

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

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<b>Corresponding Author:</b>	Anastasia Soukhov McMaster University Toronto, ON CANADA
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<b>Abstract:</b>	Recent research has aimed to address the way opportunities are counted in accessibility analysis. In conventional accessibility measures, opportunities are often multiply counted, which leads to values of accessibility that are difficult to interpret. Constraining the 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. A recent effort is spatial availability, a singly-constrained accessibility measure. In this paper we extend spatial availability for use in the case of multiple modes or, more generally, heterogeneous population segments with distinct travel behaviors. After deriving a multimodal version of spatial availability, we proceed to illustrate its features using a synthetic example. Next, we apply it to an empirical example of low emission zones in Madrid, Spain. We conclude the paper with suggestions for future research and its use in evaluating policy interventions.
<b>Order of Authors:</b>	Anastasia Soukhov, MSc.  Javier Tarriño-Ortiz, PhD  Julio A. Soria-Lara, PhD  Antonio Páez, PhD
<b>Opposed Reviewers:</b>	
<b>Response to Reviewers:</b>	<p>Please see the 'Response-to-reviewer.pdf' for the formatted letter.</p> <p>#Reviewer 1</p> <p>Thank you for this comment regarding "1. Lack of Innovation". We would like to bring to your attention the editorial philosophy of PLoS ONE, according to which editors "make decisions on submissions based on scientific rigor, regardless of novelty," (see <a href="https://journals.plos.org/plosone/s/editorial-and-peer-review-process">https://journals.plos.org/plosone/s/editorial-and-peer-review-process</a>). Nonetheless we wish to respond to this comment.</p> <p>In this paper we extend our earlier work on spatial availability (<a href="https://doi.org/10.1371/journal.pone.0278468">https://doi.org/10.1371/journal.pone.0278468</a>) for the simultaneous analysis of multiple modes of transportation. You appear to be under the misapprehension that the main difference with accessibility measures is to incorporate "the ratio of travel frequencies as weight in travel costs". This statement is not correct. The main difference is the proportional allocation mechanism that we introduced for spatial availability, and that is extended in this paper to allocate opportunities based on the proportion of travelers by different modes. This is not the same as "weighting the travel cost". In fact, each mode is modelled using its own impedance function, as shown in our empirical example, where we use origin-destination data by mode to estimate travel impedance functions specific to each mode.</p>

While this enhancement may appear minor in your opinion, it is not plainly obvious how spatial availability applies to multiple modes, which is why we believe this paper is needed. We do not dispute that this is an incremental step in the development of a more general method, but it is a step that considerably expands the range of potential applications. Further, we contend that the method has been rigorously developed and demonstrated this using an open, transparent, and reproducible example. In response to this comment we have edited the paper to more clearly describe the advantages that multimodal spatial availability offers when considering the accessibility to opportunities by different modes. In particular, proportional allocation of opportunities using mode-specific impedance functions means that the travel-cost-advantage of each mode can be analysed. Further, this mechanism ensures that the sum of all spatial availability values for all modes sum up to the total number of opportunities in the region, which is not true for any other type of accessibility measure. With respect to the "superiority" of the method, a reader of our earlier paper would already be aware of what limitations of accessibility analysis spatial availability aims to address. In this paper we also try to demonstrate throughout the manuscript what our measure does that others can't. Since spatial availability values result from proportional allocation, each value is a proportion of the total number of opportunities. Put another way, we can compare the proportion of opportunities available to users of each mode, to users at each zone, to users of each mode by zone, and so on, and the values relate directly to the total opportunities in the region. This also allows us to calculate values per capita that serve as benchmark values, as shown in the empirical example.

Thank you for this comment regarding "2. Insufficient Experimental Data". To clarify, the empirical data used is not experimental. It is observational, since it is collected using a travel survey conducted by the City of Madrid. Travel surveys are a standard instrument in transportation planning and research, and are conducted in cities around the world. The data we work with represent the most recent and most complete travel survey conducted for the region to date. We are not completely sure where you got the figure of "30,000 trips" (which you consider significantly limited); presumably you are citing the maximum 'opportunity' or 'population' numbers in Figures 2 or 3. The most job-rich TAZs have 30,000 jobs while the least have 1,000 or fewer (Figure 2). In fact, there are 847,574 jobs in the city, which is also the sum of the total spatial availability in our analysis, as well as the number of potential trips to work.

With respect to The "typicality" of the data, travel surveys are designed to provide information about personal travel on a typical day, usually during a period of maximum demand (i.e., not during the summer vacation). This is standard practice for these surveys, and the one for Madrid is no different in this respect.

Regarding "3. Lack of Data-Driven Analysis". Thank you for this comment. It is somewhat puzzling that "30,000 trips" would be significantly limited (as per your comment #2), and at the same time be "a large amount of data". We find that this comment in particular is not actionable due to its vagueness. There are no meaningful responses to "somewhat one-sided" when "somewhat" and "one-sided" do not quantify or refer to a particular side. We studied the modes available in the region, and examined the results from the perspective of each mode. What other perspectives do you suggest? What dimensions should be explored?

Despite this comment being nonactionable, we believe that with the additional detail added to the manuscript to address your and other reviewers' comments, that overall clarity has been improved.

Regarding "4. Disorganized format". Reviewer #2 identified some specific formatting issues and we fixed them. Otherwise we proofread the paper and hopefully did not leave a typo behind. We also made sure Table 1 starts on a new page, when it runs across pages the formatting resulted in some disorganization. Thank you again for your efforts reviewing our submission.

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#Reviewer 2

Thank you for your thoughtful review of our paper. Your comments were very helpful to

improve the clarity of the research.

Regarding "method limits: focuses on the competition for jobs and is not useful for studying access to non-competitive or semi-competitive resources". Thank you for this comment. We would begin by noting that there are many types of opportunities that are mutually exclusive due to competition. For this paper we focused on jobs, but there are many others, such as beds at hospitals, seats at schools, and so on. Thus, even if the measure was applicable only to exclusive opportunities, there are numerous applications to choose from.

That said, we have grappled for some time with the question of what types of opportunities are best analysed using spatial availability. Our current thinking on this matter, after much consideration, is that in practice every type of opportunity, even when not clearly exclusive, is subject at least to congestion or capacity constraint. For instance, green spaces are often considered non-competitive, however, standards for the provision of such amenities are provided in the form of units of amenity per capita. For example, a case could be the Ile-de-France region, a jurisdiction that suggested in a major planning document of 2013 that at the municipal level at least 10m<sup>2</sup> of public green space should be supplied per inhabitant (Liotta et al. 2020). But green spaces are not evenly distributed, which means that who has access to them hinges on where they are and how easy it is to reach them. Formulating the provision of amenities in these terms is not rare. For example, Natural England recommends an Accessible Natural Greenspace Standard such that the minimum supply of space is one ha of statutory Local Nature Reserves per thousand population (see <https://redfrogforum.org/wp-content/uploads/2019/11/67-Nature-Nearby%20%99-Accessible-Natural-Greenspace-Guidance.pdf>). Similarly, the World Health Organization (cited in OECD, 2013) recommends that cities provide a minimum of 9m<sup>2</sup> of green area per inhabitant (see <https://doi.org/10.1789/9789264191808-en>). For our purposes, standards of this type translate into "how much of this resource is available to one individual that has not been claimed by anyone else?". Green spaces often have large capacities, but they still have a capacity, and it is not the same for a person to have access to 5m<sup>2</sup> of uncongested green space than to 15m<sup>2</sup>. This difference is in fact a matter of justice (Lara-Valencia and García-Pérez 2015; Liotta et al. 2020). Constraining accessibility is in this way a useful way to evaluate the congested availability of any type of opportunity. As standards are emphasized in the planning literature, in particular for fairness in transportation (see Martens and Golub 2021), spatial availability analysis can be used to assess standards. We are convinced that as other researchers discover this new approach to measuring accessibility many other applications will be found.

Regarding "method limits: does not allow for absolute gains or losses to be studied". Thank you for this comment. Spatial availability can certainly be used to capture absolute gains and losses. In fact, logically, the gains and losses produced by using a competitive and constrained measure allows for a clear interpretation. This would require the analyst to estimate the accessibility before and after some change to the land use or transportation system. In this paper our empirical application is a single scenario to serve as proof of concept, but in future research we intend to use spatial availability to analyse changes in the size of Madrid's Low Emissions Zone implementation from a modal and socio-economic equity perspective.

