measures across different regions of different scales and for different income groups.

The contributions of this paper are threefold. Firstly, we provide empirical evidence that supports the validity of easy-to-communicate cumulative accessibility to jobs by using a large dataset for the comparison of multiple accessibility metrics, which paves the way for its broader use among practitioners when conducting public transit and motor vehicle infrastructure or performance evaluations. Secondly, we confirm the finding for both low and non-low-income households, which allows for the broader promotion of equity goals in transport planning. Finally, we verify that cumulative accessibility is a reliable measure by replicating the research for eight Canadian metropolitan regions, each subject to a different size, density, population, and geographic location, making it evident that such an approach to accessibility measurement is a reliable metric at least in the Canadian context.

## 2. Literature review

The last decade saw transport planning practice experiencing fundamental changes in the concepts and methods it uses to tackle the existing environmental and societal challenges and plan for improvements. A clear gradual shift can be observed from the cost and speed of vehicle operations to performance-based metrics that evaluate the benefits of transport systems in a more comprehensive way (Litman, 2022). Mobility and accessibility are the two primary concepts that attempt to assess such performance of any transport system. The former approach is mainly limited to the improvements in the system's ability to get the maximum number of users through it, while the latter perceives transport as only a mean to reach places for social interactions, services, and work, and places the larger emphasis on the destination and the reason for travel (Ferreira and Papa, 2020). There is a broad consensus that accessibility is an advantageous guiding principle for planning due to its comprehensive nature that can include objectives around employment, equity, and environment (Zhao and Lu, 2010; Lucas, 2014; Lucas et al., 2016). Nevertheless, when it comes to practice, mobility measures keep dominating the field worldwide (Boisjoly and El-Geneidy, 2017).

Accessibility is a well-defined and thoroughly studied concept in the academic literature. First discussed by Hansen (Hansen, 1959) as a proxy for the diversity and number of locations reached using the transport network, it has evolved to include other theories and measures to represent the benefits of easy access to some places over others. For example, individual accessibility stems from the space-time geography approach, it focuses on the person engaged in the travel, and relies on the information about the allocated time, as well as their social and demographic background (Geurs and van Wee, 2004). The field of economics promotes utility-based accessibility that is mainly concerned with the reward obtained from the engagement with opportunities in a given space (Geurs and van Wee, 2004). Finally, location-based accessibility is the closest to Hansen's concept as it quantifies the opportunities of a geographic location within a certain time threshold from the traveler's origin (Geurs and van Wee, 2004).

Metrics that evaluate place-based accessibility can be grouped into three categories. The least data and computation intensive is the cumulative accessibility, as it simply adds up the number of opportunities, like jobs, shopping destinations, or hospitals that a person can reach by a given mode of transport in less than a given time (Ingram, 1971), usually creating isochrones of 15, 30, or 45 min. The cumulative metric can be modified to discount the opportunities that are harder to reach instead of leaving them out of the calculations after the predefined threshold is reached. This approach is known as the gravity-based accessibility measure. Such adjustment makes it a more realistic approximation as it assumes that individuals don't stop traveling after a certain time, but value destinations that are farther away less (Koenig, 1980). However, this improvement comes at a cost of additional data requirements and more complicated computations that are harder to interpret for the policymakers and the public (Handy and Niemeier, 1997). Of course, the challenge of communication can be overcome with the use of a utility-based measure presented as a monetary value of the total utility that destinations in the choice set have, however it is an even more data-intensive approach and harder to calculate (Handy and Niemeier, 1997).

Historically, the impetus behind developing accessibility measures was to introduce the metric to assess the effect of planning proposals on transport and land use systems (Morris et al., 1979). Methodologies have been developed to evaluate accessibility from the angle of the mode used, i.e. public transport, cars, non-motorized means like bicycles and walking, and multimodal choices (Handy and Niemeier, 1997; Iacono et al., 2010; Harvey and Deakin, 1993). The latter, however, has not been widely adopted due to methodological challenges, except for utility-based measures that can incorporate multimodality in a fairly straightforward fashion (Handy and Niemeier, 1997). Moreover, there is empirical evidence that accessibility can influence mode choice, especially for low-income categories (Cui et al., 2020). Studies have shown that improved accessibility can lead to shorter travel times, higher investment attractiveness, an increase in land values, more social interactions, and better employment prospects for households of all incomes (El-Geneidy and Levinson, 2021; Levinson, 1998; Ozbay et al., 2003; Martínez and Viegas, 2009; Lucas, 2012; Andersson et al., 2018; Boisjoly et al., 2017).

Some researchers focused on the effect that a transport system has on the provision of essential services and evaluated the accessibility to education, food stores, and healthcare (Grengs, 2015; Páez et al., 2010; Bissonnette et al., 2012), however, there is a consensus that a number of jobs at a location is by far the most practical proxy for the area's appeal, as it does not only represents the employment potential but also the attractions that the jobs there provide, like cafes, performance venues, and services (Deboosere and El-Geneidy, 2018; Owen et al., 2017). As such, accessibility assessments are well-suited to not only understand the general societal impacts of transport investments but to evaluate the specific effect on vulnerable populations (Levinson, 2002), allowing for practical monitoring of the progress made toward the achievement of equity goals.

