Multimodal spatial availability: a singly-constrained measure of accessibility considering multiple modes

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Overview

Accessibility is a key concept in the analysis of land use and transportation systems. It is too coming of age from the perspective of planning (see *inter alia*, Handy 2020; El-Geneidy and Levinson 2022). Beginning with the work of Hansen (Hansen 1959), accessibility measures have been widely used to evaluate the efficiency of transportation systems when combined with the distribution of opportunities in space.

The most common form of accessibility measure is based on the gravity model, and recent research has focused on the way opportunities are counted (summed). Notably, the sums are not constrained meaning the same opportunity can enter the sum for different origins. This unconstrained counting results in accessibility values that are difficult to interpret, especially when comparing results between multiple modes.

In this paper we address this pitfall by extending spatial availability for multiple modes (Soukhov et al. 2023). Spatial availability is a singly-constrained competitive accessibility measure that constrains calculations to match a known quantity. This ensures the measurements sum up to a predetermined quantity (i.e., the total number of opportunities), and so each value can be meaningfully related to this total.

We demonstrate spatial availability's use in the case of multiple modes (i.e., heterogeneous population segments with distinct travel behaviours). We illustrate its features using a synthetic example, an empirical example of low emission zones in Madrid, Spain, and suggest future research directions in its use to evaluate policy interventions.

General form of multimodal accessibility measures

Hansen-type accessibility (Hansen 1959) - *Non competitive* and *unconstrained*:

$$S_i^m = \sum_j O_j f^m(c_{ij}^m)$$

Shen-type accessibility (Shen 1998; Luo and Wang 2003) - **Competitive** and *unconstrained*:

$$a_i^m = \sum_j O_j \frac{f^m(c_{ij}^m)}{\sum_m D_j^m} = \sum_j O_j \frac{f^m(c_{ij}^m)}{\sum_m \sum_i P_i^m f^m(c_{ij}^m)^m}$$

Spatial availability (Soukhov et al. 2023) - **Competitive** and **constrained**:

$$V_i^m = \sum_j O_j F_{ij}^{t,m} = \sum_j O_j \frac{F_i^{pm} \cdot F_{ij}^{cm}}{\sum_m \sum_i F_i^{pm} \cdot F_{ij}^{cm}}$$

Where:

- $m = 1, 2, \cdots, M$ is a set of M modes (or sub-populations) of interest.
- i is a set of origin locations ($i = 1, \cdots, N$)
- j is a set of destination locations ($j = 1, \cdots, J$).
- c_{ij}^m is a measure of the cost of moving between i and j for each m.
- $f^m(\cdot)$ is an impedance function of c_{ij}^m for each m, it can take the form of any monotonically decreasing function reflective of travel behaviour.
- O_j is the number of opportunities at location j; $O = \sum_{j=1}^{J} O_j$ is the total supply of opportunities in the study region.
- F_{ij}^{tm} is the total balancing factor for each m at each i; it consists of two factors.
  - First, the factor for allocation by population for each m at each i is $F_i^{pm} = \frac{P_i^m}{\sum_m \sum_i P_i^m}$ and
  - Then the factor for allocation by cost of travel for each m at i is $F_{ij}^{cm} = \frac{f^m(c_{ij}^m)}{\sum_m \sum_i f^m(c_{ij}^m)}$.

Spatial availability's proportional allocation mechanism

- V_i^m is always singly-constrained: $\sum_i V_i = \sum_m \sum_i V_i^m = \sum_j O_j$
- So, one can calculate spatial availability per ...
  - i: ($V_i = \sum_m V_i^m$)
  - **mode**: ($v^m = \sum_m \sum_i V_i^m$)
  - **capita in** i: ($v_i = \sum_m \frac{V_i^m}{P_{im}}$)

Synthetic example of 3 zones and 2 mode-using populations

i	Mode	Population		S		a		V	
A	z	30,000	50,000	45,000	72,292	1.6	1.3	46,946	65,919
	x	20,000		27,292		0.95		18,973	
B	z	100,000	150,000	45,000	72,292	1	0.89	102,997	134,209
	x	50,000		27,292		0.62		31,212	
C	z	7,000	10,000	3,746	5,986	1.1	0.99	7,838	9,872
	x	3,000		2,240		0.68		2,035	
TOTALS	N/A	210,000	210,000	150,570	150,570	N/A		210,000	210,000