Regarding "method limits: modal shift?". This is an excellent point. Accessibility measures, including spatial availability, are not meant to function as modal split models, but they are certainly amenable to analysis of changes in the accessibility landscape if different modal shares are used as inputs. This is similar to the case of destination choice: accessibility measures do not model this, but changes in destination choices can be incorporated via how they affect the impedance function. In terms of how this could be implemented, the process can be sketched as follows: the results of a modal split model are used to estimate new modal shares, which in turn are used to recalculate spatial availability. The new values then can be compared to the baseline scenario. In other words, the framework for spatial availability is sufficiently flexible to take in not only mode-specific travel impedance functions, but also the proportions of the populations using each mode.

	<p>Regarding "suggestions for specifying method limits". Your comments have been very helpful to improve the clarity of the paper, as well as the scope of what we do, as well as directions for future research. For example, we now note in the "Discussion and conclusions" that "our example dealt with differences in travel by mode only, but it is possible to think of the intersection between mode of travel and different types of travelers. This would expand the number of sub-populations in the analysis from, say, <math>m = M</math> (modes) to <math>m = M \cdot Q</math> (modes times population segments), each with their own characteristic impedance function. Evaluations of this kind will be especially relevant as LEZ are implemented in cities globally, and the question of their impact on disadvantaged populations who have become mobility-restricted increasingly come to the fore (De Vrij and Vanoutrive 2022; Verbeek and Hincks 2022; Liotta 2023)."</p> <p>Regarding "improvements to abstract and introduction". We have now done this. In the original version of the abstract and introduction we gave the misleading impression that we would analyse changes in the system, when in reality our intent was to demonstrate the application of the measure in an empirical example. We do plan to study changes in the system, but this requires more work than can be presented in a single paper, partly for the reasons that you identified above (modal shifts and the calculation of spatial availability for two different scenarios, as well as the analysis of the differences between them). We plan to do this in a future paper focused on the policy instead of the presentation of a new method. Thank you again for your thoughtful comments and suggestions to improve the paper.</p> <p>Regarding "minor comments". Updated! Apologies, car: '36 min' corresponds to a mean of 36 minutes and then within the brackets additional descriptive statistics (minimum value, maximum value, etc.). We also fixed the formatting issues specified.</p> <p>---</p> <p>#Reviewer 3</p> <p>Regarding "major issues". This is an excellent comment. The short answer is that whenever a destination can be reached by more than one mode, users of those modes are in competition for the opportunities there.</p> <p>In this revision we tried to improve the discussion to make this point more clear. The impedance functions for all four modes are not the same. They describe the travel behaviour of commuters as informed by the 2018 travel survey. To follow your example, someone who cannot walk to work because their job is 20 km from where they live, will not compete for that job against people from their same origin who do walk. However, if the place where their work is can be reached by anyone who can walk from other origins (say, someone who lives closer to that destination), they would be in competition for the same opportunity.</p> <p>Furthermore, average travel times for car/motor and transit are longer than bike and walk. All people don't have access to all options - completely true. But the travel impedances reflect this real travel at an aggregate based on all the trips for a mode. And on average, it is assumed that people at each origin that take a mode to a destination are in direct competition for opportunities (as opportunities are finite) – and a part of the competition is defined by the mode-specific impedance function (the second part is the population balancing factor). This assumption, that all populations, no matter their mode, are competing for the same finite set of opportunity, is part of spatial availability. We've made an effort to make this more clear in the text.</p> <p>Regarding "minor issues". We have updated the captions of the figures to reflect the meaning of grey colour blocks and the colour scheme of all Figures. We've also updated the labels on the legends to make them more interpretable.</p>
<b>Additional Information:</b>	
<b>Question</b>	<b>Response</b>
<b>Financial Disclosure</b>	AS - Canada Graduate Scholarship - Doctoral Program (CGS D) provided by the Social Sciences and Humanities Research Council (SSHRC)
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<p><b>Describe where the data may be found in full sentences. If you are copying our sample text, replace any instances of XXX with the appropriate details.</b></p> <ul style="list-style-type: none"> <li>• If the data are <b>held or will be held in a public repository</b>, include URLs, accession numbers or DOIs. If this information will only be available after acceptance, indicate this by ticking the box below. For example: <i>All XXX files are available from the XXX database (accession number(s) XXX, XXX.).</i></li> <li>• If the data are all contained <b>within the manuscript and/or Supporting Information files</b>, enter the following: <i>All relevant data are within the manuscript and its Supporting Information files.</i></li> <li>• If neither of these applies but you are able to provide <b>details of access elsewhere</b>, with or without limitations, please do so. For example:</li> </ul> <p><i>Data cannot be shared publicly because of [XXX]. Data are available from the XXX Institutional Data Access / Ethics Committee (contact via XXX) for researchers who meet the criteria for access to confidential data.</i></p> <p><i>The data underlying the results presented in the study are available from (include the name of the third party</i></p>	<p>The data underlying the work presented in the study are available from (<a href="https://github.com/soukhova/Multimodal-spatial-availability">https://github.com/soukhova/Multimodal-spatial-availability</a>).</p>

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Department of Earth, Environment and Society, Faculty of Science  
McMaster University, 1280 Main Street West  
Hamilton, Ontario, Canada, L8S 4L7

November 9th, 2023

Dear Emily Chenette,  
*Editor-in-Chief, PLOS ONE*

This letter is in support of the revised manuscript submitted titled ***Multimodal spatial availability: a singly-constrained measure of accessibility considering multiple modes***. I am the lead and corresponding author, and a doctoral graduate candidate in the School of Earth, Environment and Society at McMaster University. The co-authors are Javier Tarriño-Ortiz, a doctoral graduate from Universidad Politécnica de Madrid, Spain; Prof. Julio A. Soria-Lara from the Urban and Regional Planning at Universidad Politécnica de Madrid, Spain; and Prof. Antonio Paez from the School of Earth, Environment and Society at McMaster University.

As a continuation of our research efforts and an extension of our previously published work in PLOS ONE titled ***Introducing spatial availability, a singly-constrained measure of competitive accessibility*** published in January 2023 ([DOI](#)), this present submission expands spatial availability to quantify differences in accessibility offered by mode. An increasing number of studies within this field are concerned with inequities, particularly those arising from differences in access by mode type or other heterogenous population characteristics. However, existing methods for assessing accessibility fall short in accounting for aspects of competition for opportunities and the finite nature of opportunities themselves. In this vein, we first illustrate the features of spatial availability that make it suitable for multimodal analysis. Subsequently, we demonstrate its application through a case study of Low Emission Zones (LEZ) in Madrid (Spain), showcasing how the measure could be used to discuss competition between modes within the LEZ.

We are sincerely appreciative of the comments provided by the reviewers. We considered them carefully and revised the manuscript to clarify key concepts and define the boundaries and scope of our approach especially as related to the empirical example. We also improved the overall flow of the manuscript by splitting sub-sections into sections, reducing superfluous explanations, and adding additional literature to support certain ideas.

We look forward to hearing again from you and your expert reviewers. On behalf of my co-authors, I would like to thank you in advance for your attention.

Sincerely,

**Anastasia Soukhov**, MSc, B.Eng.  
PhD Candidate,  
School of Earth, Environment and Society, McMaster University  
Email: [soukhoa@mcmaster.ca](mailto:soukhoa@mcmaster.ca)

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

Anastasia Soukhov <sup>1</sup> \*, Javier Tarriño-Ortiz <sup>2</sup> , Julio A. Soria-Lara <sup>2</sup> , Antonio Páez <sup>1</sup>

**1** Department of Earth, Environment and Society, McMaster University, Hamilton, Canada

**2** Centro de Investigación del Transporte (TRANSyT), Universidad Politécnica de Madrid, Madrid, Spain

\* Corresponding author: soukhoa@mcmaster.ca (AS)

## Abstract

Recent research has aimed to address the way opportunities are counted in accessibility analysis. In conventional accessibility measures, opportunities are often multiply counted, which leads to values of accessibility that are difficult to interpret. Constraining the 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. A recent effort is spatial availability, a singly-constrained accessibility measure. In this paper we extend spatial availability for use in the case of multiple modes or, more generally, heterogeneous population segments with distinct travel behaviors. After deriving a multimodal version of spatial availability, we proceed to illustrate its features using a synthetic example. Next, we apply it to an empirical example of low emission zones in Madrid, Spain. We conclude the paper with suggestions for future research and its use in evaluating policy interventions.

## Introduction

Accessibility is a key concept in the analysis of land use and transportation systems [e.g., 1,2,3], and too is coming of age from the perspective of planning [see *inter alia*, 4,5–8]. Beginning with the work of Hansen [1], accessibility measures have been widely used to evaluate the efficiency of transportation systems when combined with the distribution of opportunities in space [9]. As such, it is a holistic measure of spatial systems that measures the ease of reaching destinations [10,11].

