

# Introducing spatial availability, a singly-constrained competitive-access accessibility measure

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## Abstract

Accessibility measures are widely used in transportation, urban and healthcare planning, among other applications. These measures are weighted sums of the opportunities that can be reached given the cost of movement and are interpreted to represent the potential for spatial interaction. Though these measures are useful in understanding spatial structure, their methodologies count available opportunities multiple times. This leads to interpretability issues, as noted in recent research on balanced floating catchment areas (BFCA) and competitive measures of accessibility. In this paper, we respond to the limitations of the accessibility measure by proposing a new measure of *spatial availability* which is calculated by imposing a single constraint on the conventional gravity-based accessibility. Similar to the gravity model from which spatial availability is derived, a single constraint ensures that the marginals at the destination are met and thus the number of opportunities are preserved. Through examples, we detail the formulation of the proposed measure. Further, we use data from the 2016 Transportation Tomorrow Survey of the Greater Golden Horseshoe area in southern Ontario, Canada, to contrast how the conventional accessibility measure tends to overestimate and underestimate the number of jobs *available* to workers. We conclude with some discussion of the possible uses of spatial availability and argue that, compared to conventional measures of accessibility, it can offer a more meaningful and interpretable measure of opportunity access. All data and code used in this research are openly available.

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## Introduction

The concept of accessibility is a relatively simple one whose appeal derives from combining the spatial distribution of opportunities and the cost of reaching them (Hansen, 1959). Numerous methods for calculating accessibility have been proposed that can be broadly organized into infrastructure-, place-, person-, and utility-based measures (Geurs and van Wee, 2004). Of these, the place-based family of measures is arguably the most common, capturing the number of opportunities reachable from an origin using the transportation network. A common type of place-based measure is the gravity measure of accessibility that captures the potential for interaction; since it was first developed by Hansen (1959) it has been widely adopted by literature in many forms (e.g., Cervero et al., 2002; Geurs and van Wee, 2004; Handy and Niemeier, 1997; Levinson, 1998; Paez, 2004).

Accessibility analysis is employed in transportation, geography, public health, and many other areas, particularly as mobility-based planning is de-emphasized in favor of access-oriented planning (Deboosere et al., 2018; Handy, 2020; Proffitt et al., 2017; Yan, 2021). However, while measures of accessibility are excellent indicators of the intersection between urban structure and transportation infrastructure, their interpretability has been criticized in the past. Previous research has highlighted how the weighting of opportunities using an impedance function can make gravity measures more difficult for planners and policymakers to interpret compared to simpler cumulative opportunity measures (Geurs and van Wee, 2004; Miller, 2018). Moreover, because place-based measures are sensitive to the number of opportunities and the size of the opportunity-seeking population (e.g., a large city has more nearby jobs and more job-seekers than a smaller city), raw values cannot be easily compared across study areas (Allen and Farber, 2019).

For this reason, place-based intra- and inter-regional comparisons of accessibility are challenging to interpret. While gravity-based accessibility indicators are spatially smoothed estimates of the total number of opportunities, the meaning of their magnitudes is unclear. This is evident when we consider the “total accessibility” in the region, a quantity that is not particularly meaningful since it is not constrained to resemble, let alone match, the number of opportunities available. Furthermore, while accessibility depends on the number of opportunities weighted by the travel costs associated with reaching them, the calculated accessibilities are not sensitive to the demand for those opportunities at the origins. Put another way, traditional measures of place-based accessibility do not capture the competition for opportunities. This shortcoming (Geurs and van Wee, 2004) is particularly acute when opportunities are “non-divisible” in the sense that, once taken they are no longer available to other members of the population. Examples of indivisible opportunities include jobs (when a person takes up a job, the same job cannot be taken by anyone else) and placements at schools (once a student takes a seat at a school, that particular opportunity is no longer available for another student). From a different perspective, employers may see workers as opportunities, so when a worker takes a job, this particular

individual is no longer in the available pool of candidates for hiring.

To remedy these issues, researchers have proposed several different approaches for calculating competitive accessibility values. On the one hand, this includes several approaches that first normalize the number of opportunities available at a destination by the demand for them from the origin zones and, second, sum the demand-corrected opportunities which can be reached from the origins (e.g. Joseph and Bantock, 1984; Shen, 1998). These advances were popularized in the family of two-step floating catchment area (FCA) methods (Luo and Wang, 2003) that have found widespread adoption for calculating competitive accessibility to a variety of opportunities such as healthcare, education, and food access (B. Y. Chen et al., 2020; Chen, 2019; Z. Chen et al., 2020; Yang et al., 2006; Ye et al., 2018). In principle, floating catchments purport to account for competition/congestion effects, although in practice several researchers (e.g., Delamater, 2013; Wan et al., 2012) have found that they tend to over-estimate the level of demand and/or service. The underlying issue, as demonstrated by Paez et al. (2019), is the multiple counting of both population and level of service, which can lead to biased estimates if not corrected.

A second approach is to impose constraints on the gravity model to ensure flows between zones are equal to the observed totals. Based on Wilson's (1971) entropy-derived gravity model, researchers can incorporate constraints to ensure that the modeled flows match some known quantities in the data inputs. In this way, models can be singly-constrained to match the row- or column-marginals (the trips produced or attracted, respectively), whereas a doubly-constrained model is designed to match both marginals. Allen and Farber (2019) recently incorporated a version of the doubly-constrained gravity model within the floating catchment area approach to calculate competitive accessibility to employment using transit across eight cities in Canada. But while such a model can account for competition, the mutual dependence of the balancing factors in a doubly-constrained model means they must be iteratively calculated which makes them more computationally-intensive. Furthermore, the double constraint means that the sum of opportunity-seekers and the sum of opportunities must match, which is not necessarily true in every potential use case (e.g., there might be more people searching for work than jobs exist in a region).

In this paper we propose an alternative approach to measuring competitive accessibility. We call it a measure of **spatial availability**, and it aims to capture the number of indivisible opportunities that are not only *accessible* but also *available* to the opportunity-seeking population, in the sense that they have not been claimed by competing seekers of the opportunity. As we will show, spatial availability is a singly-constrained measure of accessibility. By allocating opportunities in a proportional way based on demand and distance, this method avoids the issues that result from multiple counting of opportunities in conventional accessibility analysis. The method returns meaningful accessibility estimates that correspond to the rate of available opportunities per opportunity-seeking population. Moreover, the method also returns a benchmark value for the region under study against which results for individual origins can be compared both inter- and intra-regionally.

In the following sections we will describe and illustrate this new measure using a synthetic example and an empirical example. First, we will describe the analytical framework of the measure. Second, we calculate the spatial availability using data from the Transportation Tomorrow Survey (TTS) home-to-work commute in 2016 for the Greater Golden Horse (GGH) area in Ontario, Canada, and discuss differences with conventional unconstrained accessibility analysis. Third, we return to the synthetic example and calculate spatial availability for two additional use-cases: one use case for jobs from the perspective of the population considering catchment restrictions and another use case for workers from the perspective of employers. Finally, we conclude by discussing the advantages of the spatial availability measure and the breadth of potential uses.

In the spirit of openness of research in the spatial sciences (Brunsdon and Comber, 2021; Páez, 2021) this paper has a companion open data product (Arribas-Bel et al., 2021), and all code will be available for replicability and reproducibility purposes.

## Background

Most accessibility measures (excluding utility-based measures) are derived from the gravity model and follow the formulation shown in Equation (1). The limitations associated with this conventional and widely used measure, namely issues in interpretation and spatial bias, are the motivation for the proposed *spatial availability* measure. We begin this section by conceptually demonstrating the issues associated with the conventional accessibility measure using a simple synthetic example. We introduce the analytical framework of spatial availability and highlight the differences between the measures to demonstrate how the proposed method improves the interpretability of opportunity access.

$$A_i = \sum_{j=1}^J O_j f(c_{ij}) \quad (1)$$

where:

- $A$  is accessibility.
- $i$  is a set of origin locations.
- $j$  is a set of destination locations.
- $O_j$  is the number of opportunities at location  $j$ . These are opportunities for activity and add some sort of *supply* to the area;
- $c_{ij}$  is a measure of the cost of moving between  $i$  and  $j$
- $f(\cdot)$  is an impedance function of  $c_{ij}$ ; it can take the form of any monotonically decreasing function chosen based on positive or normative criteria (Paez et al., 2012).

As formally defined, accessibility  $A_i$  is the weighted sum of opportunities that can be reached from location  $i$ , given the cost of travel  $c_{ij}$ . Summing the opportunities in the neighborhood of  $i$ , as determined by the impedance function

Table 1: Description of synthetic example

ID	Number	Location	Type
E1	750	jobs	
E2	2250	jobs	
E3	1500	jobs	
P1	260	population	
P2	255	population	
P3	510	population	
P4	495	population	
P5	1020	population	
P6	490	population	
P7	980	population	
P8	260	population	
P9	255	population	

$f(\cdot)$ , provides estimates of the number of opportunities that can be reached from  $i$  at a certain cost. The type of accessibility can be modified depending on the impedance function; for example, the measure could be cumulative opportunities (if  $f(\cdot)$  is a binary or indicator function, e.g., El-Geneidy et al., 2016; Geurs and van Wee, 2004; Qi et al., 2018; Rosik et al., 2021) or a gravity measure using an impedance function modeled after any monotonically decreasing function (e.g., Gaussian, inverse power, negative exponential, or log-normal, among others: see, *inter alia*, Kwan, 1998; Li et al., 2020; Reggiani et al., 2011; Vale and Pereira, 2017). In practice, accessibility indicators derived from many cumulative and gravity formulations tend to be highly correlated with one another (Higgins, 2019; Kwan, 1998; Santana Palacios and El-Geneidy, 2022).