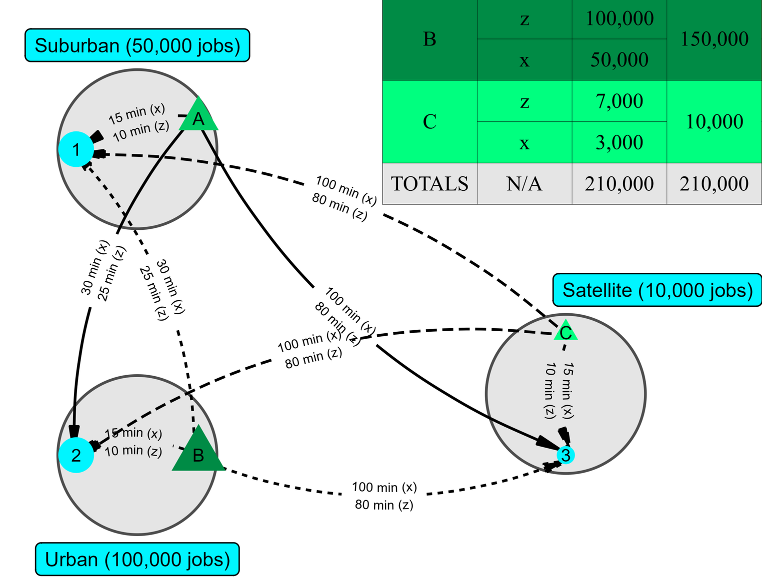

Figure 1: Calculated Hansen S, Shen-type a and Spatial Availability V assuming an impedance function of $f(c_{ij})^x = f(c_{ij})^z = exp(-0.1 \cdot c_{ij}^m)$ for the multimodal synthetic population.

When competition is not considered, **S** values for the Suburban A and Urban B are the same. Does this equivalency make sense for the differently sized A and B? Further, if constraints are not incorporated (i.e., **S** and **a**), values are hard to interpret. The regional sums of **S** and **a** are meaningless.

In considering both competition and constraints, **V** is not the same for A and B: Suburban A has more *available* jobs than mode-using population, the Urban B and the satellite C have fewer *available* jobs, and the sum of **V** is the total number of jobs in the region. We can interpret that the faster z population captures a higher proportion of availability than population in A, B, and C, unlike x. **The advantage of using spatial availability is the clarity in interpretation.**

Empirical example: multimodal access in Madrid

The low emission zone (LEZ) in the Centro of the City of Madrid was established in 2017 to pursue climate change mitigation goals. LEZs implement a form of *geographic discrimination* as they change how people can reach opportunities by making it more costly for some forms of travel, typically cars, to circulate in predetermined zones. LEZ change the accessibility landscape of a city from the perspective of multiple modes.

We ask: **what is the spatial distribution of availability that can be accessed by different mode-using population, especially for the car-using populations within and outside of the Centro LEZ?**