In practice, the most common form of accessibility measure is based on the gravity model. These measures are sums of weighted opportunities around a focal point (i.e., a potential origin), based on how expensive it is to reach them. Recent research in accessibility analysis has paid attention to the way opportunities are counted in the pertinent calculations. Conventionally, the sums are not constrained, which means that the same opportunity can enter the sum for different origins. Counting the same opportunity multiple times treats it as if it was inexhaustible. But opportunities in general are not inexhaustible, and in fact some of them are by definition exclusive: for example, once a job is taken up by someone in the population, the same job is no longer available for any other person to take. More generally, opportunities are subject to

congestion: for example, multiple people can obtain services from the same family doctor, but the more people who do, the more congested the service will be.

The issue of congestion in accessibility measures was the motivation for the development of floating catchment area approaches [12,13]. While these approaches purport to account for congestion, Paez et al. [14] demonstrate that in general they do not solve the issue of multiple counting of opportunities, thus leading to biases in the calculation of total demand and supply, sometimes inflating them, other times deflating them. In response to this, recent research has paid closer attention to the way opportunities are counted in accessibility analysis. Paez et al. [14], for example, tackle floating catchment area methods and introduce a normalization of the impedance matrix to allocate the population and then the level of service proportionally. More recently, Soukhov et al. [15] introduced a singly-constrained measure of accessibility, called spatial availability, that employs a similar, but more sophisticated proportional allocation mechanism. The work of these authors show that floating catchment area methods can be seen as singly-constrained accessibility measures, and improve on existing approaches by guaranteeing that each opportunity is counted only once - in other words, treating opportunities as *finite*. The proportional allocation of spatial availability constrains the calculations to match a known quantity, therefore ensuring 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.

A limitation of spatial availability as introduced by Soukhov et al. [15] is that it was developed for the case of a homogeneous population, for example for the case of a single mode of transportation. However, the finite nature of opportunities makes the analysis of heterogeneous populations very relevant. In the case of multiple modes of transportation, people who travel by slower modes (e.g., active modes) can usually reach fewer opportunities than people who travel by faster modes and whose range is typically far wider (e.g., car). This implies that slower travelers will often face increased competition for local opportunities from travelers who can reach said opportunities from farther afield.

The objective of this paper is to address this limitation of spatial availability. Our primary motivation is to extend spatial availability for the case of multimodal accessibility, but it is worthwhile noting that this is in fact just one case of heterogeneous populations (i.e., travel by different modes). The method itself can easily accommodate other forms of heterogeneity, for example variations in travel behavior between older and younger adults [e.g., 16], the propensity of older adults to use different modes of transportation [e.g., 17], the usually shorter trip lengths of children compared to grown-ups [e.g., 18], or the more limited travel ranges of single parents [e.g., 19].

The rest of this paper is organized as follows. In Section 2 we provide a brief review of multimodal accessibility. In the following Section 3 we demonstrate the derivation of the new spatial availability expression for multiple modes. In Section 4 we illustrate relevant issues through a synthetic example. This is followed in Section 5 by an empirical example using data from the city of Madrid after the implementation of its Low Emission Zones (LEZ). Data for this example comes from the city's 2018 travel survey. The example shows the differences in spatial availability within and outside the LEZ for travelers using different modes, namely car, transit, cycling and walking. In Section 6, we provide concluding remarks on the strengths of the use of spatial availability as a multimodal accessibility measure, and discuss potential future uses in policy planning scenarios as well as directions for future research.

## A brief review of multimodal accessibility

Location-based accessibility indicators are quantitative measures of *potential* interaction with opportunities for locations within a given region: they are summary measures of the relationship between land-use and transport systems. Arguably, the most commonly used are measures based on the gravity model [20], of which cumulative opportunity measures and weighted cumulative opportunity measures are particular forms [5]. These measures assign a weight to opportunities based on how easy it is to reach them. Given an origin ( $i$ ) and a destination ( $j$ ), an impedance function  $f^m(c_{ij}^m)$  converts the cost of travel (e.g., time, money, generalized cost) into a score that represents the propensity for interaction. These measures originate from that proposed by Hansen [1], which can take the following form in the multimodal case:  $S_i^m = \sum_j O_j f^m(c_{ij}^m)$  where  $m$  is a set of modes which have mode-specific travel costs ( $c_{ij}^m$ ) and/or travel impedance functions ( $f^m(\cdot)$ ).

Hansen-type accessibility is not constrained, which is to say it does not consider the opportunities as finite. To cite an example, Tahmasbi et al. [21] use Hansen-type accessibility to assess the potential interaction with retail locations by three modes: walking, public transit, and car (i.e.,  $m = w, p, c$ ).  $S_i^m$  is the sum of retail locations  $j$  that can potentially be reached under the travel impedance as calculated for each  $i$  and  $m$ . In other words, for each origin  $i$  three accessibility scores are calculated. In this work, Tahmasbi et al. [21] show that car travel affords the highest  $S_i^m$  values in the majority of  $i$ , i.e., travelers who use a car can potentially reach more retail opportunities than populations using other modes. However, higher  $S_i^m$  values for car do not affect the values of  $S_i^m$  for other modes: in effect, each mode is analysed as if the others did not exist. Since the measure is not constrained, each opportunity is typically counted multiple times within and between modes, and as a result the sum of accessibility is not necessarily a meaningful quantity. The accessibility scores for the modes are often values that are difficult to interpret beyond making statements about relative size. For example, Lunke [22], researching the region of Oslo, reports accessibility scores for car in the order of tens of thousands of employment opportunities. The corresponding scores for transit are lower, but still often in the thousands or tens of thousands. As reported, the ratio of the transit to the car score can be lower than 0.2 (meaning transit gives access to less than 20% of the opportunities than car). But despite the discussion about “sufficient accessibility”, it is unclear what the unconstrained scores mean: is having access to but 10,000 jobs by transit insufficient? After all, 10,000 employment opportunities are still plenty of opportunities. These ratios can be found elsewhere in the literature [e.g., 23, and 9,16,19, and 8], and they are useful as relative assessment of when some members of the public are better or worse off than others, but they do not say much about how bad is “worse off”.

Besides ratios of accessibility, another way to improve interpretability of scores sometimes seen in the literature is to standardize them to lie in the range [0-1]. This adjustment is only helpful insofar as it facilitates relative comparisons, but interpretation of the scores remains challenging because the values are specific to a region and convey no meaning about the magnitude of the scores. In this approach, zones always have values between 0 and 1, but how remarkable is a zone with a low score for pedestrians and a high value for car? And if remarkable, what does the difference in these standardized values mean for planners? By how much should transport systems and land-use configurations be changed to improve conditions? And in what way can these scores be used to track differences over time? Or between regions? These questions lack straightforward answers since certain values will always be relatively ‘low’ or ‘high’, but do not track to a quantity that can be intuitively understood. Presentation or discussion of Hansen-type accessibility that has been standardized in this way is not uncommon in the literature [e.g., 24,25].

Once we understand opportunities to be finite, it is possible for an accessibility measure to take on a crisper meaning. As considered in the long tradition of accessibility research, capacity of opportunities is limited and thus is subject to competition by population [12,15,26–30]. There are only so many school-seats, hospital capacity, employment opportunities, etc., in a region and if one person reaches an opportunity, it is taken: the supply of an opportunity and the demand for that opportunity are two components of accessibility. These are clear examples of opportunities that are unambiguously competitive. But we would go as far as to argue that every type of opportunity is subject to congestion or capacity constraint, even when the opportunities are conventionally seen as non-competitive.

Amenities are a good example of this. For instance, standards for providing green spaces are often stated in the form of *exclusive access*, in units of amenity per capita. A case in point is a the Ile-de-France region, a jurisdiction that suggested in a 2013 planning document that at the municipal level at least  $10m^2$  of public green space should be supplied *per inhabitant* [31]. Green spaces are not evenly distributed, which means that who has access to them hinges on where they are and how easy is to reach them. This formulation of provision of amenities is not unusual. For example, Natural England, an organization that recommends an Accessible Natural Greenspace Standard such that the minimum supply of space is one ha of statutory Local Nature Reserves per thousand population<sup>1</sup>. Similarly, the World Health Organization [cited in 32] recommends that cities provide a minimum of  $9m^2$  of green area per inhabitant. For our purposes, standards of this type translate into “how much of this resource is available to one individual that has not been claimed by anyone else?”. Green spaces often have large capacities, but they still have a capacity, and it is not the same for a person to have access to  $5m^2$  of *uncongested* green space as  $15m^2$ . This difference is in fact a matter of justice [31,33]. Constraining accessibility is in this way a useful way to evaluate the congested availability of any type of opportunity. As development of sound standards is emphasized in the planning literature, in particular in regards to fairness in transportation [see 34], spatial availability analysis is a useful way to develop and assess standards.