#### Introducing the synthetic example

The setup for our synthetic example is a system with three employment centers and nine population centers, as summarized in Table 1. Accessibility to jobs at each population center is calculated using the accessibility measure  $A_i$  in Equation (1). In this simple example, we use the straight line distance between the population and jobs for  $c_{ij}$  and a negative exponential function with  $\beta = 0.0015$ . As noted,  $A_i$  represents the number of jobs (i.e., opportunities) that can be reached from each population center given the estimated cost as depicted in Figure 1.

Figure 1 shows the locations of the three employment centers (black circles), where the size of the symbol is in proportion to the number of jobs at each location. We also see nine population centers (triangles), where the size of the symbol is proportional to the accessibility ( $A_i$ ) to jobs. The accessibility values illustrate the following:

- Population centers (triangles) in the middle of the plot are relatively close to all three employment centers and thus have the highest levels of job

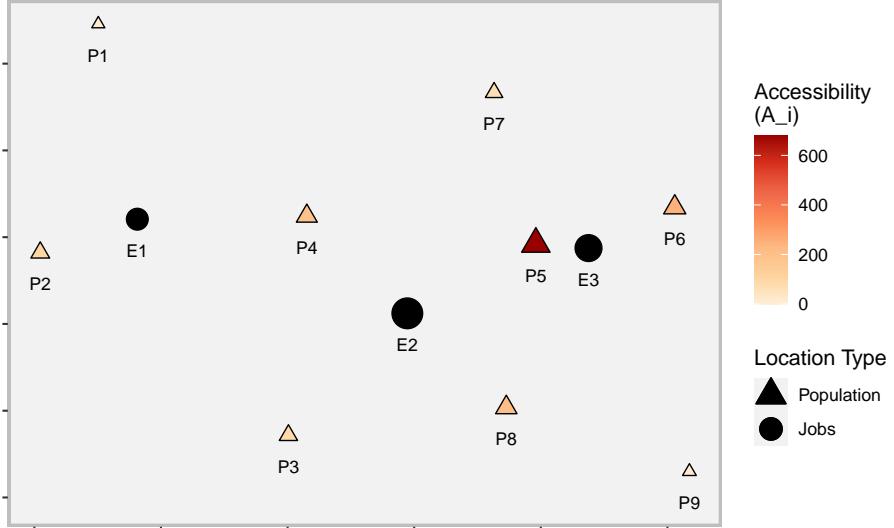


Figure 1: Accessibility of jobs from population centers for the simple synthetic example

accessibility. Population center P5 is relatively central and close to all employment centers, and it is the closest population to the second largest employment center in the region. Unsurprisingly, this population center has the highest accessibility (680.64);

- Population centers (triangles) near the left edge of the map (only in proximity to the small employment center) have the lowest levels of job accessibility. Population center P1 is quite peripheral and the closest employment center is also the smallest one. Consequently, it has the lowest accessibility with  $A_i = 17.12$ );

#### *The effect of competition for opportunities*

Accessibility measures are excellent indicators of the intersection between urban structure and transportation infrastructure (Kwan, 1998; Reggiani et al., 2011; Shi et al., 2020). However, beyond enabling comparisons of relative values they are not highly interpretable on their own (Miller, 2018). For instance, from Figure 1, P1 has lower accessibility than P5 but despite the accessibility value for P1 being relatively low it is still better than zero. On the other hand, P5 has high accessibility, but is its accessibility excellent, good, or only fair? What does it *mean* for a location to have accessibility to so many jobs?

To address this interpretability issue, previous research has aimed to index and normalize values on a per demand-population basis (e.g., Barboza et al., 2021; Pereira et al., 2019; Wang et al., 2021). However, as recent research on

accessibility discusses (see for instance Allen and Farber, 2019; Paez et al., 2019), these steps do not address the bias introduced through the uneven multiple-counting of opportunities and/or population. This is similar to the congestion effect that floating catchment area methods aim to address, although they do not necessarily solve the issue completely (see Paez et al., 2019). The underlying issue arises as a result of the assumption that for conventional accessibility  $A_i$  all opportunities are *available* to anyone from any origin  $i = 1, \dots, n$  who can reach them: in other words, they are assumed to be infinitely divisible and non-competitive. This results in every opportunity entering the weighted sum once for every origin  $i$  that can reach it. Put another way, if a densely populated population center pops up next to P5 this center too will have a high accessibility score since  $A_i$  does not consider competition of opportunities from neighbouring population centers. Neglecting to constrain opportunity counts (i.e., single-constraint) in addition to obscuring the interpretability of accessibility can also bias results in two ways:

- 1) Demand centers in the less dense outer limits of the urban core may be assigned disproportionately *high* accessibility values. These periphery areas are traditionally located in proximity to more dense urban demand centers and large urban opportunity centers and thus may have low travel cost to these large opportunity centers. Accessibility  $A_i$  does not consider opportunity-constraints and, as such, these periphery demand centers benefit from the high accessibility to opportunities without competition considerations from their more dense and more centrally located neighbours.
- 2) Remote areas which are still within the region of the analysis and have regionally-relative low demand centers, opportunity centers, and travel costs to opportunity centers, are assigned disproportionately *low* accessibility values. These more remote areas may be sufficiently supplied with opportunities proportionate to their demand but this relationship is obscured by the artificially high accessibility awarded to demand- and opportunity-rich areas in which competition disproportionately occurs.

The spatially uneven multiple-counting of opportunities (i.e., the competition effect) make it difficult to interpret resulting accessibility estimates. Recent accessibility measures which seek to improve interpretability are either vulnerable to this impact or require heroic assumptions. As previously mentioned, the floating catchment areas (FCA) method increases interpretability by purporting to account for competition, however, as discussed by Paez et al. (2019), FCA methods are vulnerable to a similar multiple-counting effect. On this same note, the doubly-constrained gravity model proposed by Allen and Farber (2019) which is based on the FCA method, accounts for competition, but requires that the magnitude of demand matches the opportunities or be re-scaled to match. As already noted, this assumption is not always realistic for many opportunity types such as in the case of job seekers and jobs.

To address the competition effect and to more accurately treat non-divisible opportunities, we propose a singly-constrained gravity measure called **spatial availability**. This measure seeks to address the following questions for an

individual at a specific demand center: “*many opportunities are accessible, but the same opportunities are also accessible to my (possibly) numerous neighbors... what does a high accessibility actually mean to me?*” and “*few opportunities are accessible to me but I am located in a remote area with proportionally few neighbors relative to the region... what does low accessibility mean to me?*”. Beyond the individual, spatial availability, can also be used as-is to evaluate the *spatial mismatch* of accessible opportunities and demand-seeking population within regions and between regions.

### The analytical framework of spatial availability

Formally, spatial availability  $V_{ij}$  is defined by the number of opportunities  $O$  that are proportionally allocated based on a population allocation factor  $F_{ij}^p$  and cost of travel allocation factor  $F_{ij}^c$  for all origins  $i$  to all destinations  $j$  as detailed in Equation (2). In line with the tradition of gravity modeling, the proposed framework distinguishes between opportunities at a destination and demand for opportunities at the origin.

$$V_{ij} = O_j \frac{F_{ij}^p \cdot F_{ij}^c}{\sum_{i=1}^K F_{ij}^p \cdot F_{ij}^c} \quad (2)$$

The terms in Equation 2 are as follows:

- $V_{ij}$  is spatial availability.
- $i$  is a set of origin locations in the region  $K$ .
- $j$  is a set of destination locations in the region  $K$ .
- $O_j$  is the number of opportunities at location  $j$  in the region  $K$ .
- $F_{ij}^p$  is the proportional allocation factor of the population in  $i$  relative to the population in region  $K$ .
- $F_{ij}^c$  is the proportional allocation factor of travel cost for  $i$  relative to the travel cost in region  $K$ ; it is a product of a monotonically decreasing (i.e., impedance) function associated with the cost of travel between  $i$  and  $j$ .

It is important to detail the role of the two proportional allocations factors in the calculation of spatial availability. We do this by first considering the population allocation factor  $F_{ij}^p$  followed by the role of the travel cost allocation factor  $F_{ij}^c$ ; finally we show how both allocation factors combine in the final general form of spatial availability  $V_{ij}$ . The calculation of spatial availability is introduced with a step-by-step example for two population centers ( $P_1$  and  $P_2$ ) in the role of demand (i.e., the number of individuals in the labour market who ‘demand’ employment) and one employment center ( $O_1$ ) in the role of opportunities.

#### *Population and travel cost allocation factors*

We begin with allocation based on demand by population; consider an employment center  $j$  with  $O_j^r$  jobs of type  $r$ . In the general case where there are  $K$  population centers in the region, we define the following factor:

$$F_{ij}^p = \frac{P_{i \in r}^\alpha}{\sum_{i=1}^K P_{i \in r}^\alpha} \quad (3)$$

The population allocation factor  $F_{ij}^p$  corresponds to the proportion of the population in origin  $i$  relative to the rest of the region's population centers  $K$ . On the right hand side of the equation, the numerator  $P_{i \in r}$  is the population at origin  $i$  that is eligible for and 'demands' jobs of type  $r$  (e.g., those with a certain level of training or in a designated age group). The summation in the denominator is over  $i = 1, \dots, K$ , the number of population at all origins  $i$  in the region  $K$ . To modulate the effect of demand by population in this factor we include an empirical parameter  $\alpha$  (i.e.,  $\alpha < 1$  places greater weight on smaller centres relative to larger ones while  $\alpha > 1$  achieves the opposite effect). This population allocation factor  $F_{ij}^p$  can now be used to proportionally allocate a share of the jobs at destination  $j$  to all origin pairs.