Previous studies have found a high correlation between gravity-based and cumulative accessibility and argued for using them due to their ease of interpretation and communication to policymakers (El-Geneidy and Levinson, 2006). These include a study of local shopping opportunities by Guy (Guy, 1983), a comparison of thirty accessibility measures that evaluated patterns for fifty-two households using cumulative, gravity-based, and space-time specifications by Kwan (Kwan, 1998), and an analysis of place rank, cumulative, and gravity-based measures by El-Geneidy and Levinson (El-Geneidy and Levinson, 2011). Giannotti et al. (Giannotti et al., 2021) have found the performance of cumulative and gravity-based accessibility consistent in London, but less so in Sao Paulo, suggesting that accessibility evaluations based on time thresholds might be reliable only in the context of the Global North. Most recently, Santana Palacios and El-Geneidy (Santana Palacios and El-Geneidy, 2022) have found cumulative and gravity-based accessibility to be highly correlated for transit commutes in Montreal, Canada, at the mean travel for the region justifying the use of cumulative in this region as a replacement for gravity measures when needed. Our study expands their approach to seven other Canadian municipalities and includes accessibility by automobile, providing an opportunity for the findings to be more universal and applicable to other regions with similar context.

## 3. Methodology

For the purpose of this study, we calculated cumulative and gravity-based accessibility to jobs for eight Census Metropolitan Areas (CMA) in Canada - Toronto, Montreal, Vancouver, Edmonton, Quebec City, Winnipeg, London, and Halifax. The geographic location of the studied regions is visualized in Fig. 1, and an overview of the main population and transport characteristics is presented in Table 1. Employment data was obtained from the 2016 Census from Statistics Canada, with each region having Census Tract (CT) level details on the number of workers, their home CT, the mode used to travel to work, as well as annual income. This last data point was used to determine the number of commuters in low-wage occupations, defined as the 30% lowest paying jobs in every metropolitan region (Deboosere and El-Geneidy, 2018; Foth et al., 2013). This approach means that a job with an annual income of less than $40,000 CAD was classified as low-income in Edmonton CMA, while the threshold was at $30, 000 CAD for the other seven regions in this study.

To estimate public transport travel times, we used archived schedule records in the General Transit Feed Specification (GTFS) format for October–November 2016 (depending on the quality of archived records) for the respective regions. This information was then processed in R statistical software using r5r package (Pereira et al., 2021) to obtain transit travel times between the centroids of each CT in each region. The travel time included walking access, waiting, in-vehicle, transferring if applicable, and walking egress times. Calculations were made for the morning rush hour on a typical weekday as suggested by Boisjoly and El-Geneidy (Boisjoly and El-Geneidy, 2016) and with adjustments for changes in trip duration due to the difference in departure time. Using Conway et al. as guidance (Conway et al., 2018), the latter was accounted for by using the median travel time for all trip pairs that began every minute between 8 AM and 9 AM. Motor vehicle travel times were procured from the Google API in 2017 accounting for congestion levels. Additional five minutes were added on average to each car trip to account for the parking and match the mean commuting time by car, truck, or van for employed persons from the 2016 Census (Statistics Canada, 2016).

The estimation of accessibility was performed using eq. (1) from Hansen (Hansen, 1959).

$$A_i = \sum_j O_j f(C_{ij}) \tag{1}$$

Where using the language from Levinson and King (Levinson and King, 2020), $A_i$ is the accessibility of the origin CT *i*, $O_j$ represents the number of jobs at the destination CT *j*, $C_{ij}$ is the travel time between the origin and destination CTs, and $f(C_{ij})$ is the impendence function.

The impendence function $f(C_{ij})$ for the cumulative accessibility is equal to zero when the travel time exceeds the threshold *t*, and it takes the value of one otherwise, as expressed by eq. (2).

$$f(C_{ij}) = 1 \ if \ C_{ij} \le t, \text{otherwise} \ f(C_{ij}) = 0 \tag{2}$$

Cumulative accessibility to jobs was estimated using multiple travel time thresholds. We considered 24 travel time thresholds ranging from 5 to 120 min for transit. For motor vehicles, we employed 11 different


**Fig. 1.** The eight metropolitan regions in Canada used for the study.

**Table 1**
Overview of studied regions.

| Region | Population | Jobs | Population density [/km$^2$] | Transit agencies | Transit modes available |
|---|---|---|---|---|---|
| Toronto | 5,928,040 | 2,566,650 | 1003.8 | Toronto Transit Commission, Metrolinx | Bus, Streetcar, Subway, Commuter Train |
| Montreal | 4,098,927 | 1,323,783 | 890.2 | Société de transport de Montréal | Bus, Subway |
| Vancouver | 2,463,431 | 1,004,375 | 854.6 | TransLink | Bus, LRT, Ferry |
| Edmonton | 1,321,426 | 551,140 | 140.0 | Edmonton Transit Service | Bus, LRT |
| Quebec City | 800,296 | 374,680 | 234.8 | Réseau de transport de la Capitale | Bus |
| Winnipeg | 778,489 | 343,365 | 147.0 | Winnipeg Transit | Bus |
| London | 494,069 | 199,090 | 185.6 | London Transit Commission | Bus |
| Halifax | 403,390 | 180,860 | 73.4 | Halifax Transit | Bus |

Source: 2016 Canadian Census.

travel time thresholds ranging between 5 and 55 min for smaller regions (Quebec City, London, Halifax) and 15 from 5 to 75 min for the rest of the studied regions.