The relevance of the considerations above is put in sharper relief when we think about the use of multiple modes (or heterogeneous populations). If we return to Oslo for a moment [22], we notice that the places that have high accessibility by transit are also the places that have *very high* accessibility by car (in their Figure 2). Those two populations are going for the same opportunities, and those travelling by transit have fewer to choose from to begin with. More generally, people in a zone who are advantaged with relatively low cost of travel will have the ability to potentially reach more opportunities than other people. Due to this advantage, through the perspective of finite opportunities, there are fewer opportunities left for everyone else, especially for those who use modes that are slower or otherwise more expensive.

As noted in the Introduction, competitive accessibility was the rationale for developing floating catchment area methods (FCA), popularized by Luo et al. [13] who reformulated the work of Shen [12] into two steps (although similar, and earlier, developments are found in [30,35]). Shen-type accessibility is formulated as:

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

where  $D_j^m$  is the potential demand for opportunities equal to travel impedance weighted population  $\sum_i P_i^m f^m(c_{ij}^m)$  and the remaining variables are repeated in the Hansen-type measure. Shen-type modal accessibility ( $a_i^m$ ) can be understood as a ratio of the travel impedance-weighted supply of opportunities for  $m$ -mode in  $i$  over the travel impedance-weighted demand for opportunities. In this way, it considers competition. That said, the measure remains unconstrained, meaning both

<sup>1</sup>see <https://redfrogforum.org/wp-content/uploads/2019/11/67-Nature-Nearby%2E2%80%99-Accessible-Natural-Greenspace-Guidance.pdf>

population *and* opportunities are multiply counted [see 14]. In other words,  
 interpretation of the Shen-type accessibility scores between modes is fraught as it is for  
 Hansen-type measures.

To illustrate, [36] calculate  $a_i^m$  to jobs for different income-group populations in  
 Shenzhen, China using  $m = \text{public transit}$  and  $m = \text{car}$ . Their results indicate that  
 zones with low-income populations have lower  $a_i^m$  than zones with higher-income  
 populations. Further, they show that  $a_i^{m=\text{public transit}}$  is lower than  $a_i^{m=\text{car}}$  at many  
 zones, arguing that this may further place those zones with lower-income populations at  
 a disadvantage.  $a_i$  and/or  $a_i^m$  are used to compare relative spatial differences in overall  
 competitive accessibility and multimodal competitive accessibility, but because  
 opportunities were doubly counted (entering the sums of both modes), this makes for  
 uneasy interpretations of the differences in  $a_i^m$  between modes. Questions that this  
 approach leaves unaddressed include: what is the impact of competition on the  
 difference in  $a_i^m$  values? How does the impact vary spatially? And what is the  
 interpretation of this difference?

Spatial availability improves on previously discussed accessibility approaches using  
 the Hansen-type measure and the Shen-type measure by constraining the sum of  
 opportunities, that is, by treating opportunities as finite. This is done by means of  
 proportional allocation factors that follow well established principles of spatial  
 interaction and the gravity model [see 37]. In Soukhov et al. [15] these factors consider:  
 the mass effect (e.g., the size of populations at different origins); and the cost of travel  
 from different zones (e.g., some sub-populations face relatively higher or lower costs).  
 The following section introduces the multimodal form of spatial availability.

## Multimodal spatial availability

In brief, we define the spatial availability at an origin  $i$  ( $V_i$ ) as the proportion of all  
 opportunities in the region that are allocated to location  $i$  from all destinations  $j$ .  $V_i$  is  
 a value of how many opportunities are available to each location  $i$  out of all the  
 opportunities in the region. The general formulation of spatial availability  $V_i$  is shown  
 in Equation (1) [see 15]:

$$V_i = \sum_{j=1}^J O_j F_{ij}^t \quad (1)$$

Where:

- $F_{ij}^t$  is a balancing factor that depends on the size of the populations at different  
 locations that demand opportunities  $O_j$ , as well as the cost of movement in the  
 system  $f(c_{ij})$ .
- $V_i$  is the number of spatially available opportunities at  $i$ ; the sum of  $V_i$  is identical  
 to the total number of opportunities in the region (i.e.,  $\sum_j O_j = \sum_i V_i$ ); in other  
 words, opportunities are dealt with as finite resources.

Compared to Hansen-type accessibility:

$$A_i = \sum_{j=1}^J O_j f(c_{ij}) \quad (2)$$

we see that spatial availability is, like the Hansen-type measure, a weighted sum of the  
 opportunities. What makes spatial availability stand apart from other approaches is  
 how the weight used in the sum, balancing factor  $F_{ij}^t$ , implements a proportional

allocation mechanisms to ensure that the sum of  $V_i$  is constrained to match the total number of opportunities in the region. As such, spatial availability is singly-constrained and naturally implements competition or congestion.  $F_{ij}^t$  consists of two parts. The first part is a population-based proportional allocation factor to model the mass effect of the gravity model:

$$F_i^p = \frac{P_i}{\sum_i P_i}$$

This factor makes opportunities available based on demand. Secondly, there is an impedance-based proportional allocation factor that models the cost effect:

$$F_{ij}^c = \frac{F_{ij}^c}{\sum_j F_{ij}^c}$$

This factor makes opportunities available preferentially to those who can reach them at a lower cost.  $F_i^p$  and  $F_{ij}^c$  are designed so that they both equal 1 when summed across all  $i$  in the region (e.g.,  $\sum_i F_i^p = 1$  and  $\sum_i F_{ij}^c = 1$ ). These factors are combined multiplicatively to yield  $F_{ij}^t$  which ensures that a proportion of the opportunities  $O_j$  are allocated to each  $i$  accordingly. In other words, assuming a finite number of opportunities in the region,  $F_{ij}^t$  proportionally allocates  $O_j$  to each  $i$  such that the resulting  $V_i$  value represents the number of opportunities *available* to the population at  $i$ . Each zonal value is a proportion of the opportunities in the region (i.e.,  $\sum_j O_j = \sum_i V_i$ ).

The focus of this paper is to extend  $V_i$  for the measurement of multimodal applications (or more generally heterogeneous populations). To do so, the balancing factors need to be reformulated so that 1) the mass effect now accounts not only for the size of the population at  $i$ , but also the size of sub-populations within  $i$ ; and 2) the cost of travel is not only for different zones, but by sub-populations within each zone (e.g., the cost of travel from  $i$  by car, transit, walking, etc.) When we introduce modes (or sub-populations)  $m$ , the proportional allocation factors need to satisfy the condition that  $F_i^{pm}$  and  $F_{ij}^{cm}$  can be summed across each  $m$  at each  $i$  and then across all  $i$  to equal to 1. They are also similarly combined multiplicatively to obtain their joint effect, represented as the combined balancing factor  $F_{ij}^{tm}$  similar to that detailed in Equation (3). This factor is given by:

$$F_{ij}^{tm} = \frac{F_i^{pm} \cdot F_{ij}^{cm}}{\sum_{m=1}^M \sum_{i=1}^N F_i^{pm} \cdot F_{ij}^{cm}} \quad (3)$$

where:

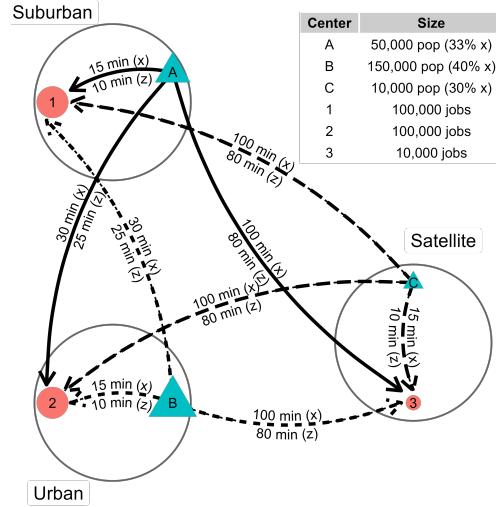
- The factor for allocation by population for each  $m$  at each  $i$  is  $F_i^{pm} = \frac{P_i^m}{\sum_m P_i^m}$ ;
- The factor for allocation by cost of travel for each  $m$  at  $i$  is  $F_{ij}^{cm} = \frac{f^m(c_{ij}^m)}{\sum_m f^m(c_{ij}^m)}$

Implementing  $F_{ij}^{tm}$ , the following Equation (4) gives the multimodal version of spatial availability  $V_i^m$ :

$$V_i^m = \sum_{j=1}^J O_j F_{ij}^{tm} \quad (4)$$

Where:

- $m = 1, 2, \dots, M$  is a set of  $M$  modes (or sub-populations) of interest.
- $F_{ij}^{tm}$  is a balancing factor  $F_{ij}^t$  for each  $m$  at each  $i$ .



