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2 ACCESSIBILITY MEASURES

Promoting a paradigm shift in urban and transport planning towards accessibility-oriented planning entails a few challenges. Among them, there is the need to develop and apply methods to measure the urban accessibility conditions in cities. The search for accessibility metrics that are easy to communicate, methodologically robust and computationally tractable lead researchers to develop a large number of different measures (Páez, Scott and Morency, 2012). These measures can be divided into two major groups: place-based measures and person-based measures (Dijst, Jong and Van Eck, 2002).

2.1 Place-based measures

Place-based metrics measure accessibility as a characteristic of a particular location. By simplification, these indicators assume that all people who are in the same place can equally access the activities distributed throughout the city. That is, if an accessibility analysis uses a place-based metric to calculate accessibility and divides the study area into a hexagonal grid, each cell of this grid (a hexagon) will have an accessibility value associated with it, which is equally assigned to all individuals residing within the cell. These measures are sensitive to land use and transport factors related to the spatial distribution of activities and to the configuration and performance of the transport network, but do not take into account people's individual characteristics.

These measures are the most widely used by transport agencies and researchers (Boisjoly and El-Geneidy, 2017; Papa et al., 2015). This is largely because they require less data and tend to be considerably easier to calculate and interpret than person-based measures. For this reason, the examples and case studies presented in this chapter and in the rest of the book focus only on place-based measures.

Place-based accessibility measures account for trip costs, usually expressed in terms of travel time (El-Geneidy et al., 2016; Venter, 2016) – i.e., if one location can be reached from another in half an hour, the cost to make this trip is 30 minutes. However, it is possible to consider other types of costs, such as the distance of the trip, its monetary cost and the passengers' perception of comfort (Arbex and Cunha, 2020; Herszenhut et al., 2022). We present below some of the place-based accessibility metrics most commonly used in the scientific literature and by transport agencies. Here, the term "cost" is used broadly, and can refer to any type of cost unit used to quantify the impedance of a trip, be it travel time, monetary cost or other alternatives.

2.1.1 Minimum travel cost

One of the simplest accessibility metrics, indicating the lowest cost required to reach the nearest opportunity from a given origin. It allows one to estimate, for example, the travel time from each block of the city to the closest health center. The indicator is calculated with the following formula:

$$A_i = min\left(c_{i1}, c_{i2}, \dots, c_{ij}, \dots, c_{i(n-1)}, c_{in}\right) \Leftrightarrow O_j \geq 1 \quad (1)$$

In which A_i is the accessibility at origin i, c_{ij} is the travel cost between origin i and destination j, n is the total number of destinations in the study area and O_j is the number of opportunities at destination j.

Advantages and disadvantages: the advantages of this measure are that it requires little data and it is easy to calculate and to communicate. Two disadvantages, however, are that it does not consider the amount of accessible opportunities at destinations and it does not take competition for opportunities into account. For example, even if a person lives very close to a hospital, this proximity does not necessarily guarantee good access to health services if that is the only hospital is subject to high demand peaks that overload the services beyond their capacities.

2.1.2 Cumulative opportunity measures

Computes the number of opportunities that can be reached within a given travel cost limit. For example, this indicator can be used to measure the number of jobs accessible by public transport in up to 60 minutes, or the number of schools accessible within 30 minutes of walking. It is calculated using the following formula:

$$A_i = \sum_{j=1}^{n} O_j \times f\left(c_{ij}\right) \quad (2)$$

$$f\left(c_{ij}\right) = \begin{cases} 1 & \text{if } c_{ij} \leq C \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

In which A_i is accessibility at origin i, O_j is the number of opportunities at destination j, n is the total number of destinations in the study area, $f\left(c_{ij}\right)$ is a binary function that assumes the values 0 or 1, depending on the travel cost c_{ij} between origin i and destination j and C is the travel cost threshold.

Advantages and disadvantages: the cumulative opportunities measure also requires little data and is easy to calculate and communicate. This helps explain why this is one of the indicators most commonly used by transport and funding agencies in accessibility analyses (Papa et al., 2015; Boisjoly and El-Geneidy, 2017).

Among its disadvantages are the fact that this indicator does not consider the competition for opportunities and that it requires the choice of a single cut-off point as a travel cost limit. Moreover, this measure assumes that all opportunities that can be reached within the travel cost limit are equally desirable and accessible. For example, if we consider a 60-minute travel time limit, an opportunity that is 40 minutes away from an origin is considered as accessible as another one that is just 10 minutes away.

2.1.3 Gravity measures

More than a specific type of accessibility metric, we can understand gravity-based accessibility as a family of measures. As in the case of the cumulative opportunities measure, gravity-based metrics consider the sum of opportunities that can be reached from a given location. However, the number of opportunities in each destination is gradually discounted as travel costs become higher. In other words, opportunities that are easier to access are considered to be more valuable, and the weight of each opportunity decreases as it gets more difficult to reach it from the trip origin.