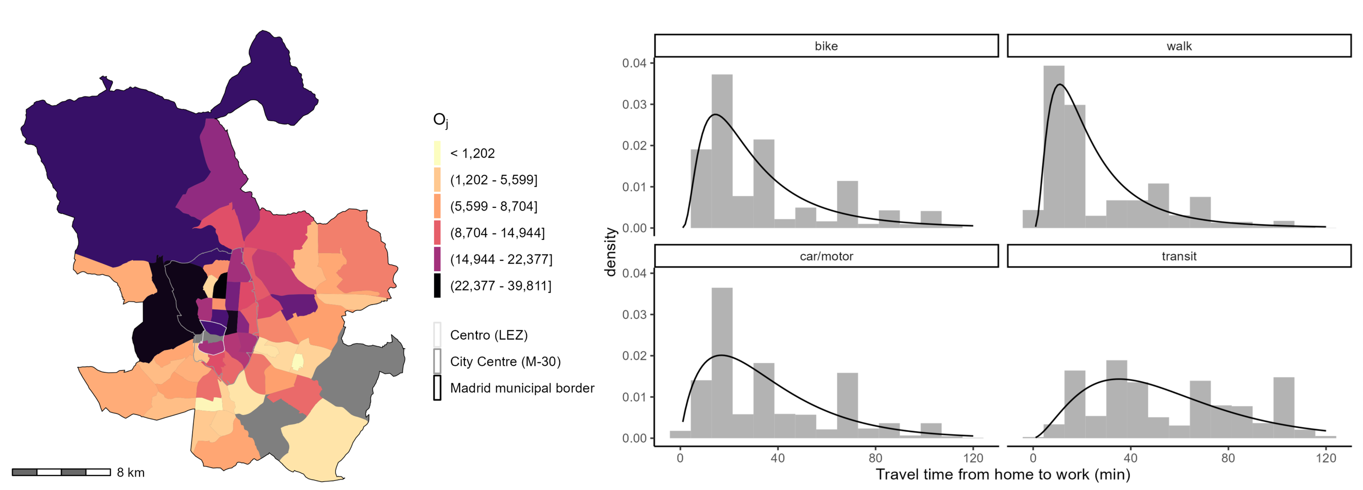

Figure 2: Spatial distribution of jobs taken by people living and working in Madrid as reported in the 2018 travel survey (left) and trip length distribution (right). Grey TAZs have no jobs. Ranges of values in the legend are quintiles. The TAZ shapefile is available from the Community of Madrid open data portal.

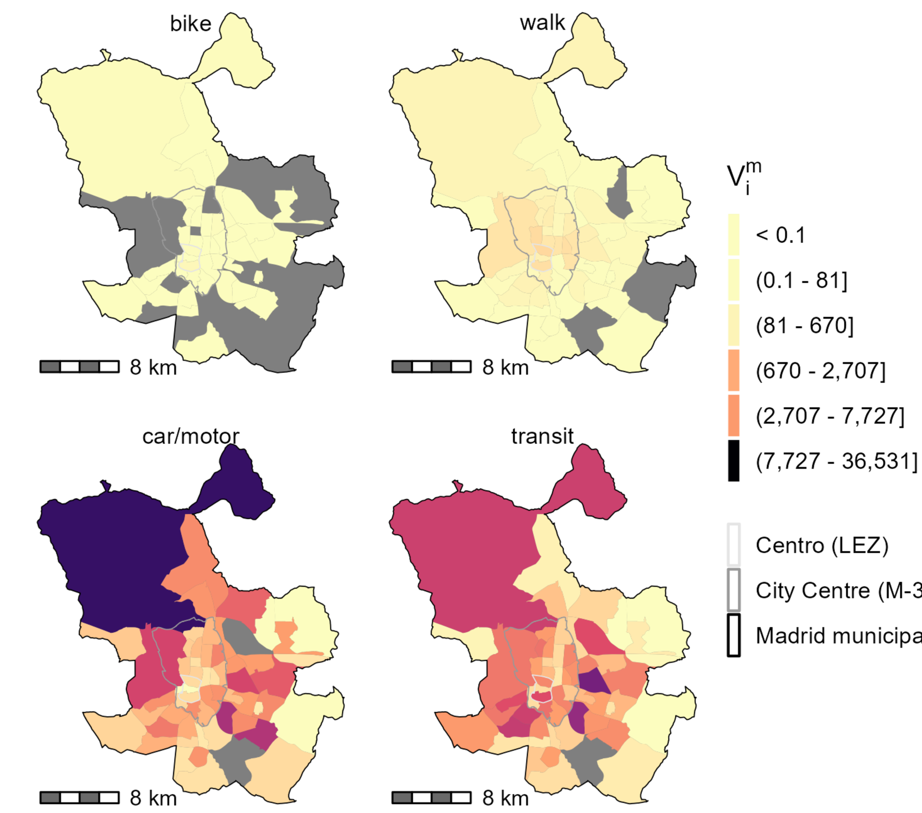

Figure 3: Spatial availability of jobs per origin and mode V_i^m.