More broadly, since the factor  $F_{ij}^p$  is a proportion, when it is summed over  $i = 1, \dots, K$  it always equals to 1 (i.e.,  $\sum_i^K F_{ij}^p = 1$ ). This is notable since the share of jobs (the spatial availability based on population  $V_{ij}^p$ ) at each destination  $j$  allocated to (i.e., available to) each origin is equal to  $V_{ij}^p = O_j \cdot F_{ij}^p$  and since the sum of  $F_{ij}^p$  is equal to 1 it follows that  $\sum_{i=1}^I V_{ij}^p = O_j$ . In other words, the number of jobs across the region is preserved. The result is a proportional allocation of jobs (opportunities) to origins based on population demand.

To illustrate the population allocation factor, suppose that the employment center in the example has 300 jobs ( $O_1 = 300$ ), and that the two population centers have 240 and 120 people, respectively, ( $P_1 = 240$  and  $P_2 = 120$ ). For simplicity, assume that all the population in the region is eligible for these jobs, that is, that the entirety of the population is included in the set  $r$ . Also assume that  $\alpha = 1$ . The population allocation factors  $F_{ij}^p$  for the jobs at  $O_1$  for each population center  $P_1$  and  $P_2$  are as shown in Equation (4).

$$\begin{aligned} F_{1,1}^p &= \frac{P_1^\alpha}{P_1^\alpha + P_2^\alpha} = \frac{240}{240+120} = \frac{240}{360} \\ F_{2,1}^p &= \frac{P_2^\alpha}{P_1^\alpha + P_2^\alpha} = \frac{120}{240+120} = \frac{120}{360} \end{aligned} \quad (4)$$

These  $F_{ij}^p$  values can be used to find a *partial* spatial availability in which jobs are allocated proportionally to population; this partial spatial availability  $V_{ij}^p$  for each population center is calculated as follows in Equation (5).

$$\begin{aligned} V_{1,1}^p &= O_1 \cdot F_{1,1}^p = 300 \cdot \frac{240}{360} = 200 \\ V_{2,1}^p &= O_1 \cdot F_{2,1}^p = 300 \cdot \frac{120}{360} = 100 \end{aligned} \quad (5)$$

When using only the proportional allocation factor  $F_{ij}^p$  to calculate spatial availability (differentiated here by being defined as  $V_{ij}^p$  instead of  $V_{ij}$ ), proportionally more jobs are allocated to the bigger population center (i.e., 2 times more jobs as it is 2 times larger in population). We can also see that the sum of spatial availability for all population centers is equal to the sum of jobs, i.e., total opportunities are preserved.

Clearly, using only the proportional allocation factor  $F_{ij}^p$  to calculate spatial availability does not account for how far population centers  $P_1$  or  $P_2$  are from employment center  $O_1$ . It is the job of the second allocation factor  $F_{ij}^c$  to account for the friction of distance, as seen in Equation (6).

$$F_{ij}^c = \frac{f(c_{ij})}{\sum_{i=1}^K f(c_{ij})} \quad (6)$$

where  $c_{ij}$  is the cost (e.g., the distance, travel time, etc.) to reach employment center  $j$  from  $i$ , and  $f(\cdot)$  is an impedance function that depends on cost ( $c_{ij}$ ); in other words, this allocation factor  $F_{ij}^c$  serves to proportionally allocate more jobs to closer locations through an impedance function. To continue with the example, assume that the impedance function is a negative exponential function with  $\beta = 1$ . This parameter modulates the steepness of the impedance effect and is empirically determined in the case of positive accessibility, or set by the analyst to meet a preset condition in the case of normative accessibility (Paez et al., 2012). Also suppose that the distance from population center  $P_1$  to employment center  $O_1$  is 0.6 km, and the distance from population center  $P_2$  to employment center  $O_1$  is 0.3 km. The proportional allocation factor  $F_{ij}^p$  for the jobs at  $O_1$  for both population centers  $P_1$  and  $P_2$  is defined as follows in Equation (7).

$$\begin{aligned} F_{1,1}^c &= \frac{\exp(-\beta \cdot D_{1,1})}{\exp(-\beta \cdot D_{1,1}) + \exp(-\beta \cdot D_{2,1})} = \frac{\exp(-0.6)}{\exp(-0.6) + \exp(-0.3)} = 0.426 \\ F_{2,1}^c &= \frac{\exp(-\beta \cdot D_{2,1})}{\exp(-\beta \cdot D_{1,1}) + \exp(-\beta \cdot D_{2,1})} = \frac{\exp(-0.3)}{\exp(-0.6) + \exp(-0.3)} = 0.574 \end{aligned} \quad (7)$$

We can see that the proportional allocation factor for  $P_2$  is larger than  $P_1$  since the cost (i.e., distance) to  $O_1$  is lower. Using the travel cost proportional allocation factors  $F_{ij}^c$  as defined in Equation (7), we can calculate the spatial availability of jobs for each population center based only on  $F_{ij}^c$  and the jobs available at  $O_1$ , as shown in Equation (8).

$$\begin{aligned} V_{1,1}^c &= O_1 \cdot F_{1,1}^c = 300 \times 0.426 = 127.8 \\ V_{2,1}^c &= O_1 \cdot F_{2,1}^c = 300 \times 0.574 = 172.2 \end{aligned} \quad (8)$$

As seen above, spatial availability defined by  $F_{ij}^c$  only (i.e.,  $V_{ij}^c$ ) allocates a larger share of jobs to  $P_2$  since the population center is closer to  $O_1$ . However, as previously discussed,  $P_2$  has a smaller population than  $P_1$ , so  $P_1$  receives a larger share of jobs when spatial availability when it is defined by  $F_{ij}^p$  (i.e.,  $V_{ij}^p$ ). It is necessary to combine both population and travel cost factors to better reflect demand; these two components are in line with how demand is conventionally modelled in accessibility calculations which are re-scaled on a per demand-population basis or also consider competition (e.g., Allen and Farber, 2019; Barboza et al., 2021; Yang et al., 2006). Fortunately, since both  $F_{ij}^c$  and  $F_{ij}^p$  preserve the total number of opportunities (jobs) as they independently sum to 1, they can be combined multiplicatively to calculate the proposed spatial availability ( $V_{ij}$ ) which considers demand to be based on both population and travel cost.

### Putting spatial availability together

We can combine the proportional allocation factors by population  $F_{ij}^p$  and travel cost  $F_{ij}^c$  and calculate spatial availability  $V_{ij}$  as introduced in Equation (2) and repeated below:

$$V_{ij} = O_j \frac{F_{ij}^p \cdot F_{ij}^c}{\sum_{i=1}^K F_{ij}^p \cdot F_{ij}^c}$$

To complete the illustrative example of employment center  $O_1$  and population centers  $P_1$  and  $P_2$ , the resulting spatial availability  $V_{ij}$  is calculated for both population centers is calculated in Equation (9).

$$\begin{aligned} V_{1,1} &= O_1 \cdot \frac{F_{1,1}^p \cdot F_{1,1}^c}{F_{1,1}^p \cdot F_{1,1}^c + F_{2,1}^p \cdot F_{2,1}^c} = 300 \frac{\left(\frac{2}{3}\right)(0.426)}{\left(\frac{2}{3}\right)(0.426) + \left(\frac{1}{3}\right)(0.574)} = 179.4 \\ V_{2,1} &= O_1 \cdot \frac{F_{2,1}^p \cdot F_{2,1}^c}{F_{1,1}^p \cdot F_{1,1}^c + F_{ik}^p \cdot F_{ik}^c} = 300 \frac{\left(\frac{1}{3}\right)(0.574)}{\left(\frac{2}{3}\right)(0.426) + \left(\frac{1}{3}\right)(0.574)} = 120.6 \end{aligned} \quad (9)$$

In this example, fewer jobs are allocated to population center  $P_1$  compared to the allocation by population only, to account for the higher cost of reaching the employment center. On the other hand, distance alone allocated more jobs to the closest population center (i.e.,  $P_2$ ), but since it is smaller, it also gets a smaller share of the jobs overall. To reiterate, the sum of jobs at employment center  $O_1$  that are allocated to population centers  $P_1$  and  $P_2$  simultaneously based on *population-* and *travel cost* allocation factors are preserved (i.e.,  $V_{1,1} + V_{2,1} = O_1$ ).

In the common case that population centers have multiple destination opportunities  $j$ , spatial availability is simply the sum of Equation (2) for all opportunities  $J$  (i.e.,  $V_i = \sum_{j=1}^J V_{ij}$ ). The resulting value of  $V_i$  represents opportunities (e.g., jobs) that can be accessed from origin  $i$  and that are *not* allocated to any other competing origin:  $V_i$  is thus the weighted sum of available opportunities. When comparing  $V_i$  to the singly-constrained gravity model (see Wilson (1971)),  $V_i$  is the result of constraining  $A_i$  to match one of the marginals in the origin-destination table, the known total of opportunities.