To compute gravity-based accessibility to jobs in the eight studied regions, we used non-linear least square methods that iteratively refined the model fit by approximating it to the linear regression. Using this approach, decay functions that describe the decline in accessible employment with the increase in travel time were estimated in the stats package (R Core Team, 2013) using R statistical software. As described above, we used GTFS data obtained for each region to estimate the transit travel time using r5r package. While for the motor vehicle congested travel times were procured using a Google API. Three functional forms were considered in the estimation of impendence function coefficient $\beta$: Negative Exponential (both for decay-probability density function (PDF) and decay-cumulative density function (CDF)) as expressed in eq. (3), Gaussian (Siddiq and Taylor, 2021), and Log-Logistic (Páez et al., 2012) decay-cumulative density functions. It should also be noted that we tested the performance of the 0.01 coefficient in a negative exponential decay function as it is often used in instances when data on travel patterns are absent (Santana Palacios and El-Geneidy, 2022). Due to its poor performance compared to other coefficients estimated from the data, it was retained from the final reporting.

$$f(C_{ij}) = e^{\beta / C_{ij}} \tag{3}$$

$$f(C_{ij}) = e^{\beta / C_{ij}^2} \tag{4}$$

$$f(C_{ij}) = \frac{1}{1 + \left(\frac{C_{ij}}{median(C)}\right)^{\beta}} \tag{5}$$

Probability distribution curves were generated from the normalized probability of a trip taking place within one of the time bins ranging from 5 to 100 min. The probabilities for each time bin were calculated as a ratio of the trips within a certain time threshold and the total number of trips in the respective metropolitan region. These probabilities were then divided by the maximum probability from all time bins to get the normalized values that increase from zero to one.

For the inverse cumulative probability distribution, we calculated the probability of the longest trip in each time period. The ratio of the trips in a time period to the total number of trips in the region informed the creation of the cumulative probability distribution, where each value was divided by the product of their cumulative sum. These estimates were then subtracted from one to obtain the inverse.

Finally, to assess the relationship between each pair of four gravity-based and cumulative accessibility measures we used the Pearson correlation coefficient for transit and motor vehicle travel in every metropolitan region for all workers. Obtained correlation coefficients were tested for statistical significance and corroborated at the 99% confidence interval. The validity of the observed trends was then confirmed with the repetition of the analysis for low and non-low-income groups with subsequent validation for statistical significance.

## 4. Results

Using travel time data and information on jobs we fitted four curves to obtain decay factors for gravity-based accessibility metrics for every metropolitan region and both modes considered in this study. For the purpose of brevity, we display the results of this step only for the largest and smallest CMAs in our study group – Toronto and Halifax – in Fig. 2. Decay parameters estimated for all regions are presented in Table 2. As Fig. 2 shows, despite its common use in the existing literature (El-Geneidy and Levinson, 2006), the Negative Exponential PDF offers the least satisfactory fit for our data. At the same time, the remaining three approaches perform at a decent level of accuracy in approximating the travel behavior captured by the Statistics Canada flows data used in this study. This can be explained by the fact that inverse cumulative distribution better satisfies Ingram's criteria (Ingram, 1971) for accessibility measurement by being relatively flat-topped at the origin, descending smoothly from the plateau, as well as approaching zero at the extremely large values. Among the three inverse cumulative distributions, Negative Exponential CDF offers the least satisfactory fit that varies from 0.78 to 0.93 depending on the mode and region, while the fit is almost perfect for Gaussian and Log-Logistic CDF. This goes in line with existing literature, as previous studies have indicated Gaussian and Log-Logistic CDF to reflect actual travel patterns more accurately (Bauer and Groneberg, 2016; Hilbers and Verroen, 1993; Geurs and van Eck, 2003), with Geurs and van Eck (Geurs and van Eck, 2003) arguing that Log-Logistic specification has less sensitivity toward small variations in travel time and is close to one for short distances while hovering just above zero for extremely long commutes.

Figs. 3 and 4 display the Pearson Correlation Tests between multiple job accessibility indexes by public transport and motor vehicle. All correlation estimates discussed in this section are statistically significant at the 99-confidence level. For every region, we display the correlation between the four gravity-based cumulative opportunity indexes estimated using the decay parameters previously described with cumulative accessibility measures calculated at multiple commute time thresholds for each region. Cumulative opportunities by transit were estimated using commute time thresholds ranging from 5 to 120 min. Commute time thresholds employed to estimate cumulative opportunity accessibility indexes by automobile ranged from 5 to 55 min in the three smaller regions (Quebec City, London, and Halifax) and from 5 to 75 min in the remaining ones. For every region, we also include the median, mean, and one standard deviation from the mean regional commute time. These benchmarks, unique for every region, allow us to establish the framework for comparison and provide guidance for metropolitan planning organizations and local public transit agencies interested in adopting accessibility as a regional performance measure.