**Fig 1.** Multimodal synthetic example: locations of employment centers (in orange), population centers (in blue), number of jobs and population, and travel times for two modes (slower mode x and faster mode z).

- $V_i^m$  is the spatial availability  $V_i$  for each  $m$  at each  $i$ ; the sum of  $V_i^m$  for all  $m$  at each  $i$  is equivalent to the total sum of opportunities in the region (i.e.,  $\sum_j O_j = \sum_i V_i = \sum_m \sum_i V_i^m$ ).

Next we use a synthetic example to contrast multimodal accessibility and spatial availability.

## An illustrative synthetic example

Consider the simple system shown in Figure 1. The figure shows a region with population at three population centers ( $A, B, C$ ) and jobs at three employment centers ( $1, 2, 3$ ). The population at each origin  $i$  consists of two sub-populations, one using a faster mode  $z$  and another using a slower mode  $x$ , to travel to employment centers. Population center  $A$  is Suburban: it is closest to its own relatively large employment center at 1, close to the Urban's equally large employment center 2, and has a population that is smaller than the Urban  $B$  and larger than the Satellite  $C$ .  $B$  has the largest  $x$ -using population, followed by then  $A$ , then  $C$ . This synthetic example is inspired by the single-mode example used in [12] and reconfigured in [15].

From the perspective of access to a *finite* amount of opportunities in the region (210,000 jobs), the sub-population that is most proximate to jobs (low cost to reach), furthest from large populations (less competition), and uses the fastest mode  $z$  (greater range) can potentially reach the largest number of opportunities. This appears to be the sub-population at  $A$  using mode  $z$ . Sub-populations located in opposite conditions (i.e., more distant from jobs, close to large populations, and using slow mode  $x$ ) are at a relative disadvantage. The competition for opportunities between different mode-using populations matters as it reflects how well the land-use and transport system serves (or does not serve) certain populations.

**Table 1.** Accessibility values at each origin ( $i$ ) per mode ( $m$ ) (columns three to five) and aggregated per  $i$  (columns six and seven) for the synthetic example.

$i$	$m$	$S_i^m$	$a_i^m$	$V_i^m$	$a_i$	$V_i$
A	x	27,292.18	0.95	15,696.89	1.36	67,482.61
	z	44,999.80	1.57	51,785.72		
B	x	27,292.18	0.64	38,170.03	0.88	132,638.94
	z	44,999.80	1.05	94,468.91		
C	x	2,240.38	0.68	2,035.86	0.99	9,878.45
	z	3,745.89	1.12	7,842.59		
TOTALS		150,570.22	N/A	210,000.00	N/A	210,000.00

The values calculated for  $S_i^m$  (Hansen-type accessibility),  $a_i^m$  (Shen-type accessibility), and  $V_i^m$  (spatial availability) for each  $i$  and  $m$  are shown in the middle three columns and are aggregated for each  $i$  in the final two columns in Table 1 . As in the example in Shen [12], we use a negative exponential impedance function  $f^m(c_{ij}^m) = \exp(-\beta \cdot c_{ij})$  with  $\beta = 0.1$  for both  $x$  and  $z$  modes for all accessibility measures calculations. Notice that in this example we use the same impedance function but the travel times are different for the two modes. More generally, it is possible to use different impedance functions for the modes, as demonstrated in the empirical example in the following section.

Hansen-type accessibility  $S_i^m$  is presented for each origin and mode in the third column of Table 1 . For all  $i$ , the travel by  $z$  results in higher values of  $S_i^m$  than travel by  $x$ . Lack of competition, or alternatively the assumption of an inexhaustible resource in the calculation of  $S_i^m$ , lead to a curious result. Since the populations in  $A$  and  $B$  have the same travel impedance to employment centers 1, 2 and 3 (either 15, 30, or 100 minutes using  $x$  or 10, 25, or 80 minutes using  $z$ ), their values of  $S_i^m$  are the same for both  $A$  and  $B$ . Furthermore, the total sum of  $S_i^m$  in the region is equal to 150,570.2. This value lacks an intuitive interpretation: it represents the weighted sum of opportunities that may be reached within the region according to the travel impedance (i.e., the travel behavior and the characteristics of the modes) and does not usefully translate into any sort of benchmark. To connect this example to the aforementioned literature,  $S_i^m$  is calculated in the work of Tahmasbi et al. [21]; they contrast differences in  $S_i^m$  values between modes in a relative and comparative sense, but make no further interpretation of the  $S_i^m$  values. More densely populated metropolitan regions will tend to have more opportunities and hence large  $S_i^m$  values and less densely regions, smaller values; how much of these differences may simply an artifact of region density?

In the fourth and sixth columns in Table 1 the results for Shen-type accessibility are reported: first for both origin and mode  $a_i^m$  as well as aggregated by the weighted mean mode-population (  $\sum_m \frac{P_i^m}{P_i} * a_i^m$  ) to represent a value for each origin  $a_i$ . Unlike  $S_i^m$ , this measure does consider competition. For instance, the population travelling by  $x$  from  $A$  and  $B$  do not have the same values of  $a_i^m$  as those travelling by  $z$ . In fact,  $A$  has the highest values  $a_i^m$  and  $a_i$  values since this center has the lowest travel impedance to opportunities (lower than at  $C$ ,  $A$  and  $B$  are equal) and faces relatively low competition, not being close to a relatively large population (lower than at  $B$ ).

However, the calculations of  $a_i^m$  are not constrained: the total sum of  $a_i^m$  or  $a_i$  is practically meaningless since it represents a sum of ratios. For instance, the population travelling by  $z$  from  $A$  has a value of 1.57 jobs per job-seeking population compared to 0.95 for users of mode  $x$ . What is the meaning of these values? The difference between

these modes is equal to 0.62, but 0.62 of what? How many more job opportunities can users of  $z$  reach compared to user of  $x$ ? When  $a_i^m$  is aggregated to  $a_i$  as shown in the sixth column, the values face similar interpretability issues. The Shen-type measure is implemented in aforementioned work of Tao et al. [36] to calculate modal  $a_i^m$  values and the aggregated  $a_i$  is implemented in the work of Carpentier et al. [38]. However, similar to Hansen-type accessibility, these works discuss relative and spatially comparative differences in values, but veer from interpreting the values of  $a_i^m$  or  $a_i$  themselves. In fairness, interpretation is complicated by the multiple counting of opportunities between zones and modes.

In contrast, spatial availability  $V_i$  considers competition and is constrained such that the total sum of values is equal to the total number of opportunities in the region (i.e., 210,000 jobs). Seen in fifth column of Table 1, the values of  $V_i^m$  in  $A$  and  $B$  are not the same within each mode (as this measure considers competition). In fact, at  $A$ , users of mode  $z$  capture 36,088.84 more spatially available jobs (of the 210,000 jobs in the region) than the sub-population travelling by  $x$ . The numerical difference is clear since it refers to opportunities out of the total.

Furthermore, the proportional allocation mechanism also means that the values of  $V_i^m$  for any origin  $i$  can be aggregated across  $m$  and compared between zones ( $V_i = \sum_m \sum_i V_i^m$ ). This aggregation,  $V_i$ , is shown in the seventh column in Table 1. Again looking at center  $A$ ,  $A$  is allocated 67,482.61 spatially available opportunities for both modes. 77% of this spatial availability allocated to  $A$  is assigned to users of mode  $z$  despite representing 66% of  $A$ 's population.

Spatial availability can be further aggregated to better interpret competition between modes. Across the entire region, 130,000 people use  $z$  (62% of the region population). However, users of  $z$  account for 73% of the region's total spatial availability - while the remaining 27% is allocated to users of mode  $x$  who are 38% of the total population. Notably, the population who uses  $x$  have 11% fewer spatially available opportunities than its share in the population. This realization leads us to ask normative questions such as, how unequal should availability of opportunities be by mode? What intervention could help to redistribute spatial availability to sub-populations commensurate with their proportion of the total?