Since the sum of opportunities is preserved in the procedures above, it is possible to calculate an interpretable measure of spatial availability per capita (lower-case  $v_i$ ) as shown in Equation (10).

$$v_i = \frac{V_i}{P_i} \quad (10)$$

To complete the illustrative example, the per capita spatial availability of jobs is calculated in Equation (11).

$$\begin{aligned} v_{1,1} &= \frac{V_{1,1}}{P_1} = \frac{179.4}{240} = 0.8 \\ v_{2,1} &= \frac{V_{2,1}}{P_2} = \frac{120.6}{120} = 1.0 \end{aligned} \quad (11)$$

We can see that since  $P_2$  is closer to  $O_1$  and has less competition (as it has a smaller population than  $P_1$ ),  $P_2$  benefits with a higher spatial availability of

jobs per job-seeking population. We can also compare these values to the overall ratio of jobs-to-population in this region of one job center and two population centers is  $300/(240 + 120) = 0.83$ .

### **Empirical example: spatial accessibility and availability of jobs in the GGH**

In this section we use population and employment data from the Golden Horseshoe Area (GGH). This is the largest metropolitan region in Canada and includes the cities of Toronto and Hamilton. We present two examples. The first demonstrates how accessibility broadly overestimates *job access* (relative to spatial availability) and particularly overestimates job access for areas in the less dense outer limits of the urban core. The second example demonstrates how accessibility underestimates job access for areas in the urban periphery. We first introduce the data used, then calibrate an impedance function, and finally discuss the results.

#### *Data*

Population and employment data are drawn from the 2016 Transportation Tomorrow Survey (TTS). This survey collects representative urban travel information from 20 municipalities contained within the GGH area in the southern part of Ontario, Canada (see Figure 2) (Data Management Group, 2018). The data set includes Traffic Analysis Zones (TAZ) ( $n=3,764$ ), the number of jobs ( $n=3,081,885$ ) and workers ( $n=3,446,957$ ) at each origin and destination.

To generate the travel cost for these trips, travel times between origins and destinations are calculated for car travel using the R package `r5r` (Rafael H. M. Pereira et al., 2021) with a street network retrieved from OpenStreetMap for the GGH area. A the 3 hr travel time threshold was selected as it captures 99% of population-employment pairs (see the travel times summarized in Figure 2). This method does not account for traffic congestion or modal split, which can be estimated through other means (e.g., Allen and Farber, 2021; Higgins et al., 2021). For simplicity, we carry on with the assumption that all trips are taken by car in uncongested travel conditions.

All data and data preparation steps are documented and can be freely explored in a companion open data product `TTS2016R`.

#### *Calibration of an impedance function*

In the synthetic example introduced in a preceding section, a negative exponential function with an arbitrary parameter was used. For the empirical example, we calibrate an impedance function on the trip length distribution (TLD) of commute trips. Briefly, a TLD represents the proportion of trips that are taken at a specific travel cost (e.g., travel time); this distribution is commonly used to derive impedance functions in accessibility research (Batista et al., 2019; Horbachov and Svirchynskyi, 2018).

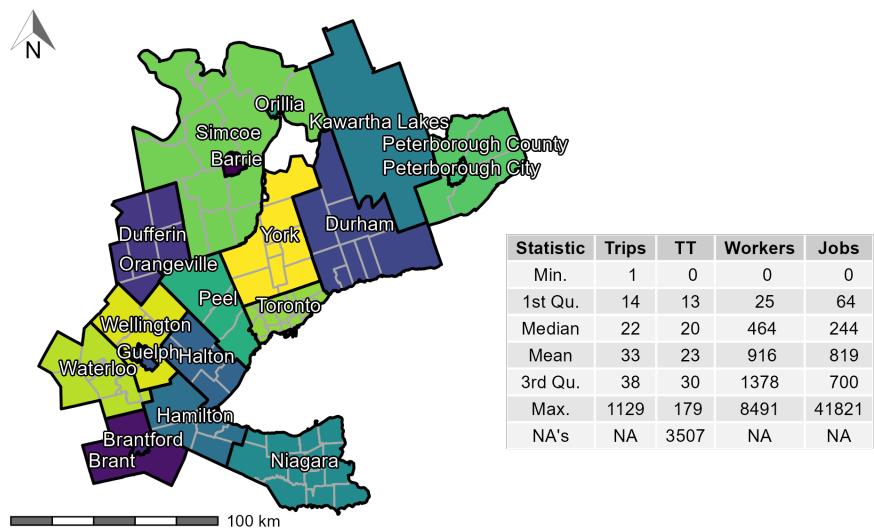


Figure 2: TTS 2016 study area within the GGH in Ontario, Canada along with the descriptive statistics of the trips, calculated origin-destination car travel time (TT), workers per TAZ, and jobs per TAZ. Contains 20 regions (black boundaries) and sub-regions (dark gray boundaries).

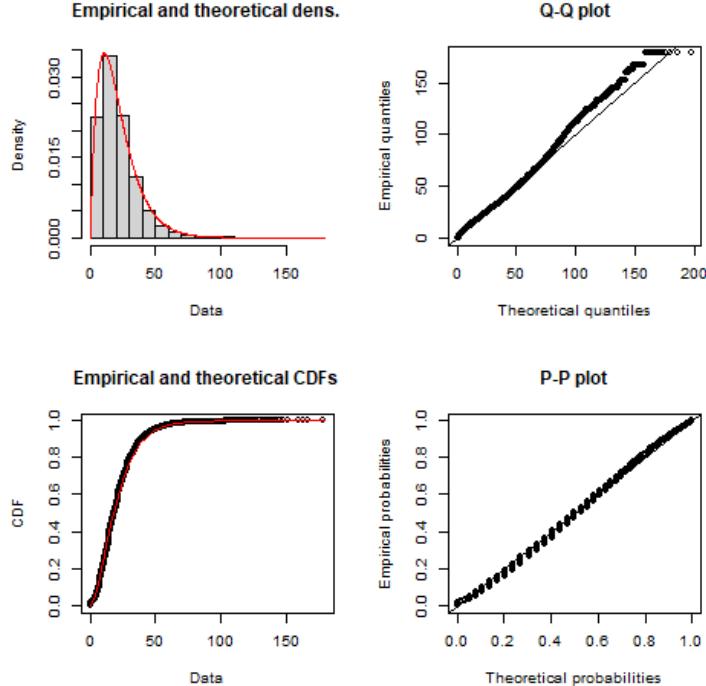


Figure 3: Empirical TTS 2016 home-based car trip length distribution (black points) and calibrated gamma distribution impedance function (red line) with associated Q-Q and P-P plots

The empirical and theoretical TLD for this data set are represented in the top-left panel of Figure 3. Maximum likelihood estimation and the Nelder-Mead method for direct optimization available within the `fitdistrplus` package (Delignette-Muller and Dutang, 2015) were used. Based on goodness-of-fit criteria and diagnostics seen in Figure 3, the gamma distribution was selected (also see Figure 12 in Appendix A).

The gamma distribution takes the following general form where the estimated ‘shape’ is  $\alpha = 2.019$ , the estimated ‘rate’ is  $\beta = 0.094$ , and  $\Gamma(\alpha)$  is defined in Equation (12).

$$f(x, \alpha, \beta) = \frac{x^{\alpha-1} e^{-\frac{x}{\beta}}}{\beta^\alpha \Gamma(\alpha)} \quad \text{for } 0 \leq x \leq \infty \quad (12)$$

$$\Gamma(\alpha) = \int_0^\infty x^{\alpha-1} e^{-x} dx$$

#### *Toronto*

Toronto is the largest city in the GGH and represents a significant subset of workers and jobs in the GGH; 51% of workers in the GGH travel to jobs in Toronto and 73% of jobs are located within Toronto. As will be discussed, when accessibility and spatial availability values are compared, this significant subset

of jobs in Toronto illustrates both issues associated with the competition effect. Specifically, since accessibility does not include the single-opportunity constraint like spatial availability does, it *overestimates* the jobs available for most TAZs in proximity to Toronto (i.e., GTA) and *underestimates* the jobs available for TAZs in the periphery of the GGH.

Accessibility is first calculated and presented in Figure 4. Conventionally, higher accessibility is interpreted as the ability to reach more opportunities. The accessibility values in Figure 4 follow a radial trend where the majority of TAZs in the core of Toronto have high accessibility values and increasingly lower values in TAZs which are further from the city boundary. This general trend is echoed in qualitative studies which find the further from Toronto the longer the employment commute (Axisa et al., 2012) and the closer to core of Toronto the more opportunities are accessible (for some to certain types of jobs, see Páez et al., 2013).

Next, spatial availability is presented alongside the accessibility plot in Figure 4. Similar to the accessibility plot, the higher the value the more access that TAZ has to jobs in the city of Toronto. Since spatial availability constrains the total to match the number of opportunities, high values of spatial availability can be seen as higher access to *available* jobs (i.e., competitive job access) and we can observe which TAZs have spatial availability values which are above or below the regional average of 642.

The visual differences between accessibility and spatial availability plots in Figure 4 are stark. The TAZ within and 10-20 km outside of Toronto's boundary have relatively lower values (i.e., fewer purples and blues) as measured by spatial availability than as measured by accessibility. There are also more pockets of low job availability (i.e., yellows) within the city of Toronto once competition for those jobs is accounted for.