### 4.1. Public transport accessibility to all jobs

Fig. 3 provides evidence of how sensitive the correlation coefficient between accessibility measures to all jobs by transit is to the commute time threshold. Across all eight regions, the correlation factor increases as the commute time threshold used to estimate job accessibility by

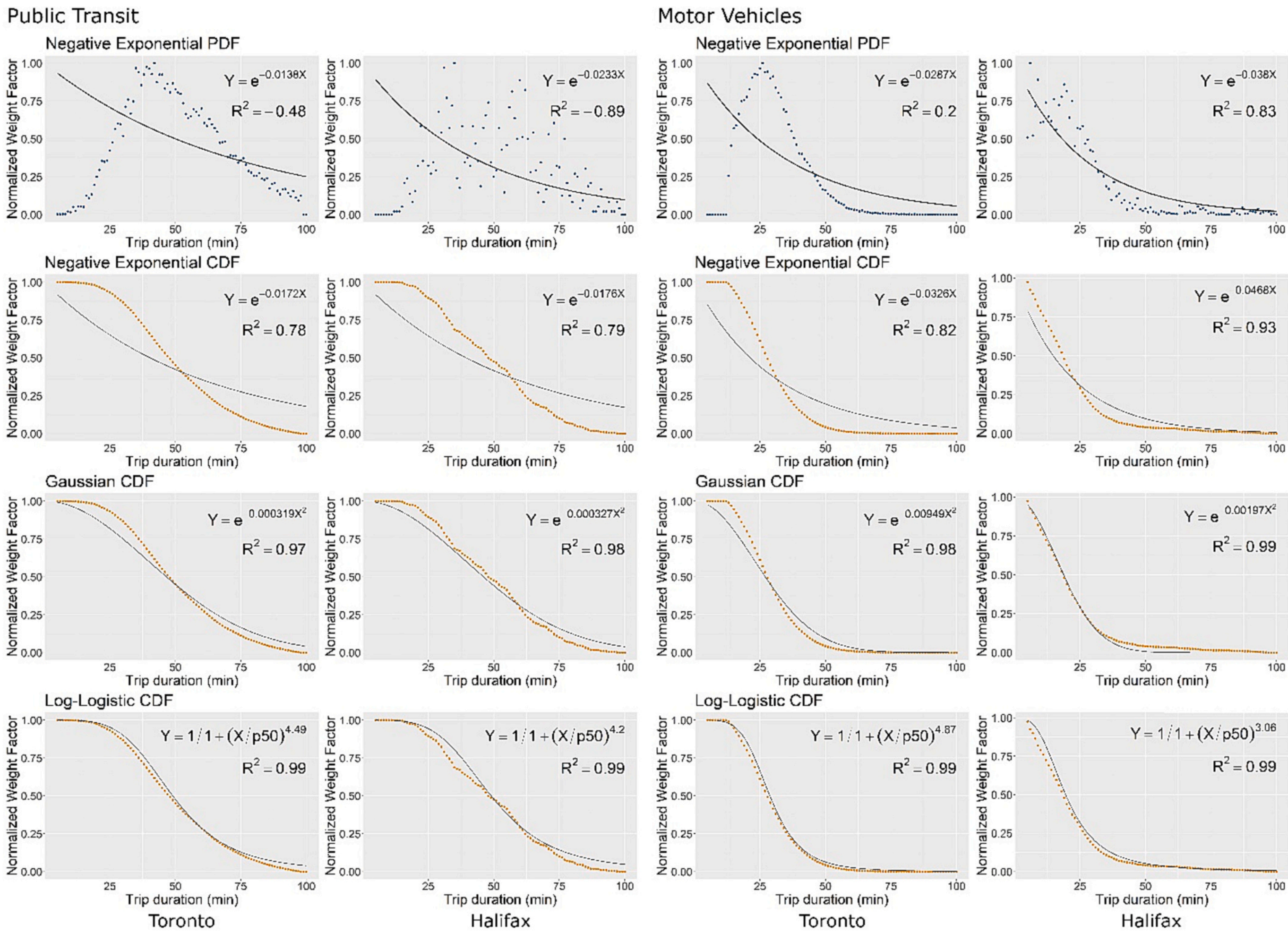


**Fig. 2.** Calculated weights, commute-time decay curves and parameters in Toronto and Halifax.

**Table 2**
Estimated distance decay function parameters and $R^2$ values.

| Region | Mode | Neg Exp PDF | | Neg Exp CDF | | Gaussian CDF | | Log-Logistic CDF | |
|---|---|---|---|---|---|---|---|---|---|
| | | β | $R^2$ | β | $R^2$ | β | $R^2$ | β | $R^2$ |
| Toronto | Transit | −0.0138 | −0.48 | −0.0172 | 0.78 | −0.0003 | 0.97 | 4.4856 | 0.99 |
| | Motor Vehicles | −0.0287 | 0.2 | −0.0326 | 0.82 | −0.0009 | 0.98 | 4.8662 | 0.99 |
| Montreal | Transit | −0.015 | −0.41 | −0.0181 | 0.79 | −0.0004 | 0.98 | 4.1168 | 0.99 |
| | Motor Vehicles | −0.0294 | 0.39 | −0.0372 | 0.84 | −0.0012 | 0.98 | 4.5590 | 0.99 |
| Vancouver | Transit | −0.0165 | −0.37 | −0.0190 | 0.81 | −0.0004 | 0.98 | 4.1339 | 0.99 |
| | Motor Vehicles | −0.0269 | 0.44 | −0.0365 | 0.85 | −0.0012 | 0.99 | 4.0718 | 0.99 |
| Edmonton | Transit | −0.0193 | −1.03 | −0.0158 | 0.75 | −0.0003 | 0.96 | 5.0643 | 0.99 |
| | Motor Vehicles | −0.0324 | 0.46 | −0.0417 | 0.85 | −0.0015 | 0.99 | 4.4193 | 0.99 |
| Quebec City | Transit | −0.0137 | −0.44 | −0.0174 | 0.80 | −0.0003 | 0.98 | 4.1947 | 0.99 |
| | Motor Vehicles | −0.0443 | 0.46 | −0.0483 | 0.85 | −0.0021 | 0.98 | 4.3722 | 0.99 |
| Winnipeg | Transit | −0.0238 | −0.74 | −0.0194 | 0.78 | −0.0004 | 0.97 | 4.6869 | 0.99 |
| | Motor Vehicles | −0.0332 | 0.54 | −0.0447 | 0.86 | −0.0017 | 0.99 | 4.2937 | 0.99 |
| London | Transit | −0.0263 | −0.88 | −0.0184 | 0.78 | −0.0004 | 0.97 | 4.6801 | 0.99 |
| | Motor Vehicles | −0.0434 | 0.46 | −0.0480 | 0.46 | −0.0020 | 0.99 | 4.4211 | 0.99 |
| Halifax | Transit | −0.0232 | −0.89 | −0.0176 | 0.79 | −0.0003 | 0.98 | 4.2019 | 0.99 |
| | Motor Vehicles | −0.0380 | 0.83 | −0.0467 | 0.93 | −0.0020 | 0.99 | 3.0633 | 0.99 |