Since spatial availability is constrained and has an interpretable meaning as a proportion of the total opportunities in the region, the values at  $i$  have a straightforward interpretation. Inequality in  $V_i^m$  values can be explored through a variety of approaches. For instance, consider travel times. The population of travelers who use  $z$  accounts for 67% of the potential travel time traveled in the region: this is 7% less travel time than the proportion of spatial available opportunities that is allocated to them. In other words, the population of users of  $z$  travels fewer minutes overall and has more spatial availability of opportunities than users of the slower mode  $x$ .

Alternatively, inequities in spatial availability between modes can be explored through proportional benchmarks. A spatial availability per capita  $v_i^m$  is presented in Equation (5):

$$v_i^m = \frac{V_i^m}{P_i^m} \quad (5)$$

The values of  $v_i^m$  for  $A$ ,  $B$ , and  $C$  for users of  $x$  are 0.95, 0.64 and 0.68 spatially available jobs per capita, respectively. The values of  $v_i^m$  for users of  $z$  are much higher, with values of: 1.57, 1.05 and 1.12 respectively. Users of  $x$ , especially those at  $B$  and  $C$ , are directly impacted by the jobs that are spatially available to users of  $z$  *in addition to* the mass effect (occurring at  $B$ , high population density) and high travel impedance (occurring at the Satellite  $C$ ).

If, let us say, the planning goal was to have one spatially available job per

mode-using population, a policy intervention could be devised, to reduce the values of  $v_i^z$  (making it slower or more expensive) and increase the values of  $v_i^x$  (making it faster or less expensive). The purpose of this simple demonstration is to show how spatial availability can be used to quantify the competitive (dis)advantage in a multimodal application. In what follows, we demonstrate the use of multimodal spatial availability through an empirical example.

## Empirical example

### Context

The context for the empirical example is Madrid, Spain. This city implemented a Low Emission Zone (LEZ) in 2017 to: pursue goals set out in the national climate change agenda, cut nitrogen dioxide levels, and to prioritize people's movement in the city. LEZs elsewhere have similarly been implemented as interventions to reduce GHG emissions, improve air quality, and support sustainable mobility [39,40]. Though the rules of exclusion vary by city, LEZs aim to deter/reduce traffic in designated zones under threat of penalty (e.g., fines, seizure of vehicle). In other words, 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. When considering opportunities as finite in a region, this discrimination reduces the competition of one mode and opens up opportunities for other modes to better thrive. At their core, LEZs operate by changing the accessibility landscape of a city from the perspective of multiple modes.

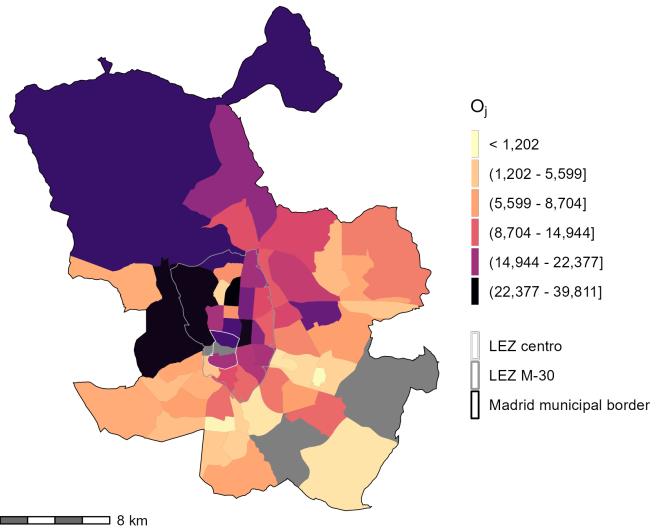
In geographic scope, the 2017 boundaries of the LEZ in Madrid were relatively modest, covering only approximately 4.72 km<sup>2</sup> of the central business district of the city (the so-called LEZ Centro). As of this writing, there are plans to expand these boundaries to the area inside the M-30, an orbital highway in proximity to the city center (i.e., LEZ M-30). Within the 2017 LEZ Centro implementation, all cars, motorcycles and freight vehicles with environmental labels A or B (older makes and models of fossil fuel internal combustion engine vehicles), were disallowed from entering the zone unless they are used by residents or meet other exemptions. This restriction impacted approximately half of all car trips that used to travel into what is now the LEZ Centro [41].

For this case study, we use spatial availability to quantify access to opportunities by different modes in Madrid. Particularly, we demonstrate how  $V_i^m$  can be used to derive insights into how the restriction of car mobility in areas around/within the LEZ Centro may have allowed more sustainable (but often slower or more costly modes) to become more competitive.

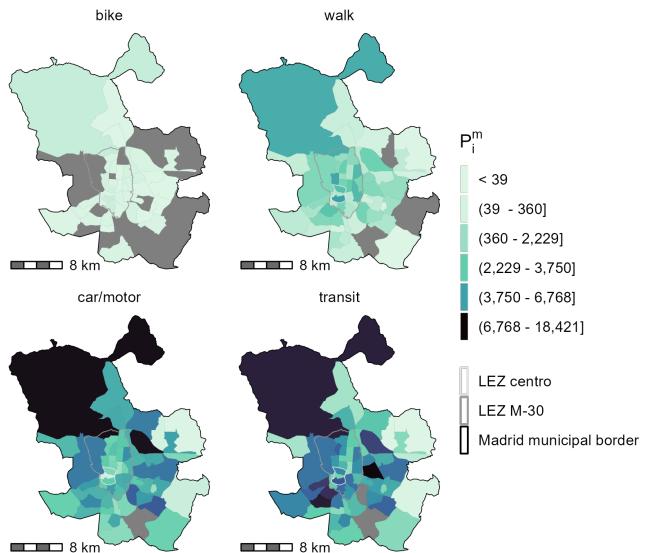
### Data

The source of data for our empirical example is the 2018 Travel Survey of the Community of Madrid [42]. This is a representative survey that offers a snap-shot of travel patterns for a typical weekday in 2018. The survey collected 222,744 trips from a representative sample of 85,064 households across the traffic analysis zones (TAZ) in the Community of Madrid. For context, the population older than 3 years in the Community is 6,507,184.

In this example, we use all home-to-full-time-work trips, by all modes. The trips are expanded using population weights. Figures 2 and 3 show the number of workers and the distribution of full-time jobs in the City of Madrid by TAZ. The light grey boundary represents the LEZ Centro in effect in 2017. The survey was conducted after the



**Fig 2.** Distribution of jobs taken by people living and working in Madrid as reported in the 2018 travel survey. Grey TAZs has no jobs. Ranges of values in the legend are quintiles.



**Fig 3.** Population living and working in Madrid by mode of transportation as reported in the 2018 travel survey. Grey TAZs have no population. Ranges of values in the legend are quintiles.

introduction of LEZ Centro. The dark grey boundary represents the LEZ planned for the boundaries of the M-30 highway and is present in the plots as a spatial reference for areas in proximity to the LEZ Centro.

The total sum of jobs  $O_j$  are shown in Figure 2 and the populations that go to a work destination by four modal categories  $P_i^m$ , is displayed in Figure 3. The modal shares in Figure 3 are calculated based on those measured in the survey. The modal categories and the mode types within each category are reported as follows:

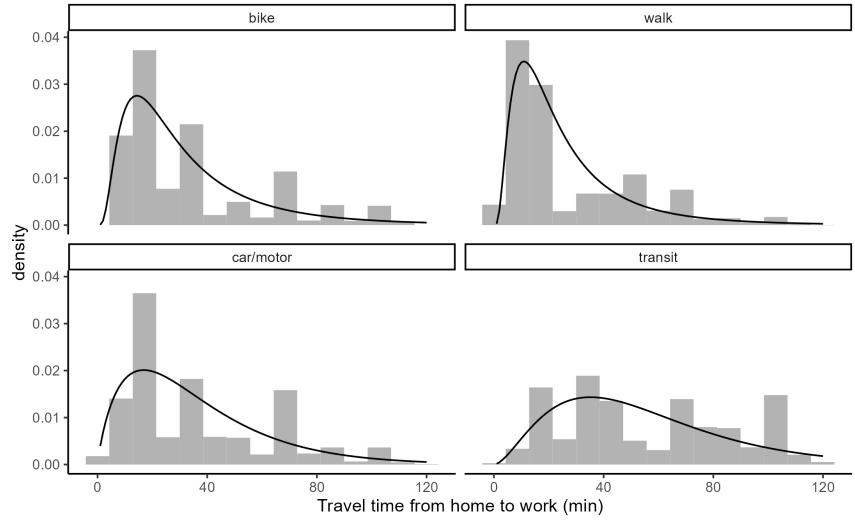
- Car/motor: all cars and operating modes (e.g., cab, private driver, company, rental car, main driver of a private car, passenger in a private car) and all public, private or company motorcycle/mopeds.
- Transit: all bus, trams, and trains.
- Bike: all bicycle trips (e.g., private, public, or company bike trips) and “other” types of micromobility options.
- Walk: walking or by foot.

