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

Anastasia Soukhov[1], Javier Tarriño-Ortiz[2], Julio A. Soria-Lara[2], Antonio Páez[1]

[1] Department of Earth, Environment and Society, McMaster University, Hamilton, Canada
[2] Centro de Investigación del Transporte (TRANSyT), Universidad Politécnica de Madrid, Madrid, Spain

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Abstract

A pitfall in conventional accessibility measures are opportunities are often multiply counted, which leads to values of accessibility that are difficult to interpret.

Our purpose: a method for measuring accessibility for multiple modes that addresses this pitfall.

We extend spatial availability (Soukhov et al. 2023) for the case of multiple modes. Spatial availability constrains calculations to match a known quantity ensures that 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 its use in the case of multiple modes or, more generally, heterogeneous population segments with distinct travel behaviors. We proceed to illustrate its features using a synthetic example, an empirical example of low emission zones in Madrid, Spain, and suggestions for future research in evaluating policy interventions.

Overview of multi-modal 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.
- 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.
- i is a set of origin locations ($i = 1, \cdots, N$).
- j is a set of destination locations ($j = 1, \cdots, J$).
- 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 $F_{ij}^{cm} = \frac{f^m(c_{ij}^m)}{\sum_m \sum_i f^m(c_{ij}^m)}$.

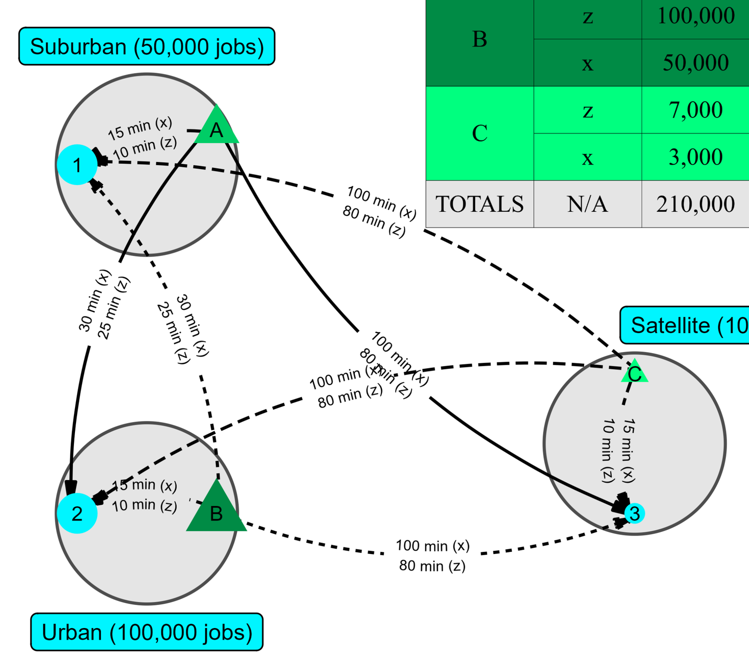
Spatial availability's proportional allocation mechanism

- 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: ($V_i = \sum_m V_i^m$)
  - **per mode**: ($v^m = \sum_m \sum_i V_i^m$)
  - **per capita in** i: ($v_i = \sum_m \frac{V_i^m}{P_{i^m}}$)
  - Etc.
  - Etc.

Synthetic example of 3 zones and 2 mode-using populations

The calculated Hansen (**S**), Shen-type (**a**) and Spatial Availability (**V**) assuming an impedance function of $f(c_{ij})^x = f(c_{ij})^z = exp(-0.1 \cdot c_{ij}^m)$ is also shown in the table.

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



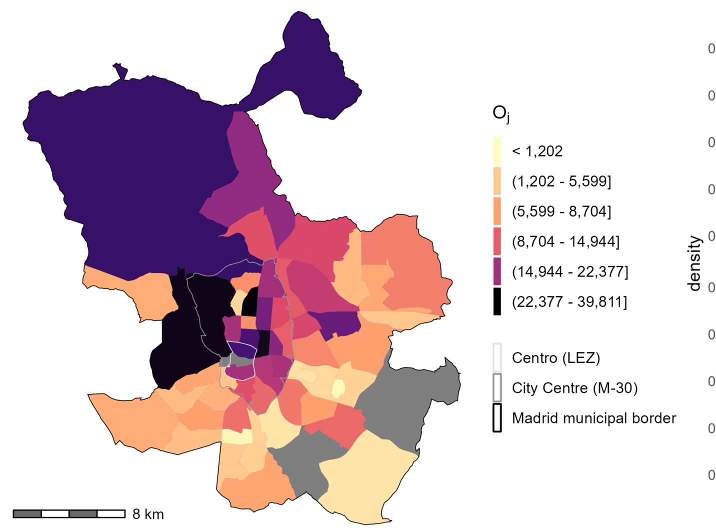
When competition is not considered, **S** values for the Suburban A and Urban B are the same. Does this equivalency make sense for the differently sized A and B? Further, if constraints are not incorporated (i.e., **S** and **a**), values are hard to interpret. The regional sums of **S** and **a** are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