#### *Greater Golden Horseshoe*

Next, we repeat the spatial accessibility and availability calculations for all origins to *all* jobs in the GGH. The full TTS data set again demonstrates both issues associated with the competition effect: the *overestimation* of job access and the *underestimation* of job access. This underestimation occurs in TAZ that are located in the periphery of the GGH which are relatively isolated (by travel cost) from the relatively highest concentration of opportunities located in Toronto. Within the full TTS data set we also observe the first issue of *overestimation* in TAZ that are on the outer limits outside the Toronto border but for reasons that differ from the analysis of jobs only in Toronto.

Figure 5 presents the accessibility and spatial availability for the full TTS data set. Interestingly, general trends between Figure 4 and Figure 5 are similar for the accessibility plots but not for the spatial availability plots. Within the two accessibility plots, job access values follow a radial trend where the majority of TAZ in Toronto have high accessibility values and values decrease in TAZ which are further from the city boundary. This radial effect is less pronounced in Figure 4 than in the following Figure 5 since opportunities are only present in Toronto for the former and all opportunities are present in the later. Conversely,

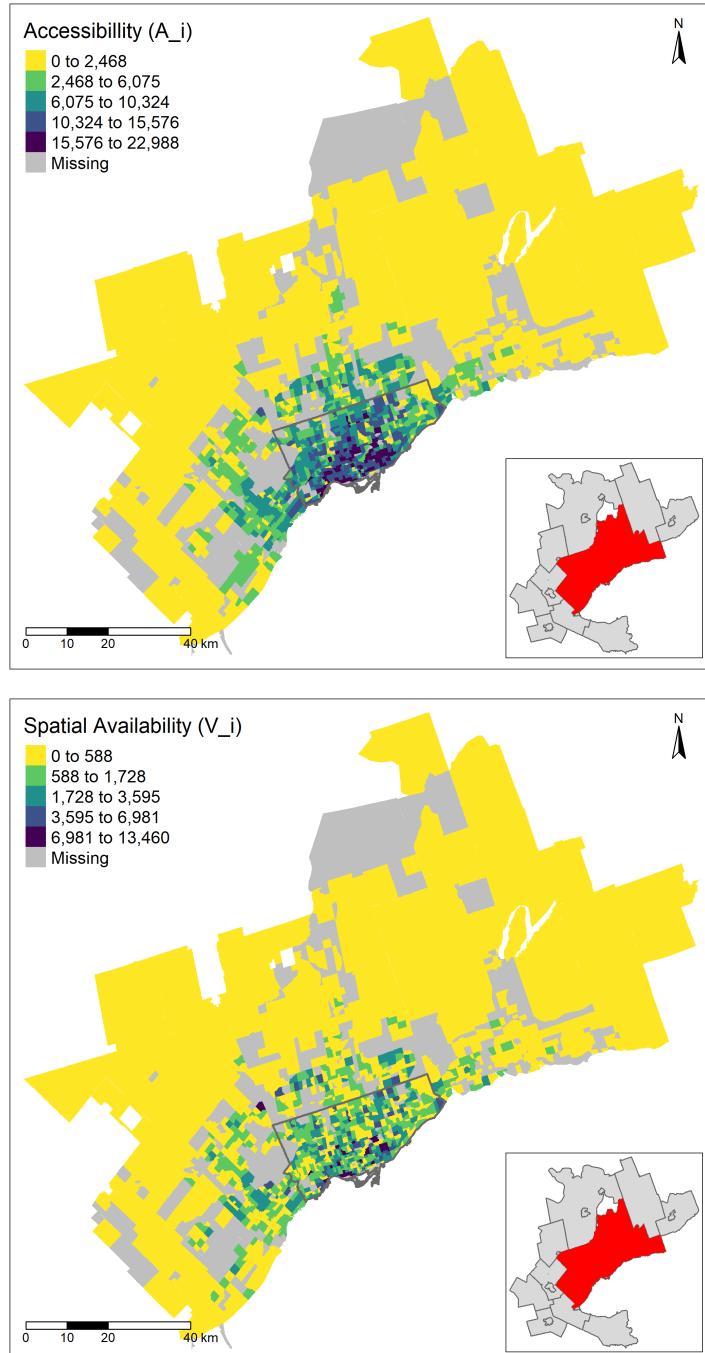


Figure 4: Calculated accessibility (top) and spatial availability (bottom) of employment to destinations in the City of Toronto. Only regions of the GTA (a subset of the GGH) are shown.

the two spatial availability plots do not appear to follow this radial trend; job access, as measured by spatial availability, appears much more even throughout the GGH (in comparison to job access as measured by accessibility). This can be noted in higher values around the north east and south west periphery TAZ and more moderate values in and around Toronto.

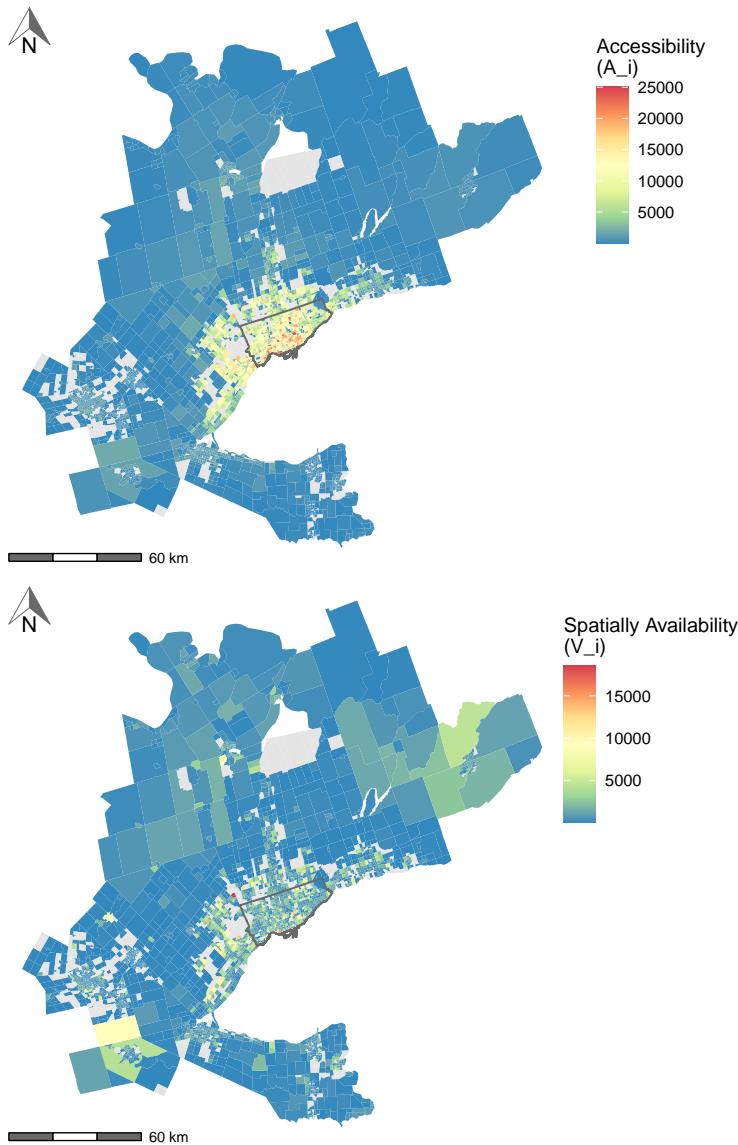


Figure 5: Calculated accessibility (top) and spatial availability (bottom) of employment from origins in the GGH to destinations in the GGH

To enhance the interpretability of spatial availability, the measure can be normalized to provide more meaningful insight into how many jobs are *available* to each TAZ compared to the regional average. This normalization, shown in Figure ??, demonstrates which TAZ have above (reds) and below (blue) the average (0.39) available jobs per worker in the GGH to jobs located within the city of Toronto. Similarly, we can also observe an uneven spatial distribution of job access within Toronto (as also shown in the spatial availability plot in Figure 4) where spatially available jobs are consistently distant from the average and often greater than 1 job per worker for the south-central and south-west TAZ in Toronto, although this trend is not as pronounced in the south-east and other pockets in the City.

Similar to the per worker spatial availability plot for jobs in Toronto, the following Figure 6 depicts which TAZ have above or below average job access after being normalized by the number of workers in each TAZ (i.e., 0.89 jobs per worker) considering all jobs and workers in the GGH. Similar to the spatial availability plot of the GGH jobs in Figure 5, we can see that many average or above average jobs per worker TAZ (whites) and reds) are present in southern Peel and Halton (south-west of Toronto), Waterloo and Brantford (even more south-west of Toronto), and Hamilton and Niagara (south of Toronto), however, the distribution is uneven and many TAZ within these areas do have below average values (blues).

Interestingly, when considering the jobs which are *available*, many areas outside of Toronto have similar jobs per worker values as TAZ in Toronto. This is contrary to the common belief that Toronto is one of the only hubs for employment opportunities . For instance, urban centers outside of Toronto such as those found in Brantford, Guelph, southern Peel, Halton, and Niagara have TAZ which are far above the the TTS average jobs per worker and higher than TAZ within Toronto. This finding is not seen in the accessibility plot (Figure 5) which suggests that these less densely populated areas may have sufficient employment opportunities for their populations; This finding is obscured when only considering the accessibility measure for job access as will be later discussed.

It is also worth noting that there is almost two times more jobs per worker in the GGH jobs spatial availability results than the GGH toronto spatial availability results. This suggests that all GGH people who work in the city of Toronto, on average, face more competition for jobs than all GGH people who work anywhere in the GGH .