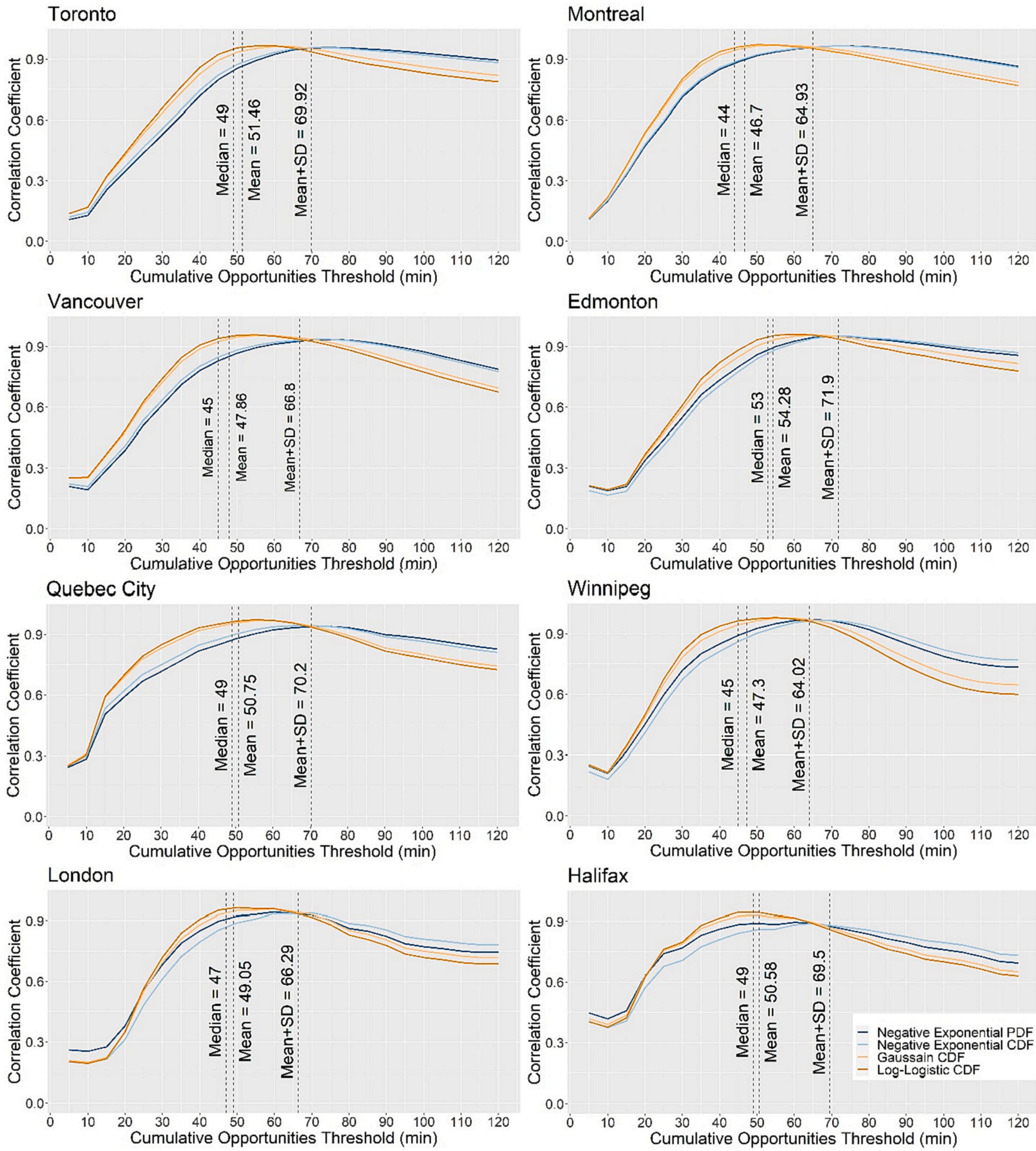


**Fig. 3.** Correlation coefficient between gravity- and cumulative opportunity-based accessibility to jobs by public transport.

transit using a cumulative opportunities approach rapidly reaches its maximum possible value, and then slightly decreases once such maximum is achieved. Our findings indicate that the slope of the curve, or the speed at which the correlation coefficient increases before reaching its maximum value, is subject to the distance-decay function used to estimate gravity-based job accessibility. The maximum correlation value is reached faster when comparing cumulative opportunities accessibility indexes with ones estimated using a gravity-based approach assuming a Log-Logistic decay cumulative density function than assuming any of the two Negative Exponential