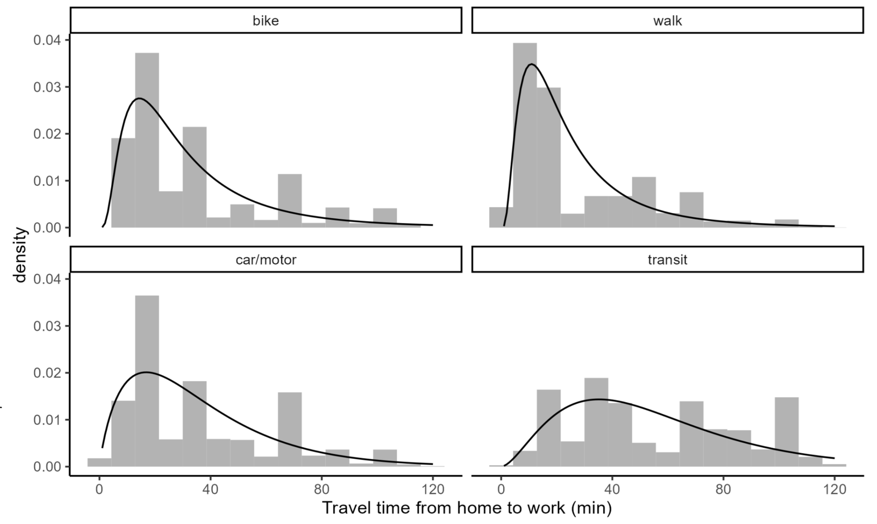
In considering both competition and constraints, **V** is not the same for A and B: Suburban A has more *available* jobs than mode-using population, the Urban B and the satellite C have fewer *available* jobs, and the sum of **V** is the total number of jobs in the region. We can interpret that the faster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

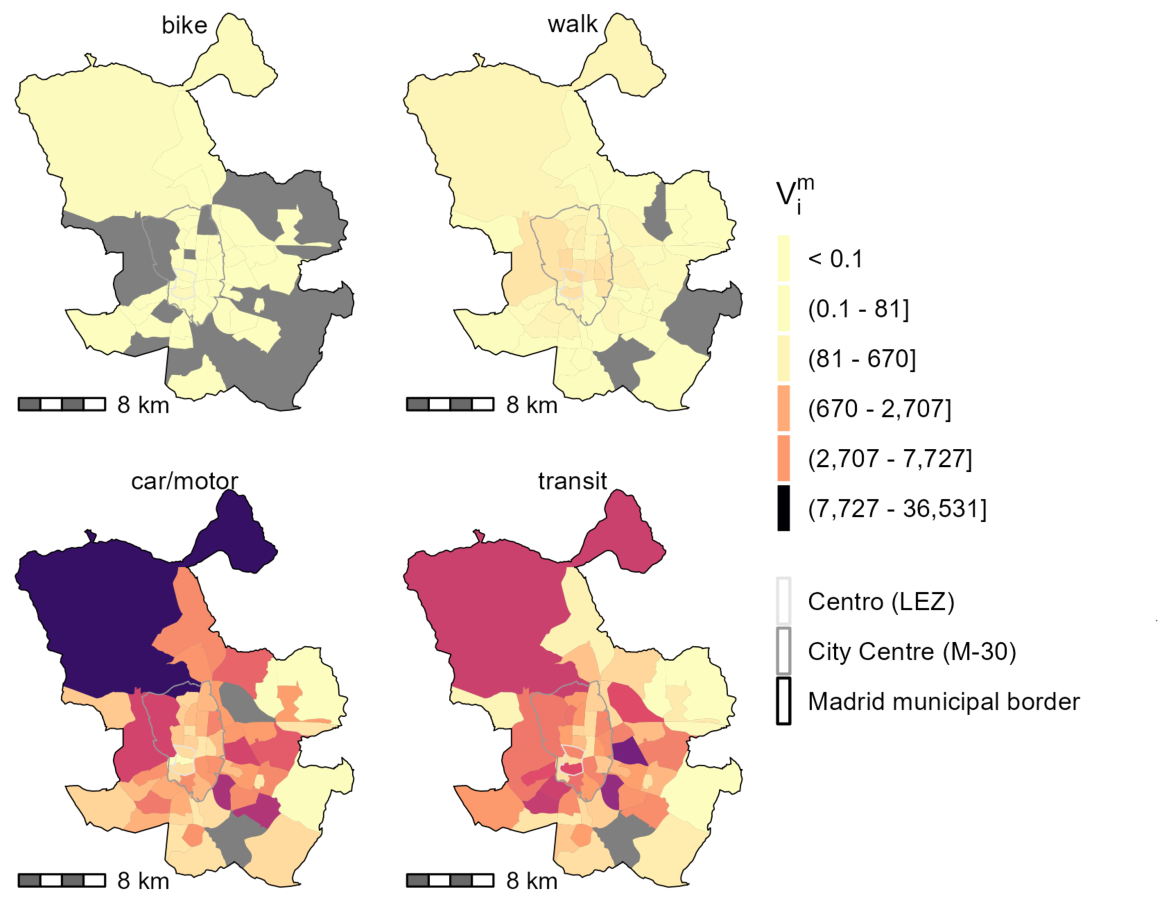
Empirical example: quantifying multimodal access in Madrid