- Each V_i^m is a proportion of the 847,574 jobs in the City of Madrid (OD full-time work flows from the 2018 Community of Madrid travel survey (Comunidad de Madrid 2020)). They represent the number jobs spatially available to m-using workers at that i, relative to all the jobs in the city.
- Note the differences in magnitudes between modes: the majority of availability is allocated to car- and transit- populations. This is to be expected as these modes represent 84.1% of the total population and reflect greater travel speeds.
- Car users outside of the M-30 broadly have greater spatial availability, while many zones inside the M-30 offer greater spatial availability to transit users.
- Overall, the magnitude of V_i^m for cyclists and pedestrians are lower than for car and transit, but the highest values of V_i^{bike} and V_i^{walk} are within the M-30 and zones with higher spatial availability by transit.

Interpreting multimodal spatial availability

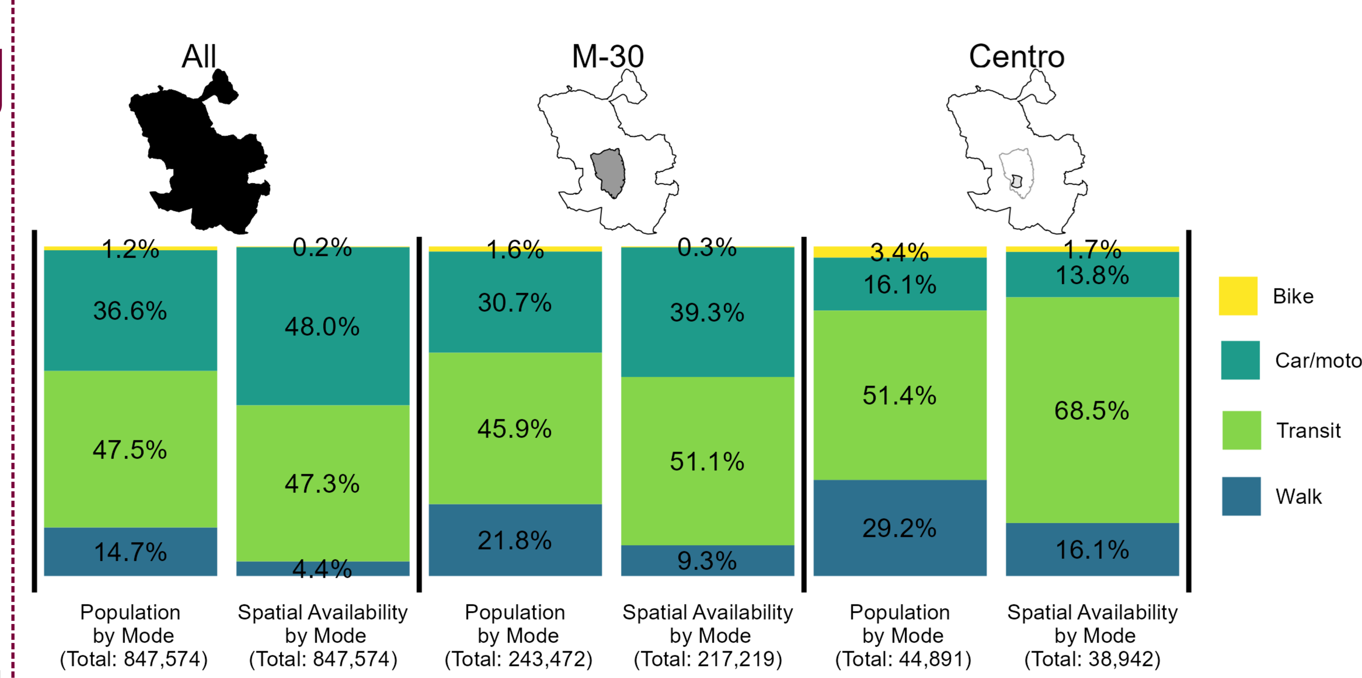

Figure 4: Proportion of population by mode and spatial availability of jobs by mode (V_i^m) aggregated for the city of Madrid (All), the area within the M-30 highway, and within the Centro.