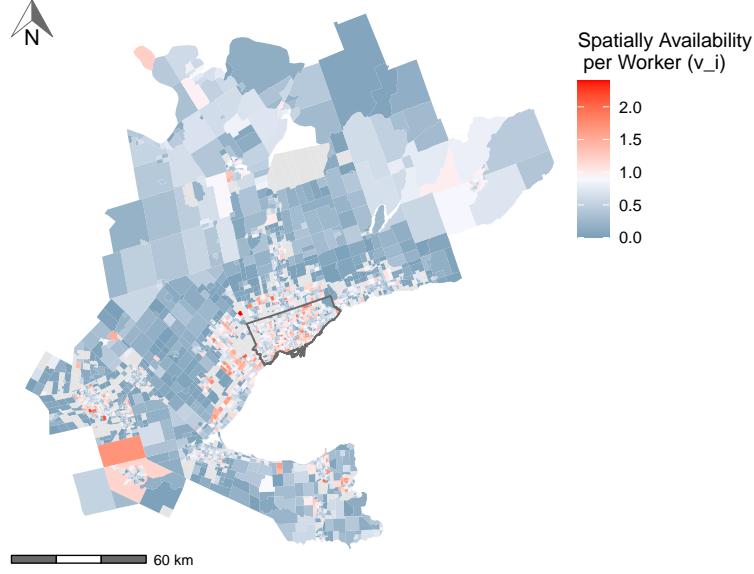


Figure 6: Calculated spatial availability of employment, per worker, from origins to destinations in the GGH.

## Discussion

In the preceding section we used both spatial accessibility and availability measures to explore the landscape of employment opportunities in the GGH. To build on these findings, we return to the two issues associated with spatial accessibility. As noted earlier, accessibility has the tendency to overestimate job access for areas which may experience high competition (issue 1) and underestimate job access for areas with low competition (issue 2).

To compare both accessibility and spatial availability, we calculate their relative magnitudes by re-scaling both measures from 0 to 100 where each value of the measure is divided by the maximum value as described in Equation 13 by  $A_{ij}^I$  and  $V_{ij}^I$ . Re-scaling is repeated for both measures for the subset of jobs in Toronto and for all jobs in the GGH and differences are calculated as described in Equation 14.

$$\begin{aligned} A_{ij}^I &= \frac{A_{ij}}{\max(A_{ij})} \cdot 100 \\ V_{ij}^I &= \frac{V_{ij}}{\max(V_{ij})} \cdot 100 \end{aligned} \quad (13)$$

$$Dif_{ij} = \frac{V_{ij}^I - A_{ij}^I}{A_{ij}^I} \cdot 100 \quad (14)$$

### *Overestimation of opportunities in space: first issue with accessibility*

For the subset of jobs in Toronto and all origins in the GGH, 98.9% of TAZ have re-scaled spatial availability values which are lower than re-scaled

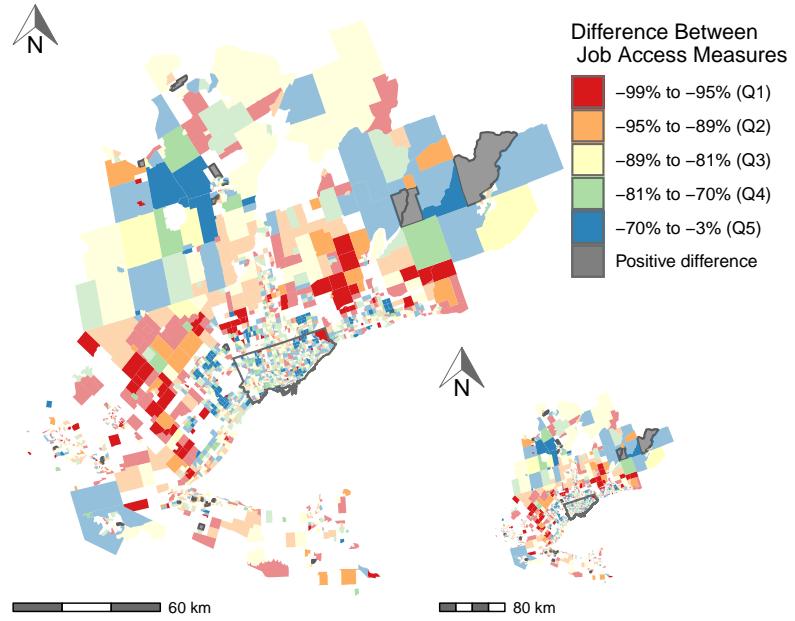


Figure 7: Difference between re-scaled the accessibility and the spatial availability job access measure in the context of employment from origins in the GGH to destinations in the City of Toronto. Values are expressed in five quantile ranges. Vivid TAZs represent a significant spatial autocorrelation and dimmed TAZs represent a non-significant autocorrelation as measured by Local Moran's I. TAZs with values which are higher than re-scaled accessibility (positive difference) are shown fully in grey.

accessibility values. Of this 98.9%, the spatial availability value is on average -80.69% different than the accessibility value and the difference ranges between -2.83% to -99.9%. Furthermore, to emphasize the similarity of this difference measure between neighbouring TAZ, the spatial autocorrelation is calculated using Moran's I statistic (Anselin, 1995) and TAZ with a significant p-value ( $p \leq 0.10$ ) are more vividly presented. Figure 7 displays the described plotted comparison, where the more negative the value, the more the accessibility measure overestimation job access relative to spatial availability for each TAZ. It should be noted that although the majority of TAZ job access values are overestimated by accessibility, the 23 TAZ which are underestimated are shown in grey.

We can see from Figure 7 that when we re-scale both job access values, accessibility consistently *overestimates* job access compared to the spatial availability measure for jobs within the city of Toronto. Overestimation ranges from -100% to -3% and is on average -81%. However, while job access is consistently overestimated, it is overestimated in a variable way. The TAZ with the largest difference in measure are depicted in red and orange (quantiles 1 and 2) and can be seen, in sometimes concentrated clusters (as indicated by the 2050 TAZ with a significant Moran I's statistic) approximately 10-20 kms outside of Toronto's

border and along the south side of the GGH. These TAZ also have a relatively low density of people who work in Toronto so the difference between measures has a significant correlation (0.878) with the number of workers in each TAZ.

Nonetheless, the density of workers within each TAZ alone does not fully explain the variation in overestimation as the travel cost and the number of opportunities factor into the calculation for both measures. From the perspective of accessibility, since opportunity-constraints are not considered, the *overestimated* TAZ (relative to spatial availability) are awarded higher values because they are more centrally located to opportunities (i.e., low travel cost) and are not discounted from being in proximity to highly competitive TAZ (i.e., high density of workers). On the other hand, spatial availability considers this competition by proportionally allocating jobs to TAZ relative to their travel cost and worker population. In other words, TAZ appears *overestimated* when the impact of travel cost alone outpaces the impact of both travel cost and workers thus the proportional allocation of opportunity results in a significantly smaller job access than the resulting value for accessibility. This is why TAZ which are exceptionally overestimated (reds and oranges) are on the periphery of more densely populated urban cities. These TAZ are located far enough away from workers in densely populated TAZ but still relatively close enough to jobs in Toronto. As such, their high accessibility value is a result of counting many more opportunities than the single-constrained spatial availability proportionally allocates.

#### *Underestimation of opportunities in space: second issue with accessibility*

Next, we demonstrate the difference between the two job access values for the full data set, namely, all jobs within the GGH and all workers within the GGH. While the majority of TAZ have difference values which correspond to accessibility being overestimated relative to spatial availability, 17% of TAZ are underestimated. These underestimated TAZ are plotted in Figure 8 alongside the overestimated TAZ for comparison. Of the underestimated TAZ, the spatial availability value is on average 214.7% different than the accessibility value and the difference ranges between 0% to -99.9%. The overestimated TAZ have a spatial availability value that is on average 214.7% different than the accessibility value and the difference ranges between 0% to -99.9%. Moran's I is not plotted but the statistics is significant (i.e., there is spatial autocorrelation) for the full data set ( $p < 0.001$  for all difference values).

As observed from Figure 8, TAZ with underestimated job access (i.e., re-scaled accessibility values are smaller than re-scaled spatial availability values) are located on the periphery of the GGH area. The majority of these underestimated TAZ are not within the center of the GGH where Toronto and the Greater Toronto Area (GTA) is located but are in proximity to other, smaller, employment areas within smaller municipalities. It can be understood that the underestimation of TAZ is a result of both high spatial availability as a result of low job competition and low accessibility scores that are a by-product of the job multiple-counting occurring within more densely job-populated TAZ in the GTA. Accessibility's multiple-counting effectively deflates the job access in these peripheral TAZ

