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

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.

Introduction

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). The concept of accessibility derives its appeal 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 accessibility measure is based on the gravity model of spatial interaction; since it was first developed by Hansen (1959) it has been widely adopted in many forms (Arranz-López et al., 2019; e.g., Cervero et al., 2002; Geurs and van Wee, 2004; Handy and Niemeier, 1997; Levinson, 1998; Paez, 2004). Accessibility analysis offers a powerful tool to study the intersection between urban structure and transportation infrastructure - however, the interpretability of accessibility measures can be challenging (Geurs and van Wee, 2004; Miller, 2018). A key issue is that accessibility measures are sensitive to the number of opportunities in a region (e.g., a large city has more jobs than a smaller city), and therefore raw values cannot be easily compared across study areas (Allen and Farber, 2019).

Gravity-based accessibility indicators are in essence spatially smoothed estimates of the total number of opportunities in a region, but the meaning of their absolute magnitudes are unclear as they measure the *potential* for interaction (as originally defined by (1971)XXX). For instance, in the study by (XXX) high-income areas in Metropolitan Saul Paulo have high accessibility to employment (e.g., X jobs per all jobs available) and low-income areas have low accessibility to employment (e.g., Y jobs per all jobs available). Though X or Y reflect the urban structure, and correlates identifiy the relationship with employment, X and Y values can only be used within the context of employment accessibility in Saul Paulo. For example, in study XX which used the same employment accessibility method but for ZZ region, the X and Y accessibility values from Saul Paul cannot be immediately compared, but the X and Y low and high accessibility values in ZZ reflect the region's urban structure. That being said, decision-makers and planners find it difficult to operationalize accessibility since it reflects urban structure and is harder to interpet as an opportunity *provision* measure. For instance, if a small city creates 1000 more housing units in an employment rich neighborhood (ex., 15% of all employment opportunities are located within the neighbourhood (X)), could the city achieve a provider-provision-ratio of 1.5 jobs per person? Conventional accessibility cannot be standardized or normalized to reflect this ratio as a result of *inconsistent* opportunity-side and population-side counting.

This inconsistent counting embedded in traditional accessibility methods result in lack of clairty on how to interpret the resulting values. Returning to

XX, the maximum job accessibility in Saul Paulo is XYZ, and the maximum job accessibility is XY in region ZZ. This the highest count of opportunities, weighted by associated travel costs, which a certain population can accessing the region. This maximum value, outside of reflecting urban structure, is difficult to interpret from a decision-maker's perspective who is deliberating planning interventions. We believe the issue in interpretation arises since opportunities are adjusted based on population-side travel and usage behaviour (i.e., travel costs, catchments, time-windows). Accessibility is not constrained to match the number of opportunities available. Put another way, traditional measures of accessibility do not capture the competition for opportunities but instead quantify access as if every person can reach every (travel and usage behaviour-adjusted) opportunity. This *inconsistency* is not necessarily problematic if a case study calls for the quantification of a accessibility assuming a "greedy" population. For instance, a greater accessibility to parks correlates with property values even though those that live in those properties don't use all the parks all the time, but this correlate suggests that the *potential* to access parks is enough. However, this *inconsistent* opportunity-adjustment can be acute when opportunities are "non-divisible" in the sense that, once taken they are no longer available to other members of the population (also discussed by Geurs and van Wee, 2004). Examples of these types of opportunities include jobs (e.g., when a person takes up a job, the same job cannot be taken by anyone else) and placements at schools (e.g., once a student takes a seat at a school, that opportunity is no longer available for another student). Though these non-divisible opportunities can still be modelled by conventional accessibility (e.g., Saul Paul and Z region), the measure does not reflect the *spatial availability* of the opportunity.

To re-calibrate accessibility for a more interpretable understanding of opportunity-provision, researchers have proposed several different approaches for considering competition in the conventional accessibility method. These include several approaches that first normalize the number of opportunities available at a destination by the demand 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 effects, although in practice several researchers (e.g., Delamater, 2013; Wan et al., 2012) have found that they tend to over-estimate accessibility values. The underlying issue in FCAs, as demonstrated by Paez et al. (2019), is the multiple counting of opportunities (ex., population 1 in a catchment accesses opportunities and population 2 in an overlapping catchment access a few opportunities which population 1 access as well as additional opportunities). The multiple counting of the *same* opportunities across populations can lead to biased estimates if not corrected (Paez et al., 2019).