Note the differences between proportions between mode depending on the spatial neighbourhood examined: car captures more availability than its population proportion overall (black) but this is not the case within the Centro (light grey). As such, non-car modes are better at capturing spatial availability within the M-30 (dark grey) and especially the Centro (light grey).

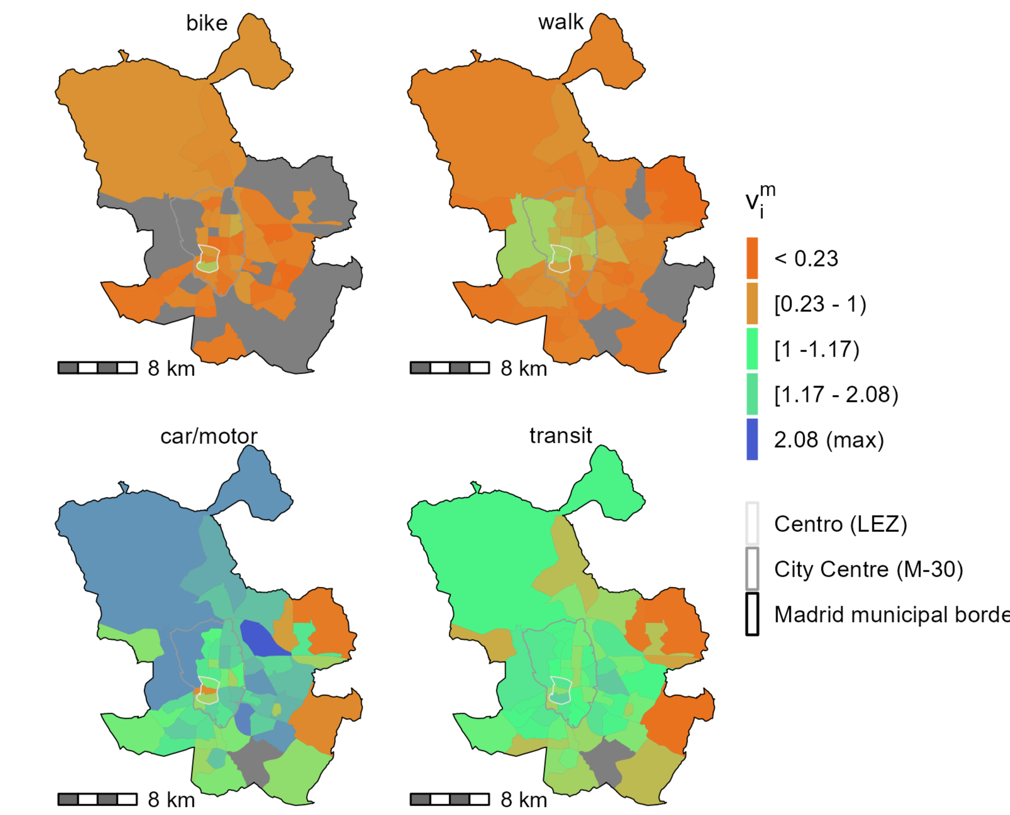

Figure 5: Distribution of spatially available jobs per capita by mode of transportatin (v_i^m).

Do we want a city where the spatial availability of opportunities is equal for all mode users? V_i^m can be divided by the mode-using population at each i to yield mode-population scaled values and used as a planning benchmark. Zones that are orange could be targets for interventions; and car-using populations can be further dissuaded.

Conclusions and future work

Opportunities are finite: spatial availability uses this idea as a constraint to consider competition for opportunities by the population. This consideration, through the proportional allocation factors, adds a new-found interpretation of accessibility values.

With spatial availability, the magnitude of opportunities that are available as a proportion of all the opportunities in the region is equal to V_i. Heterogeneous population characteristics, like difference in travel times due to mode used, can be easily incorporated, as done in this multimodal extension. The flexibility of spatial availability can be helpful in identifying zones and modes in need of intervention and highlights the spatial competitive advantage of certain modes.

Future works will look to model policy scenarios considering normative equity standards, and consideration of population and opportunities characteristics like income, travel mode used, and quality of opportunity.

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