The low emission zone (LEZ) in the Centro of the City of Madrid was established in 2017 to pursue national climate change 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?**

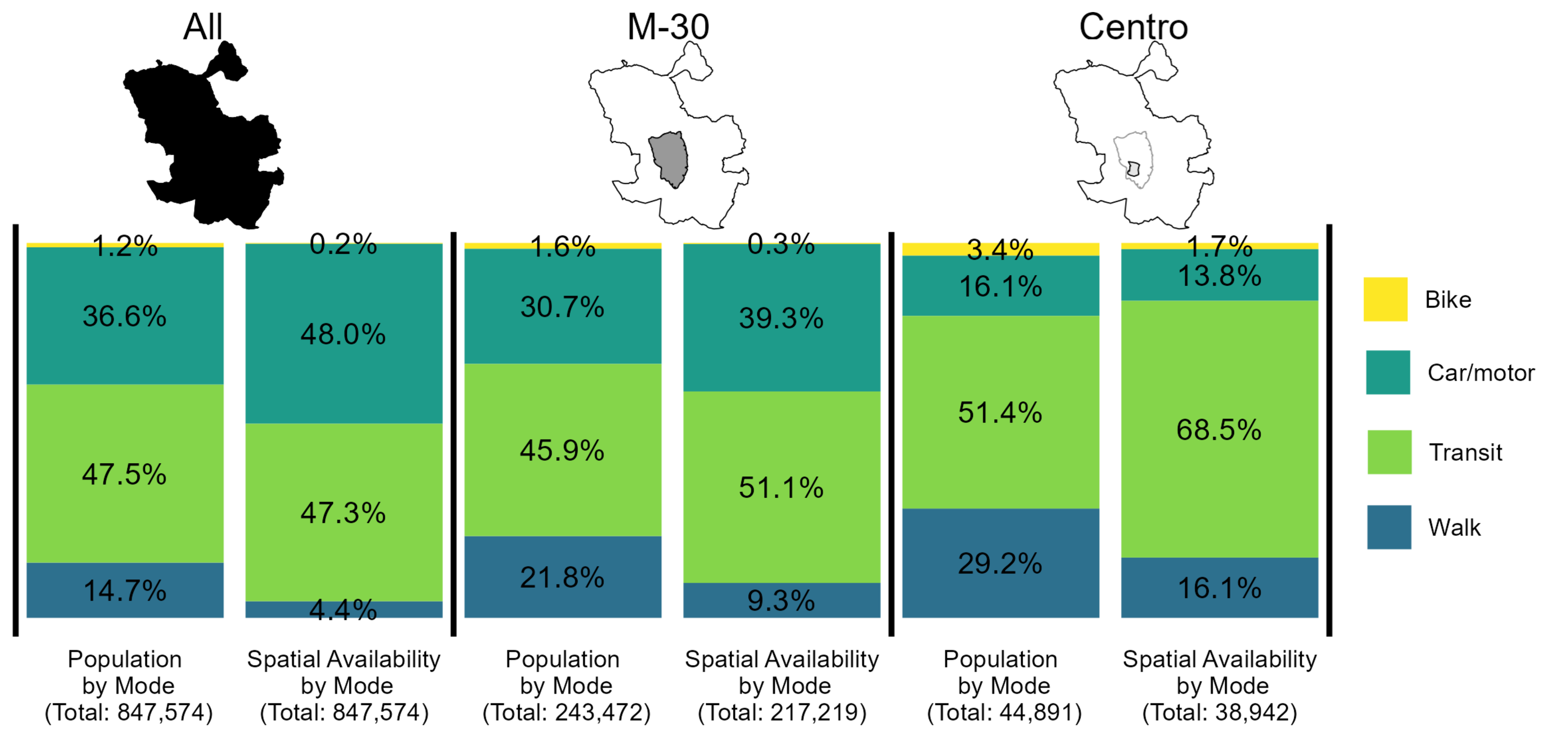




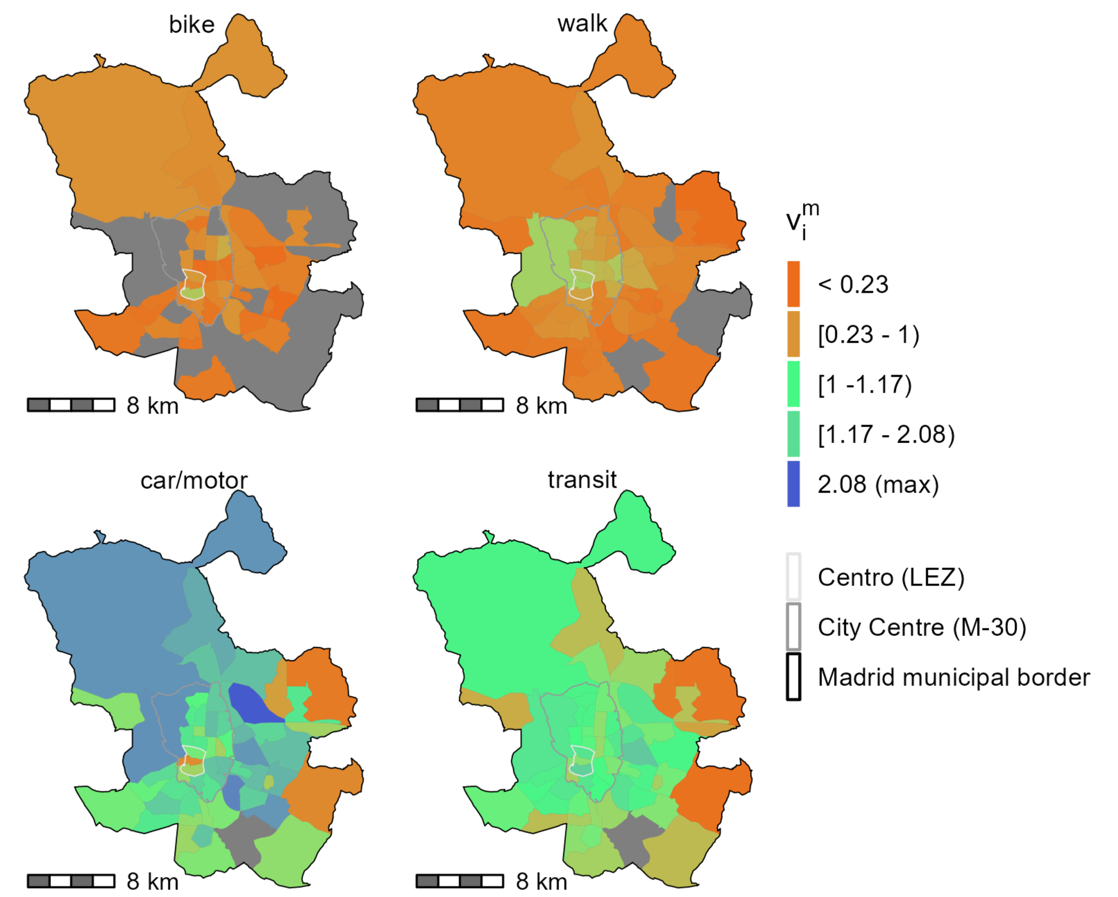


- Each V_i^m is a proportion of the 847,574 jobs in the City of Madrid (OD full-time work flows from the 2018 Community of Madrid travel survey (Comunidad de Madrid 2020)). They represent the number jobs spatially available to m-using workers at that i, relative to all the jobs in the city.
- Note the 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



Note how the differences between these proportions change: 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 fair much better at capturing spatial availability within the M-30 (dark grey) and especially the Centro (light grey).



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 should be targets for interventions; and car-using populations can be further targeted.

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 in need of intervention and highlights the spatial competitive advantage of certain modes.

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

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