Another approach which research have used to consider competition in accessibility has been the imposition of constraints on the gravity model to ensure potential interaction 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 (i.e., 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 FCA 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 opportunities that are not only *accessible* but also *available* to the opportunity-seeking population, in the sense that they have not been claimed by a competing seeker 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 in a single step, this method avoids the issues that result from multiple counting of opportunities in conventional accessibility analysis. The method returns a measure of the rate of available opportunities per opportunity-seeking population. Moreover, the method also returns a benchmark value for the study region against which results for individual origins can be compared both inter- and intra-regionally and used in the context of opportunity provision assessment. This novel approach comes at a time when the quantity and resolution of data is exponentially increasing and the need to operationalize accessibility methods in city-planning objectives is urgent.

This paper is split into two main parts. The first part introduces a synthetic example that is used to calculated spatial availability alongside conventional unconstrained accessibility and popular competitive accessibility measures (XXX). The aim is to demonstrate the formulation of the proposed measure and what it represents relative to other accessibility measures. In the second part, we calculate, compare, and contrast the spatial availability, conventional accessibility, and Shen's competitive accessibility (XX) values for 2016 employment data in the city of Toronto, Canada (Transportation Tomorrow Survey (TTS)). The motivation of this part is to demonstrate how accessibility and a popular competitive accessibility measure, both suffer from a lack of interpretability. Additionally, the competitive accessibility measure (XX) and spatial availability reinforce the ways in which accessibility double-counts opportunities thus cautioning practitioners from using it for opportunities where populations' are not greedy (i.e., 1 person can only access 1 opportunity at any given time; the presence of many opportunities doesn't matter when there are many neighbours since their utilization is normalized). Finally, we conclude by cautioning the limits of conventional accessibility measure use in its *concept* and outlining the advantages of the spatial availability measure and the breadth of potential uses from the perspective of opportunity-provision planning.

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.

Part 1: Access measures on an synthetic example

We begin this part by introducing a synthetic example, calculating conventional accessibility, and demonstrating the interpretation issues associated with this widely used measure. We then present the proposed *spatial availability* measure, calculate the spatial availability values for the synthetic example and discuss how the interpretation of the resulting values from the perspective of opportunity-provision. Spatial availability values are then compared and contrasted with other competitive accessibility measures (XXX) and the interpretability of spatial availability is further elaborated.

Conventional accessibility

Many accessibility measures (excluding utility-based measures) are derived from the gravity model (Wilson, 1971) and follow the formulation shown in Equation (1).

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

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; $\sum_j O_j$ is the total supply of opportunities in the study region.
- 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 $f(\cdot)$, 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

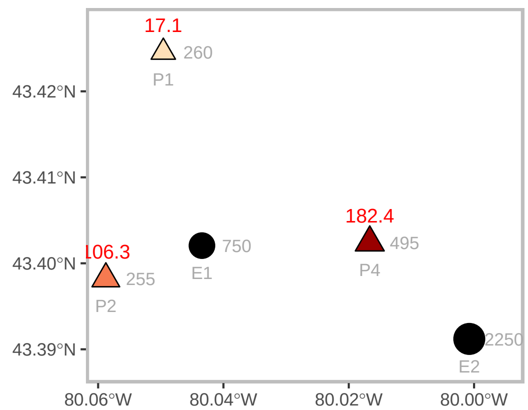


Figure 1: Accessibility to jobs (red text) from population centers (P) to employment centers (E) for the synthetic example. Values of population and employment are shown in white text.

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, the accessibility measures 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).

The setup for our synthetic example is a system with two employment centers and three population centers. Accessibility to jobs at each population center is calculated using the accessibility measure A_i in Equation (1). In this synthetic 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.

The conventional accessibility measure is sometimes an excellent indicator 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 P4 but despite the accessibility value for P1 being relatively low it is still better than *zero*. On the other hand, P4 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 (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. 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 $i = 1, \cdots, n$ 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 P4 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 spatially which will be discussed later on in the paper.