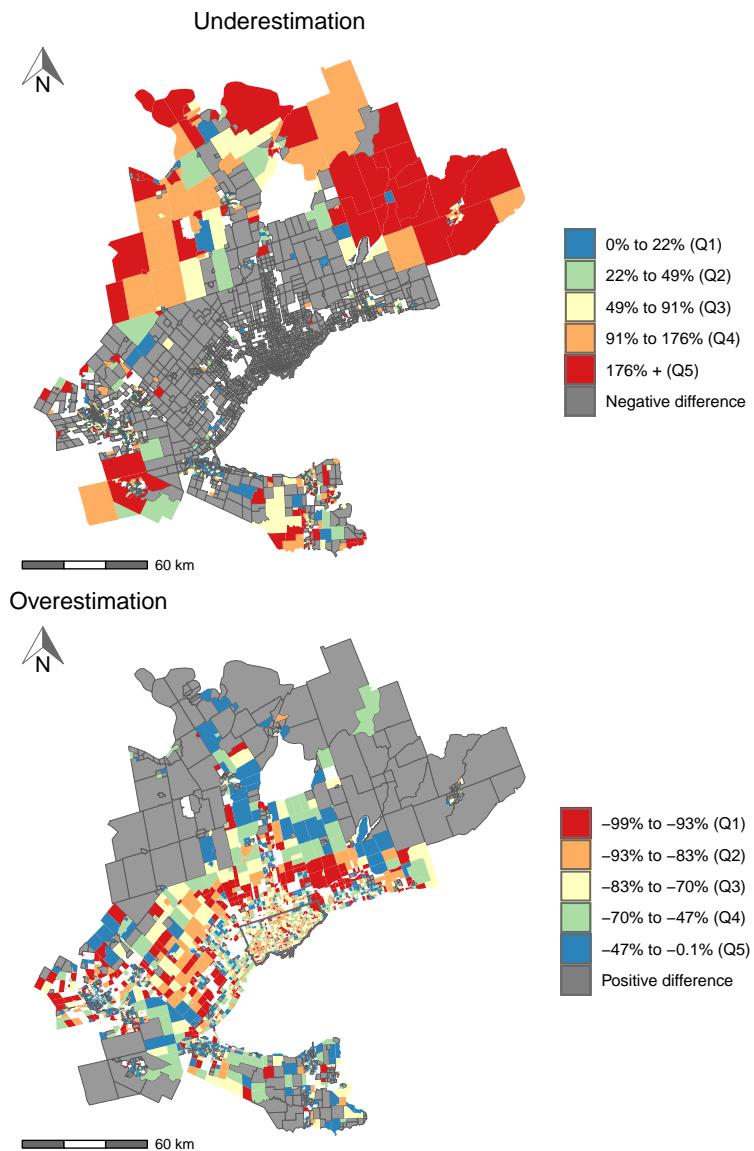


Figure 8. Difference between re-scaled the accessibility and the spatial availability job access measure in the context of employment from all origins and destinations in the GGH. Values are expressed in five quantile ranges. Vivid TAZs represent a significant spatial autocorrelation and dimmed TAZs represent a non-significant autocorrelation as measured by Local Moran's I only for underestimated TAZs. TAZs with values which are higher than re-scaled accessibility (positive difference) are shown fully in grey.

since their accessibility values are significantly lower compared to their multiple-counted GTA TAZ neighbours. The impact of this multiple-counting is starkly apparent when compared to the re-scaled spatial availability measure since spatial availability allocates jobs proportionally based on workers and travel cost, TAZ do not multiple-count of jobs and TAZ which are not in the position to multiple-count are not deflated as a consequence. This is supported by viewing the spatial availability of jobs per worker (Figure 6) where we can see that commercial areas throughout the GGH area have similar job access values as within some commercial areas in the GTA; this is not the case for the accessibility measure (see trends in Figure 5).

Next, it is worth explaining why accessibility's multiple-counting does not also result in the underestimation of job access when only considering the jobs available in Toronto. As depicted in the previous Figure 7, almost all TAZ are overestimated (i.e., accessibility values are *higher* than spatial availability). Within this subset of jobs in these peripheral TAZ, spatial availability is proportionally allocated based on their high travel cost (compared to the region) and Toronto-working population. In essence, these TAZ experience moderately high job competition and thus have low spatial availability. When accessibility is calculated, these peripheral TAZ have low accessibility as a result of the multiple-counting which occurs within and around Toronto but when the two measures are compared, however, accessibility is still *higher* than spatial availability. The difference in the two measures flips when the workers who work in areas outside of Toronto are re-introduced to these peripheral TAZ as represented in Figure 8. Since more workers (more competition) and more jobs with lower travel costs (less competition) are introduced, it can be inferred that these peripheral TAZ experience moderately higher job access (compared to spatial availability per worker within these periphery TAZ in Figure ?? and Figure 6). Conversely, for the accessibility measure, the introduction of additional workers does not meter the accessibility gained by the introduction of additional jobs and as such, the re-scaled accessibility values are *higher* than the spatial availability resulting in underestimated TAZ.

It is also worth noting that the right panel of Figure 8, by contrast, depicts all the TAZ with overestimated job access (i.e., re-scaled accessibility values are larger than re-scaled spatial availability values). Similar to the difference between measures depicted in the previous Figure 7 for the subset of jobs located in Toronto, these TAZ which are mostly within the GTA reflect an increased accessibility as a result of multiple-counting of jobs and a comparatively low spatial availability as a result of high job competition. Overall, within the full set of jobs in the GGH, the first and second issue associated with accessibility's competition effect are observed.

### **Other use cases for spatial availability**

In addition to measuring access to jobs for workers, spatial availability can be used to measure many other opportunity types and scenarios. In this section we briefly discuss two additional ways in which spatial availability can be applied

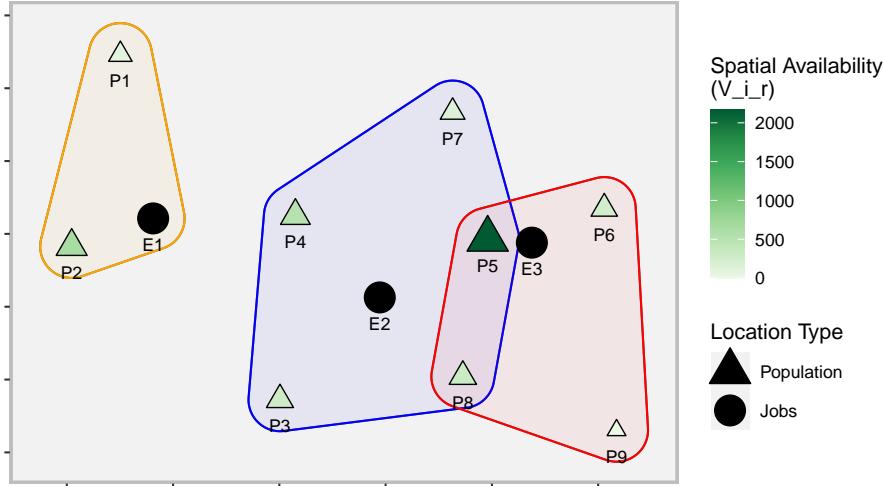


Figure 9: Spatial availability of jobs from population centers assuming catchment restrictions for the simple synthetic example

in practice. Since spatial availability singly-constraints opportunities which are allocated to the demand seeking population, opportunities or demand seeking populations can be subset while the resulting access measure does not lose any interpretability. As such, we firstly present an example with specialized population subsets and specialized employment centers. We then present an example where the focus is changed to employers seeking worker.

To illustrate these two additional examples, we return to the synthetic example initially introduced in Background section.

#### *Specialized populations*

Suppose that population centers P1 through P8 are not all eligible for employment at the three employment centers E1, E2, and E3. This can be due to education attainment or more simply a geographic barrier (i.e., river without a bridge) making it impossible for certain populations to be employed at certain employment centers. In this example, we consider that only population center P1 and P2 are eligible for employment at employment center E1. Next assume that jobs in employment center E2 can be taken by individuals in population centers P3, P4, P5, P7, and P8. Lastly, jobs in employment center E3 require qualifications available only among individuals in population centers P5, P6, P8, and P9. In essence, eligibility criteria creates catchments as seen in Figure 9.

For higher interpretability, we can inspect Figure 10 which presents plots of spatial availability per capita with and without catchments.

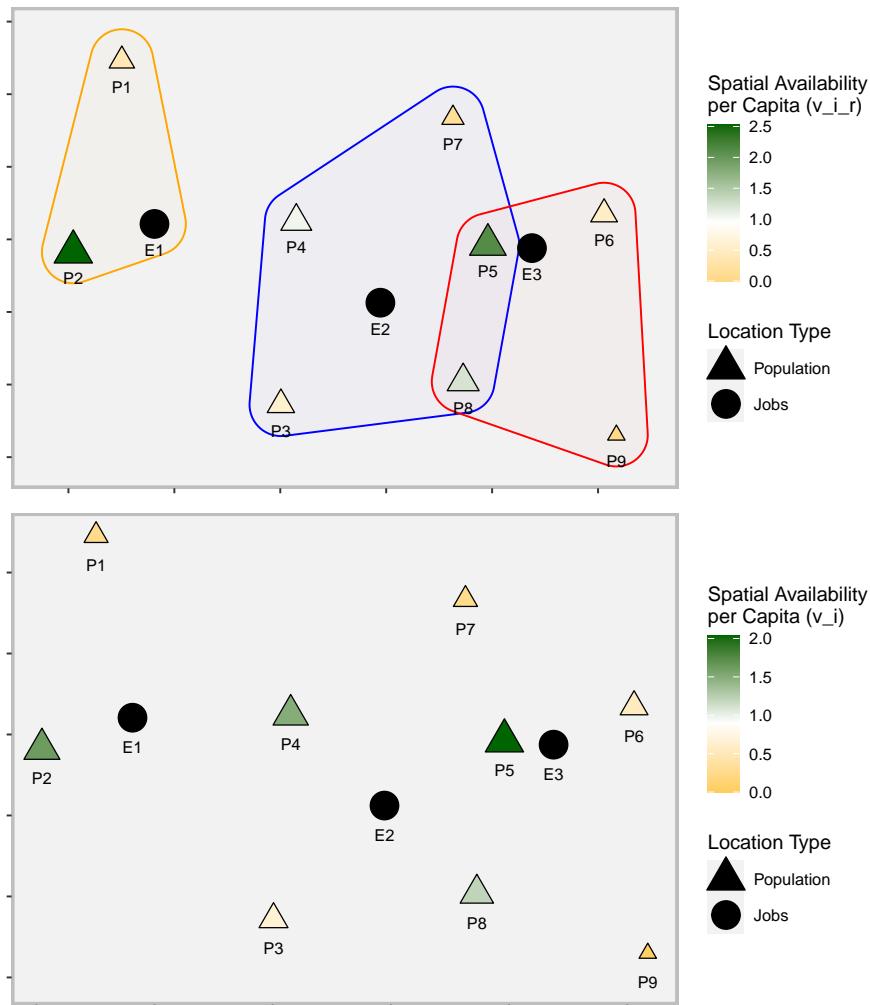


Figure 10: Spatial availability of jobs per capita for each population centers with catchment restrictions (top) and without catchment restrictions (bottom) for the synthetic example