functions tested. In almost all regions, the maximum correlation coefficient is reached between the median and one standard deviation from the mean, never surpassing a value of 0.98.

Our accessibility-by-transit analyses also indicate that the correlation coefficient is consistently above 0.90 when the commute time threshold approximates the regional mean travel time value and when gravity measures are estimated using a Log-Logistic or Gaussian decay function. The correlation coefficient hovers around 0.95 at a mean regional commute time in Winnipeg and London, and approximately 0.90 in Toronto, Vancouver, and Edmonton, with other regions'

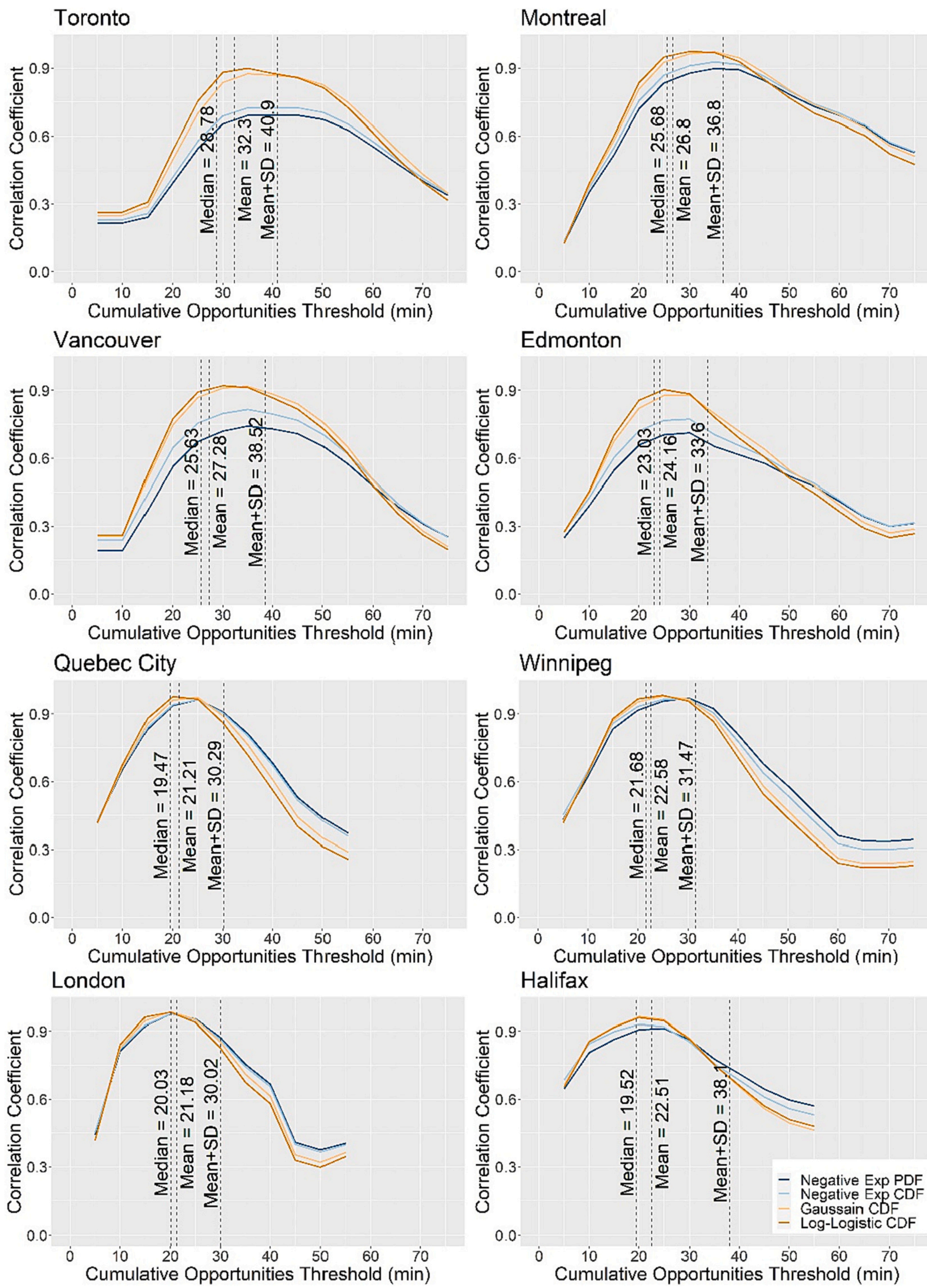


**Fig. 4.** Correlation coefficient between gravity- and cumulative opportunity-based accessibility measures to jobs by motor vehicle.