Popular competitive measures - the family of floating catchment approaches

Considering competition in accessibility is not new. A highly cited work was Shen 1998 (XX) work in which, in one step, he divides conventional accessibility by the travel-cost adjusted population seeking the opportunities in a given region. This work was popularized by the 2-step floating catchment approach (2SFCA) introduced by Wang (XX) and used today. The three population center and 2 employment centre example of this measure is solved for in Figure XX-left, and the formulation of the 2SFCA approach is shown in step 1 (Equation (2)) where the PPR R_j is calculated for each opportunity and then allocated to populations based on travel cost $f(\cdot)$ in step 2 (Equation (3)). The synthetic example is solved in detail for the 2SFCA and all other accessibility measures in the Appendix (XX).

$$R_j = \frac{O_j}{\sum_i P_i \cdot f(c_{ij})} \tag{2}$$

$$A_i = \sum_j R_j \cdot f(c_{ij}) \tag{3}$$

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;
- P_i is the population at location i; $\sum_j R_j$ is the total supply of opportunities in the study region.
- R_j is the provider-to-population (PPR) ratio at location j;
- c_{ij} is a measure of the cost of moving between i and j;
- $f(\cdot)$ is an impedance function of c_{ij}.

Another advancement in competitive measures has been Allen (XX) work. It is an iterative process which involves matching the travel-cost weighted opportunities to the travel-cost weighted population in the region. It requires that the total population and opportunities are equal in the region. Since this process requires converage, the answer's don't fully match up but the solved synthetic example is in Figure XX - middle, and the formulation of the method is as follows:

$$R_j = \frac{O_j}{\sum_i P_i \cdot f(c_{ij})} A_i = \sum_j R_j \cdot f(c_{ij})$$

Shen, Wang, and Allen introduce competition but the way in which they are applied is inconsistent and/or difficult to interpret. Wang yields a measure which is X jobs per weighted population. Jeff yields… . To account for this, Paez (2019) introduced a balancing factor to the 2SFCA, the 'balanced' S2FCA. The Figure XX - right displays the solved synthetic example and the formulation for the method is as follows:

XXX

The BS2FCA proportionally assigns the number of opportunities from the PPR to each origin, this results in a consistent number of opportunities being assigned but the total number of opportunities is not preserved.

(add all calculations for each of these in the appendix)

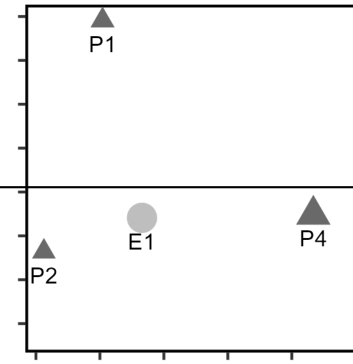
Introducing spatial availability

Thus we finally introduce spatial availability

Part 2: Empirical example of Toronto

Table 1: Summary description of synthetic example

Origin	Destination	Population	Jobs	Distance
Population 1	Employment Center 1	260	750	2548.060
Population 1	Employment Center 2	260	2250	5419.120
Population 2	Employment Center 1	255	750	1314.074
Population 2	Employment Center 2	255	2250	4762.588
Population 4	Employment Center 1	495	750	2170.200
Population 4	Employment Center 2	495	2250	1790.100



Appendix A: Step-by-step accessibility calculations for synthetic example

Details for the synthetic example:

Conventional accessibiliy

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

Solved in one step:

2 step floating catchment approach

2 step floating catchment approach

References

Allen, J., Farber, S., 2019. A Measure of Competitive Access to Destinations for Comparing Across Multiple Study Regions. Geographical Analysis 52, 69–86. doi:10.1111/gean.12188

Arranz-López, A., Soria-Lara, J.A., Witlox, F., Páez, A., 2019. Measuring relative non-motorized accessibility to retail activities. International Journal of Sustainable Transportation 13, 639–651. doi:10.1080/15568318.2018.1498563

Arribas-Bel, D., Green, M., Rowe, F., Singleton, A., 2021. Open data products-a framework for creating valuable analysis ready data. Journal of Geographical Systems 23, 497–514. doi:10.1007/s10109-021-00363-5

Barboza, M.H.C., Carneiro, M.S., Falavigna, C., Luz, G., Orrico, R., 2021. Balancing time: Using a new accessibility measure in Rio de Janeiro. Journal of Transport Geography 90, 102924. doi:10.1016/j.jtrangeo.2020.102924