In the bottom plot of Figure 10, we see that population center P5 has the highest level of spatial availability, due to being a large population center that is relatively close to jobs. We also see population centers which are further from employment centers have low spatial availability (P1, P3, P6, P7, P9) and population centers which are more central have, evidently, higher job access. We can also discern that the regional spatial availability per capita is 0.908. In contrast, when catchments are introduced, as shown in the top plot of Figure 10, we see that the number of opportunities available for population centers in the blue catchment decreases as job competition increases. However, we also observe that access marginally increases for the population centers in the yellow catchment and the regional spatial availability per capita increases slightly to 0.964.

#### *Employers seeking workers*

In this use case, we remove the catchments and switch the demand and opportunity roles of the employment centers and population centers. In this way, the spatial availability measure reflects the opportunities to find workers from the perspective of employers. In this example, workers are allocated proportionally to employment centers based on travel cost (i.e., distance) and population (i.e., jobs at each employment center). Figure 11 presents spatial availability generally and per capita for this use case.

As shown in Figure 11, the top plot demonstrates the spatial availability which measures accessibility to labor for the three employment centers. As with all spatial availability calculations, the number of all opportunities (in this case *workers*) are proportionally allocated to each employment center so employment center E3, E2 and E1 have access to 2205.19, 1709.52, and 610.29 workers respectively. Again, this totals to 4500 workers in the area. In the bottom plot, these spatial availability values are normalized per job (i.e. the ‘population’ of the employment centers) and we can see that employment center E3 has an above average worker access of 1.47 workers per job while E2 and E1 have 0.76 and 0.81 workers per job respectively.

#### **Concluding remarks**

In this paper, we introduce a singly-constrained accessibility measure that we term *spatial availability*. This measure is an alternative to conventional accessibility calculations that provides more meaningful estimates than accessibility by ensuring that the estimates match the observed number of opportunities. This enables the calculation of per-capita measures and measures relative to regional averages. This development makes it easier to compare opportunity landscapes across regions and/or time.

We demonstrated the use of spatial availability and compared it to spatial accessibility in an empirical example of workers and jobs in the GGH. We also discussed two additional use cases to emphasize the versatility of our new measure. The examples highlight how intuitive the per demand population access values.

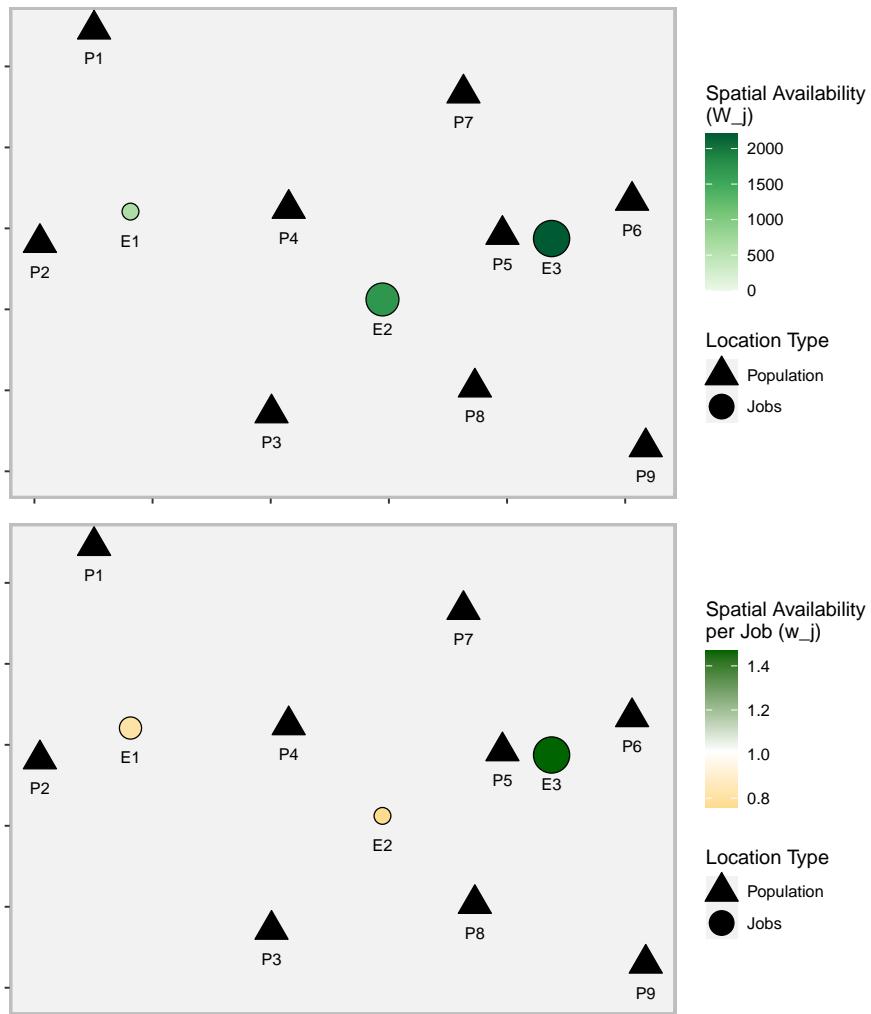


Figure 11: Spatial availability of workers for each employment center (top) and the spatial availability of workers per job for each employment center (bottom) for the simple synthetic example

Fundamentally, accessibility measure's methodology results in the overestimation or underestimation of opportunity access as a result of the competition effect. Accessibility does not include factors to bound the summation so origins, hypothetically, can have infinite opportunity access.

By including an intuitive single-sided constraint in spatial availability, a new measure results that can be used to calculate access to non-divisible opportunities. In this paper, we focused on employment, but any competitive opportunities such as schools, hospitals, and other essential services with finite capacity at a given time can be studied. Additionally, opportunities which are non-competitive in the sense that they have always larger capacities than population can still benefit from this measure as access will not be over or underestimated as a result of the competition effect seen in accessibility; non-competitive opportunities can include large natural parks and beaches. As such, values measured for opportunities of any type can benefit from an availability perspective through the reduction in competition effect (from accessibility) and a meaningful benchmark of demand per population unit.

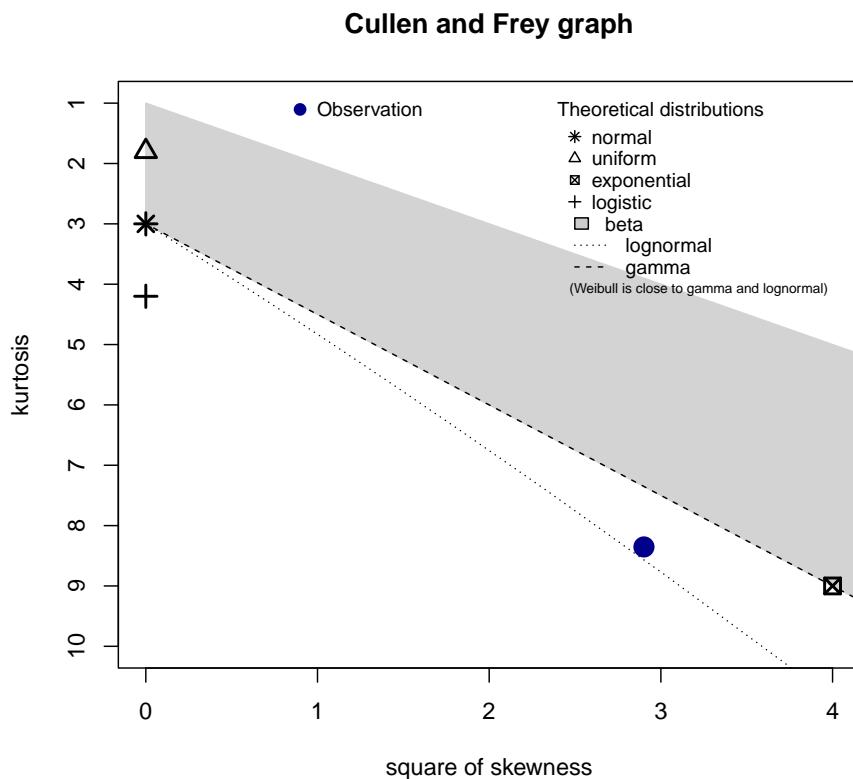


Figure 12: Cullen and frey graphy for the 2016 TTS calculated travel times.

## Appendix A

```
summary statistics
-----
min: 0.1   max: 179
median: 18
mean: 21.4344
estimated sd: 14.61254
estimated skewness: 1.703326
estimated kurtosis: 8.353363
```

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