Some aggregation of modes is necessary to calculate the travel impedance functions by mode. From Figure 2, it can be seen that the largest concentration of jobs is within, near, and to the north of LEZ Centro. The populations with access to those jobs by mode (Figure 3) are spatially distinct. Travel by car and transit represent 37% and 47% of the modal share respectively. The population that travels by transit is more spatially distributed than those using cars - particularly near and within LEZ Centro. This distribution is likely caused by a variety of factors including: transit coverage and service within with city, effective car infrastructure outside of the M-30, and/or the impact of the LEZ Centro itself. From Figure 3, it can be seen that active travel is less common than motorised trips at 1% and 15% for cycling and walking respectively. Noticeably, there is a positive trend between the walking and cycling in zones where transit is also present. This positive trend is higher than for car trip populations.

Travel times are provided within the travel survey by mode. This information is used to calibrate mode-specific travel impedance functions  $f^m(c_{ij}^m)$ . To illustrate the modal differences in travel times, the following descriptive statistics per mode are presented:

- Car/motor: mean 36 minutes (min: 0 minutes, Q2: 15 minutes, Q3: 55 minutes, max: 120 minutes)
- Transit: mean 55 minutes (min: 1 minutes, Q2: 30 minutes, Q3: 80 minutes, max: 120 minutes)
- Bike: mean 34 minutes (min: 5 minutes, Q2: 15 minutes, Q3: 40 minutes, max: 115 minutes)
- Walk: mean 27 minutes (min: 1 minutes, Q2: 10 minutes, Q3: 45 minutes, max: 119 minutes)

Impedance functions  $f^m(c_{ij}^m)$  are calibrated from the travel times in the survey via the empirical trip length distribution (TLD). An empirical TLD is given by the proportion of trips at various travel cost bins. This distribution is then used to estimate the parameters of a function for the travel impedance [as done in 43,44,45]. To fit the impedance functions, we use the Maximum likelihood estimation and the Nelder-Mead method for direct optimization available within the R `{fitdistrplus}` package [46]. Based on goodness-of-fit criteria and associated diagnostics, the gamma and log-normal probability density functions are selected as best fitting curves for the motorised and non-motorised modes respectively. The selection of functional forms aligns with empirical examples in other regions [15,47,48]. The shape and rate parameters for the gamma functions (motorised modes) are 1.8651852 and 0.051468 for car/motor and 2.7566235 and 0.0499193 for transit; for the log-normal functions (non-motorised



**Fig 4.** Fitted impedance function against empirical TLD (bars) corresponding to the home to full-time work origin destination flows for the City of Madrid from the 2018 travel survey.

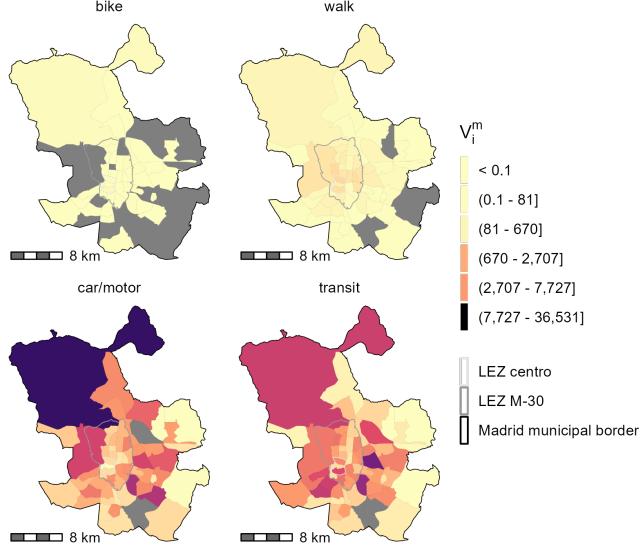
modes), the mean and standard deviation parameters are 3.2372212 and 0.7575986 for bike and 2.9918042 and 0.7575986 for walk.

Figure 4 includes four plots to visualize the calibrated impedance functions (represented as black lines) superimposed on the empirical TLD. The impedance functions can be interpreted as the propensity to travel (y-axis) given a trip travel time (x-axis). The functions reflect a combination of possibilities and preferences: the travel behavior given the transportation technologies available. For example, trips shorter than 5 minutes do not occur frequently for any mode; this reflects the spatial separation between places of residence and places of work commonly seen in many cities. In terms of the non-motorised modes, there is a preference towards walking trips around 15 minutes in duration, as seen from the highest value of  $f_{walk}(c_{ij}^{walk})$ . With respect to travel by bicycle, longer travel times are more common; although the highest value of the impedance also corresponds to approximately 15 minutes, the curve has a longer tail and values decrease less rapidly at longer travel times than is the case of  $f_{walk}(c_{ij}^{walk})$ . A similar trend can be observed for the motorised modal options where transit mode is more spread out than car/motor mode. All in all, these functions represent the propensity of travel by mode by duration of trip, and are used to calculate the proportional allocation factors  $F_{ij}^m$  for  $V_i^m$ .

## Results

At this point, it is worthwhile reiterating that the empirical example is a snap-shot of spatial availability by mode using data from the 2018 travel survey. Our purpose in this empirical example is to investigate the trends in availability of employment opportunities by mode, and illustrate how spatial availability can be used in discussions about the competitive advantage of various modes within Madrid Centro. The spatial availability of jobs  $V_i^m$  is calculated for each of the four modes  $m$  at the level of traffic analysis zones  $i$  in Madrid and displayed in Figure 5.

In the figure,  $V_i^m$  is a proportion of the total number of 847,574 jobs in the region. Since  $V_i^m$  is calculated based on the population of workers and the distribution of jobs, the values can be understood as the number of full-time jobs that are spatially available

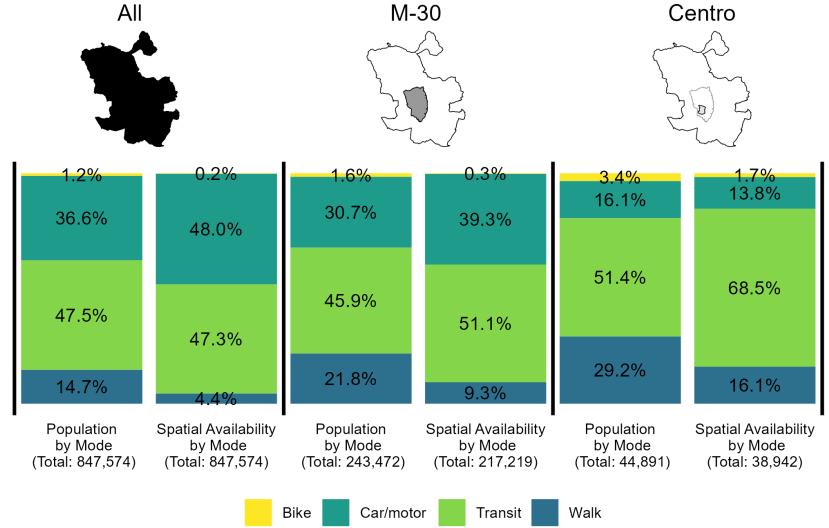


**Fig 5.** Spatial availability of jobs per origin and mode  $V_i^m$  in Madrid. Grey TAZs have no population. Ranges of values in the legend are quintiles.

to full-time workers at that  $i$  traveling by mode  $m$ , relative to all the jobs in the city. There are noticeable differences in the magnitude of  $V_i^m$  between modes as seen in Figure 5. The majority of  $V_i^m$  (which is to say of spatially available jobs) are allocated to workers travelling by car and transit. In a way, this is to be expected since users of these modes represent 84.1% of the total population. However, the ability to travel at greater speeds also impacts these results. Furthermore, differences in  $V_i^m$  values within modes also exist in space: car users outside of the M-30 region appear to enjoy greater spatial availability, while some zones inside the M-30 to have greater spatial availability for transit. Overall, the magnitude of  $V_i^m$  values for cyclists and pedestrians are lower than for car and transit but the highest values of  $V_i^{\text{bike}}$  and  $V_i^{\text{walk}}$  tend to be found in zones within the M-30 and origins with higher spatial availability by transit.