The rate at which this weight decreases is determined by a *decay function*. For example, the *linear* decay function considers that the weight of each opportunity decreases linearly up to a certain cost limit, after which the weight becomes zero. The *negative exponential* function, on the other hand, considers that the weight of each opportunity is divided by a factor that grows exponentially, causing the weight to decrease rapidly at low travel costs and to approach 0 at high costs. The equations below present the generic formulation of a gravitational measure, as well as the linear and negative exponential decay functions mentioned above.

$$A_i = \sum_{j=1}^{n} O_j \times f(c_{ij}) \tag{4}$$

$$f_{lin}(c_{ij}) = \begin{cases} 1 - c_{ij}/C & \text{if } c_{ij} \leq C \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

$$f_{exp}(c_{ij}) = e^{-\beta c_{ij}} \tag{6}$$

In which A_i is the accessibility at origin i, O_j is the number of opportunities at destination j, n is the total number of destinations in the study area, $f(c_{ij})$ is a decay function whose result varies with the travel cost c_{ij} between origin i and destination j, $f_{lin}(c_{ij})$ is the linear decay function, C is travel cost limit, $f_{exp}(c_{ij})$ is the negative exponential decay function and β is a parameter that dictates the decay speed.

There are numerous types of decay functions that can be used when calculating gravity-based accessibility measures. The cumulative opportunities measure, for example, can be understood as a special case of a gravity-based measure in which the weight of each opportunity is set by a binary function, rather than a function that decays gradually. Levinson and King (2020, p. 49) present a list of decay functions often used by transport agencies and researchers in analyses involving gravity measures.

Advantages and disadvantages: the main advantage of gravity-based accessibility measures is that, by discounting the weight of opportunities by travel cost, these measures reflect to some extent how people perceive access to opportunities: services and activities that are closer to them tend to be perceived as more valuable, all else equal. This indicator, however, has at least two disadvantages. The first is that the estimated accessibility levels are difficult to interpret because of the way in which the number of opportunities is discounted by travel costs. Additionally, the decay rate of the impedance function (the β parameter of the negative exponential function, for example) needs to be calibrated if one wants the accessibility estimates to be representative of people's travel behavior. Therefore, gravity-based metrics require additional travel behavior data to be used in the calibration process, coming, for example, from household travel surveys or mobile phone services.

2.1.4 Accessibility measures with competition: floating catchment area

In many cases, access to opportunities is affected not only by geographical proximity and transportation costs, but also by the competition of many people trying to access the same opportunity. This is very common, for example, in the cases of access to health services, schools and jobs. A job opening can only be occupied by one person at a time, and the same goes for an Intensive Care Unit (ICU) bed or a school seat.

There are various measures that seek to account for competition effects in accessibility estimates. Some of the most widely used are those in the floating catchment area (FCA) family of indicators. For example, these indicators try to take into account how the same person can potentially access multiple ICU beds and, simultaneously, how each ICU bed can potentially be accessed by multiple people. Thus, a person's access to ICU beds is influenced both by transportation costs and by the availability of beds, given the potential competing demand for them.

Within the FCA measures' family, the most commonly used is the 2-step floating catchment area (2SFCA), originally proposed by Luo and Wang (2003). One limitation of 2SFCA is that it considers that the same person can demand multiple services/opportunities at the same time and that the same service can be used by multiple people at the same time. These issues are known as the demand and supply inflation problems, respectively, and can generate biased or inaccurate accessibility estimates (Páez, Higgins and Vivona, 2019). To deal with these problems, Páez, Higgins and Vivona (2019) proposed the balanced floating catchment area (BFCA), one of the most recent measures of the FCA family.

Advantages and disadvantages: different FCA measures have different advantages and disadvantages, to a greater or lesser extent. However, in general, the main advantage of measures from this family is their ability to incorporate aspects of competition into accessibility estimates. The main disadvantage, on the other hand, is the difficulty to interpret and communicate their results.

2.2 Person-based measures

Person-based accessibility measures are sensitive not only to the spatial distribution of activities and to the configuration and performance of transportation networks. Indicators in this group also take into account how the individual characteristics of each person (such as gender, age, physical disability etc.), and even the participation in certain activities and personal commitments, can affect people's ability to access opportunities. This category includes, for example, activity-based indicators (Dong et al., 2006) and space-time measures (Kim and Kwan, 2003; Neutens et al., 2012).

Advantages and disadvantages: although person-based accessibility measures are more sophisticated, they often require large amounts of data, such as travel diary records, household travel surveys, etc. Therefore, the calculation of these measures is computationally more intensive, which makes them less frequently used than place-based measures (Neutens et al., 2010; Miller, 2018). In contrast to place-based measures, which yield a single accessibility estimate for all individuals in the same place, person-based measures results associate one accessibility estimate to each person in the study area. While this allows for more nuanced accessibility analyses, as the resultant accessibility estimates take the particularities of each individual into account, this also makes the communication and interpretation of results more complex.