Brunsdon, C., Comber, A., 2021. Opening practice: Supporting reproducibility and critical spatial data science. Journal of Geographical Systems 23, 477–496. doi:10.1007/s10109-020-00334-2

Cervero, R., Sandoval, O., Landis, J., 2002. Transportation as a Stimulus of Welfare-to-Work: Private versus Public Mobility. Journal of Planning Education and Research 22, 50–63. doi:10.1177/0739456X0202200105

Chen, B.Y., Cheng, X.-P., Kwan, M.-P., Schwanen, T., 2020. Evaluating spatial accessibility to healthcare services under travel time uncertainty: A reliability-based floating catchment area approach. Journal of Transport Geography 87, 102794. doi:10.1016/j.jtrangeo.2020.102794

Chen, X., 2019. Enhancing the Two-Step Floating Catchment Area Model for Community Food Access Mapping: Case of the Supplemental Nutrition Assistance Program. The Professional Geographer 71, 668–680. doi:10.1080/00330124.2019.1578978

Chen, Z., Zhou, X., Yeh, A.G., 2020. Spatial accessibility to kindergartens using a spectrum combinational approach: Case study of Shanghai using cellphone data. Environment and Planning B: Urban Analytics and City Science 239980832095422. doi:10.1177/2399808320954221

Deboosere, R., El-Geneidy, A.M., Levinson, D., 2018. Accessibility-oriented development. Journal of Transport Geography 70, 11–20. doi:10.1016/j.jtrangeo.2018.05.015

Delamater, P.L., 2013. Spatial accessibility in suboptimally configured health care systems: A modified two-step floating catchment area (M2SFCA) metric. Health & Place 24, 30–43. doi:10.1016/j.healthplace.2013.07.012

El-Geneidy, A., Levinson, D., Diab, E., Boisjoly, G., Verbich, D., Loong, C., 2016. The cost of equity: Assessing transit accessibility and social disparity using total travel cost. Transportation Research Part A: Policy and Practice 91, 302–316. doi:10.1016/j.tra.2016.07.003

Geurs, K.T., van Wee, B., 2004. Accessibility evaluation of land-use and transport strategies: review and research directions. Journal of Transport Geography 12, 127–140. doi:10.1016/j.jtrangeo.2003.10.005

Handy, S., 2020. Is accessibility an idea whose time has finally come? Transportation Research Part D: Transport and Environment 83, 102319. doi:10.1016/j.trd.2020.102319

Handy, S.L., Niemeier, D.A., 1997. Measuring Accessibility: An Exploration of

Issues and Alternatives. Environment and Planning A: Economy and Space 29, 1175–1194. doi:10.1068/a291175

Hansen, W.G., 1959. How Accessibility Shapes Land Use. Journal of the American Institute of Planners 25, 73–76. doi:10.1080/01944365908978307

Higgins, C.D., 2019. Accessibility toolbox for r and ArcGIS. Transport Findings. doi:10.32866/8416

Joseph, A.E., Bantock, P.R., 1984. Rural Accessibility of General Practitioners: the Case of Bruce and Grey Counties, ONTARIO, 1901–1981. The Canadian Geographer/Le Géographe canadien 28, 226–239. doi:10.1111/j.1541-0064.1984.tb00788.x

Kwan, M.-P., 1998. Space-Time and Integral Measures of Individual Accessibility: A Comparative Analysis Using a Point-based Framework. Geographical Analysis 30, 191–216. doi:10.1111/j.1538-4632.1998.tb00396.x

Levinson, D.M., 1998. Accessibility and the journey to work. Journal of Transport Geography 6, 11–21. doi:10.1016/S0966-6923(97)00036-7

Li, A., Huang, Y., Axhausen, K.W., 2020. An approach to imputing destination activities for inclusion in measures of bicycle accessibility. Journal of Transport Geography 82, 102566. doi:10.1016/j.jtrangeo.2019.102566

Luo, W., Wang, F., 2003. Measures of Spatial Accessibility to Health Care in a GIS Environment: Synthesis and a Case Study in the Chicago Region. Environment and Planning B: Planning and Design 30, 865–884. doi:10.1068/b29120

Miller, E.J., 2018. Accessibility: measurement and application in transportation planning. Transport Reviews 38, 551–555. doi:10.1080/01441647.2018.1492778

Paez, A., 2004. Network accessibility and the spatial distribution of economic activity in eastern asia. Urban Studies 41, 2211–2230.