coefficients being somewhere in between. The correlation coefficient is always higher at this benchmark when assuming a Log-Logistic decay function than a Gaussian decay function. Correlation coefficients decrease in some regions more than others when cumulative opportunity measures are compared with gravity-based ones estimated using any of the two Negative Exponential decay functions reaching values as low as 0.85 in Halifax.

### 4.2. Motor vehicle accessibility to all jobs

Fig. 4 presents how the correlation between gravity-based and cumulative opportunity accessibility to jobs by automobile changes for different commute time thresholds. Like in our previous analysis of job accessibility by public transit, the correlation coefficients between cumulative opportunities accessibility measures and gravity-based measures rapidly reach a maximum, however, such value decreases faster than in our analysis of transit once the maximum is reached. The correlation coefficients between cumulative opportunities-based accessibility measures and gravity-based indexes estimated using Log-Logistic and Gaussian decay functions consistently resulted in higher values than when assuming a Negative Exponential distribution when evaluated at the regional commute time for motor vehicles as well.

The maximum correlation coefficient found for the job accessibility comparisons at the regional commute time mean benchmark for motor vehicles is also surprisingly high. The correlation coefficient for job-accessibility by motor vehicle comparisons hovers around 0.95 in Montreal, Quebec City, Winnipeg, and London, and approximately 0.90 in Toronto, Vancouver, and Edmonton, with other regions' coefficients being somewhere in between when comparing cumulative opportunities with Log-Logistic or Gaussian-gravity-based measures. For some regions like Quebec City, Winnipeg, and London the measures derived using a Negative Exponential function correlate with cumulative accessibility as strongly as the other two measures discussed above.

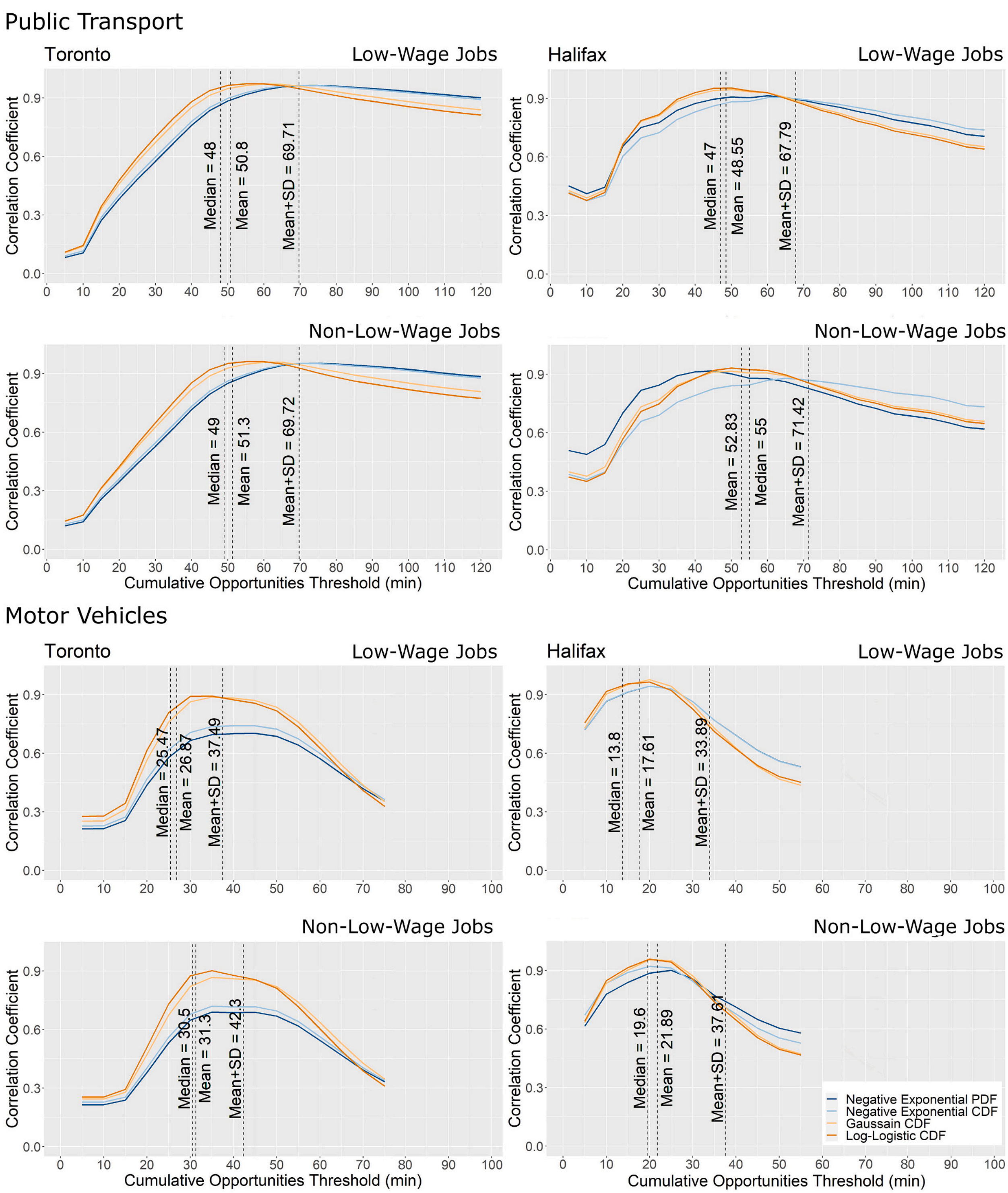


**Fig. 5.** Correlation coefficient between gravity- and cumulative opportunity-based accessibility measures to low-wage and non-low-wage jobs by different modes for the largest and the smallest regions in the study.

### 4.3. Public transport and motor vehicle accessibility to low-wage and non-low-wage jobs

Our final analysis tests the correlation between cumulative opportunities and gravity-based access jobs for low- and non-low-wage jobs by transit and motor vehicles. It is possible that accessibility to low-wage jobs might not be well-captured by cumulative measures due to the existing low level of transit service, or the potential lack of representativeness for such employment in the sample. This step aimed to ensure that the findings are not sensitive to income types and that a more nuanced relationship between cumulative and gravity-based measures is not hidden when aggregate data is analyzed. Fig. 5 shows correlation coefficients for Toronto and Halifax by job type and mode. The best-performing decay functions reach a correlation coefficient of approximately 0.90 when the threshold to calculate cumulative opportunities accessibility is set to the average commute time for the type of opportunities in question in Toronto and Halifax, as well as in the other six regions analyzed. This latter evidence is also consistent with our first analyses and suggests that estimating access to low- and non-low-wage jobs by public transport or motorized vehicle using the cumulative opportunities approach highly approximates the best-performing gravity-based access measures promoted in transport planning. Moreover, these findings are consistent with correlation coefficients at the mean commute time for all other regions.

## 5. Conclusions

This study compared the results of four gravity-based accessibility measures estimated using decay-probability density, decay-cumulative density, Gaussian, and Log-Logistic decay-cumulative density functions, and a cumulative accessibility measure. Our findings showed a strong correlation between the comparison pairs, especially for cumulative opportunities measures calculated at the mean travel time by public transport and motor vehicles, indicating that data-hungry and complex gravity-based accessibility measures are not always substantially better than cumulative opportunity accessibility measures and can be replaced by simple and easy to communicate cumulative opportunities measures calculated at the mean travel time in each region, regardless of the region's size or the mode used (car or public transport).

Our findings are also robust to income class, which we tested by comparing outcomes from low and non-low-wage jobs accessibility. We found that a coefficient of approximately 0.90 is reached when the threshold to calculate cumulative opportunities accessibility is set to the average commute time for both low- and non-low-wage jobs accessibility analyses by transit and motor vehicles. This latter finding is also indicative that employing cumulative opportunity accessibility measures would be suitable for equity analyses where jobs are matched with population groups by wage.

This paper provides empirical evidence that using cumulative opportunities measures, with the mean travel time observed in the region can substitute more complex gravity-based measures when evaluating transport and land use interactions in Canadian cities, as well as to advance the equitable distribution of transport system benefits. Several research avenues can be explored building on the findings of this paper. Despite the reliably high level of correlation between the cumulative and gravity-based measures, factors that affect the remaining variation could be further investigated, as well as the spatial distribution of the areas where the correlation goes down. However, it should be noted that our preliminary spatial analysis did not identify any patterns in the spatial distribution of the areas where discrepancy between cumulative and best-performing Log-Logistic accessibility exist. While it is important to identify factors that cause additional variation between cumulative and gravity-based measures, this spatial analysis confirmed that there should be no concern regarding the overall reliability of the findings of this study. On the other hand, future research should also assess whether our findings hold in other contexts, including cities in the Global South. Finally, it is worth testing whether findings from this paper are generalizable to active transportation modes, travel behavior for discretionary trip purposes, and other population groups segmentation variables such as gender and age. Despite the many questions this paper opens, our findings provide a step toward simplifying the adoption of accessibility as a fundamental transport and land-use performance metric in planning practice.

## Author statement

The authors confirm their contribution to the paper as follows: Conceptualization: Ahmed El-Geneidy, Manuel Santana Palacios, Bogdan Kapatsila, and Emily Grisé; Data curation: Bogdan Kapatsila; Formal analysis: Bogdan Kapatsila, Ahmed El-Geneidy, Manuel Santana Palacios, and Emily Grisé; Writing: Bogdan Kapatsila, Ahmed El-Geneidy, Emily Grisé, and Manuel Santana Palacios. All authors reviewed the results and approved the final version of the manuscript.

## Data availability

Data will be made available on request.

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