Paez, A., Higgins, C.D., Vivona, S.F., 2019. Demand and level of service inflation in Floating Catchment Area (FCA) methods. PLOS ONE 14, e0218773. doi:10.1371/journal.pone.0218773

Paez, A., Scott, D.M., Morency, C., 2012. Measuring accessibility: Positive and normative implementations of various accessibility indicators. Journal of Transport Geography 25, 141–153. doi:10.1016/j.jtrangeo.2012.03.016

Páez, A., 2021. Open spatial sciences: An introduction. Journal of Geographical Systems 23, 467–476. doi:10.1007/s10109-021-00364-4

Pereira, R.H.M., Banister, D., Schwanen, T., Wessel, N., 2019. Distributional effects of transport policies on inequalities in access to opportunities in Rio de Janeiro. Journal of Transport and Land Use 12. doi:10.5198/jtlu.2019.1523

Proffitt, D.G., Bartholomew, K., Ewing, R., Miller, H.J., 2017. Accessibility planning in American metropolitan areas: Are we there yet? Urban Studies 56, 167–192. doi:10.1177/0042098017710122

Qi, Y., Fan, Y., Sun, T., Hu, L.(Ivy)., 2018. Decade-long changes in spatial mismatch in Beijing, China: Are disadvantaged populations better or worse off? Environment and Planning A: Economy and Space 50, 848–868. doi:10.1177/0308518X18755747

Reggiani, A., Bucci, P., Russo, G., 2011. Accessibility and Impedance Forms: Empirical Applications to the German Commuting Network. International

Regional Science Review 34, 230–252. doi:10.1177/0160017610387296
Rosik, P., Goliszek, S., Komornicki, T., Duma, P., 2021. Forecast of the Impact of Electric Car Battery Performance and Infrastructural and Demographic Changes on Cumulative Accessibility for the Five Most Populous Cities in Poland. Energies 14, 8350. doi:10.3390/en14248350
Santana Palacios, M., El-geneidy, A., 2022. Cumulative versus Gravity-based Accessibility Measures: Which One to Use? Findings. doi:10.32866/001c.32444
Shen, Q., 1998. Location characteristics of inner-city neighborhoods and employment accessibility of low-wage workers. Environment and Planning B: Planning and Design 25, 345–365. doi:10.1068/b250345
Shi, Y., Blainey, S., Sun, C., Jing, P., 2020. A literature review on accessibility using bibliometric analysis techniques. Journal of Transport Geography 87, 102810. doi:10.1016/j.jtrangeo.2020.102810
Vale, D.S., Pereira, M., 2017. The influence of the impedance function on gravity-based pedestrian accessibility measures: A comparative analysis. Environment and Planning B: Urban Analytics and City Science 44, 740–763. doi:10.1177/0265813516641685
Wan, N., Zou, B., Sternberg, T., 2012. A three-step floating catchment area method for analyzing spatial access to health services. International Journal of Geographical Information Science 26, 1073–1089. doi:10.1080/13658816.2011.624987
Wang, S., Wang, M., Liu, Y., 2021. Access to urban parks: Comparing spatial accessibility measures using three GIS-based approaches. Computers, Environment and Urban Systems 90, 101713. doi:10.1016/j.compenvurbsys.2021.101713
Wilson, A.G., 1971. A Family of Spatial Interaction Models, and Associated Developments. Environment and Planning A: Economy and Space 3, 1–32. doi:10.1068/a030001
Yan, X., 2021. Toward Accessibility-Based Planning. Journal of the American Planning Association 87, 409–423. doi:10.1080/01944363.2020.1850321
Yang, D.-H., Goerge, R., Mullner, R., 2006. Comparing GIS-Based Methods of Measuring Spatial Accessibility to Health Services. Journal of Medical Systems 30, 23–32. doi:10.1007/s10916-006-7400-5
Ye, C., Zhu, Y., Yang, J., Fu, Q., 2018. Spatial equity in accessing secondary education: Evidence from a gravity-based model: Spatial equity in accessing secondary education. The Canadian Geographer / Le Géographe canadien 62, 452–469. doi:10.1111/cag.12482