The differences between the shares of modes and their shares of spatially available opportunities highlights the competitive advantage of certain modes, although this effect is not geographically uniform. As seen in the left-most columns of Figure 6, users of 'car/motor' and 'transit' together can avail 95.3% of all jobs in the city (Spatial Availability by Mode). However, car/motor users have a disproportionate share of  $V_i^m$  relative to the population of users of this mode (Population by Mode), compared to opportunities that are spatially available to transit users. The combined population of car and transit users is 36.6% and 47.5% respectively, but these populations are allocated 48.0% and 47.3% respectively, of the city's jobs. When treating the number of opportunities that can be reached as a finite value (total: 847,574 opportunities), fewer opportunities are spatially available to slower modes (i.e., walking and cycling), even taking into account that their share is smaller overall. These modes are at a disadvantage as a result of: the travel impedance for longer trips (see Figure 4; their low population values values overall; and larger populations in origins with high shares of travel by motorised modes. These factors all contribute to the the car/motor mode being most advantaged in capturing spatially available job opportunities overall.

The big picture demonstrates how car is the most advantageous mode, however it is interesting to notice that this advantage appears to be blunted by the LEZ. Unlike the results for the whole city and even within the M-30 ring, the proportion of car users in Centro is larger than the proportion of opportunities spatially available to them. The

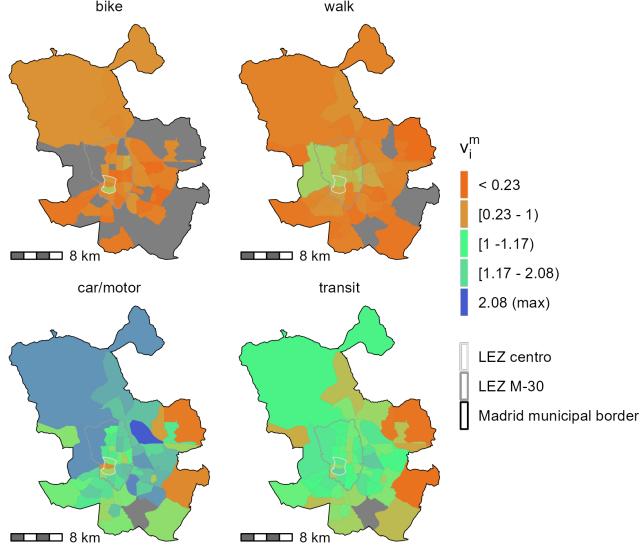


**Fig 6.** Proportion of population by mode and spatial availability of jobs by mode aggregated for three areas. From left to right, the city of Madrid (All), the area within the M-30 highway (M-30), the area within the Centro region (Centro).

restriction on cars in effect reduces competition by this mode, and leads to a relative increment of the mass effect of the modes allowed within the LEZ, which also contains a large number of jobs (see Figure 2). As summarized in the two right-most columns in Figure 6, the proportion of jobs spatially available to car in Centro is (13.8% or 5,373 opportunities). For reference, this is less than the proportion of the car users in Centro (16.1%), evidently less than the proportion of car users in the city, and is the opposite of the overall trend (left-most columns) and within the M-30 (middle columns).

It is also clear that more opportunities are spatially available to non-car users within Centro. In the case of active travel, the proportions of cyclists and walkers within LEZ Centro still exceeds the proportions of jobs spatially available to them — however, the disparity is drastically reduced compared to the rest of the city. As seen in Figure 6, there is a higher proportion of opportunities that are spatially available to pedestrians and cyclists in Centro than in the City overall and in areas within the M-30. Notably, within Centro, 1.7% and 16.1% of opportunities are spatially available to bike and walk modes respectively, while their populations represent 1.2% and 14.7% of the population. By restricting the ability of cars to enter Centro, the LEZ seems to contribute to leveling the playing field for slower modes, in particular cycling and walking, but also transit. As seen in the Figure 6, transit users are generally close to parity across the region, with nearly as many spatially available jobs as transit users. Still, this mode has the greatest advantage in LEZ Centro with 68.5% of spatially available jobs in Centro for 51.4% of transit users in Centro. This result makes intuitive sense: after car, it is the mode with the greatest range, and unlike car it is unrestricted in the LEZ Centro.

The spatial differences in the competitive dis/advantage of spatial availability between modes can also be visualized at a finer level of granularity. Figure 7 shows  $v_i^m$ , the spatial availability  $V_i^m$  divided by the population of users of  $m$ . Values of  $v_i^m$  below one are shown in shades of orange, and indicate TAZs with less than one spatially available opportunity per capita for the mode. Values above one are shown in shades of green, and indicate TAZs with more than one spatially available opportunity per capita for the mode. The highest spatial availability per capita (shown in blue) is for car users in a zone northeast just beyond the M-30. These plots illustrate in unambiguous



**Fig 7.** Distribution of spatially available jobs per capita by mode of transportation ( $v_i^m$ ). Grey TAZs have no population that use the mode. Ranges of values in the legend are quintiles.

fashion, and in a quantity that is comparable over space and time, the advantage in terms of spatial availability of car for most of the city (bottom left plot, areas denoted with green  $v_i^m$  values above one). It can also be observed that spatial availability of jobs is relatively well balanced for transit users over most of the regions (i.e., many zones are light orange or light green). Spatial availability of jobs for non-motorised modes, in contrast, is low (under one) overall, although less so within LEZ Centro.

Incidentally,  $v_i^m$  values for car within and near LEZ Centro is close to or below one in Figure 7, while all non-car modes have relatively higher  $v_i^m$  values. Since these values are comparable across regions and over time, Figure 7 potentially provides a benchmark for quantifying changes in LEZ policies in the future. As Figure 7 also shows, many areas within the M-30 have high (white/green)  $v_i^m$  values for car, but the results for LEZ Centro give reasonable grounds to speculate that a spatial expansion of the LEZ to include all areas within the M-30 would likely increase the spatial availability of jobs for transit users, cyclists and pedestrians.

## Discussion and conclusions

Accessibility measures are an important tool in transportation research [9] and are increasingly seen as valuable for planning purposes [4–8]. They boast a long history of development, beginning with Hansen-type  $S_i^m$  measures, with other developments like Shen's  $a_i^m$ , to account for competition/congestion. The more recent spatial availability measure  $V_i^m$  has in common with these accessibility indicators that it is a weighted sum of the opportunities in a region from the perspective of a determined origin  $i$ . Aggregations of opportunities embody principles of gravitational/spatial interaction modelling that date back to at least H.C. Carey [49], and are part of a line of research that includes the work of Ravenstein [50], Reilly [51], Stewart [52–54], Zipf [55,56], Wilson [37], and many others. In this way,  $S_i^m$ ,  $a_i^m$ , and yes,  $V_i^m$ , can be interpreted as scores of the potential for interaction with opportunities in space.

Different accessibility indicators are characterized by how they weight and aggregate opportunities. Spatial availability's contribution to the literature is to incorporate a

proportional allocation mechanism that essentially constrains the sums to match the  
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number of opportunities in the region; in this way it is a singly-constrained accessibility  
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measure that naturally accommodates congestion and competition. The effort with  
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spatial availability is in line with previous research on proportional allocation by Paez et  
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al. [14]. As initially introduced by Soukhov et al. [15], spatial availability was designed  
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for a homogeneous population traveling by a single mode of transportation. In this  
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paper, we extended spatial availability for the case of heterogeneous populations. We  
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discussed this in terms of multiple modes of transportation, but the framework can  
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accommodate equally well variations in travel behavior by population segments.  
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An empirical example using data from Madrid helped to illustrate the potential of  
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multimodal spatial availability analysis, including its ability to account for competition  
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for opportunities within and between modes. Particularly relevant is the fact that  
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spatial availability scores relate directly to the total number of opportunities in the  
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region. This makes it possible to compare the results to intuitive benchmarks, such as  
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opportunities per population, in ways that other accessibility measures cannot or tend  
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to obfuscate. This comparability is preserved between regions and over time. The  
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example suggests that once that opportunities are treated as being finite, restrictions to  
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travel by car leave more spatially available opportunities for non-car-users. This  
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difference for car travel in locations within and immediately around the LEZ Centro  
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seems to increase the number of opportunities spatially available to transit users  
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(transit being the second most competitive mode), as well as the spatial availability  
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from the perspective of non-motorised modes. In effect, a policy such as Low Emission  
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Zones help to improve the accessibility situation of active travel and transit in the parts  
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of the city where it is implemented.  
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The purpose of the empirical example is to illustrate the kind of insights that can be  
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derived from the application of multimodal spatial availability. But there are some  
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intriguing opportunities for future research. Accessibility indicators are not designed to  
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work as modal split models, and yet, in the case of policies that alter the relative cost of  
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various forms of transportation, one can reasonably expect to see some shifts between  
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modes. In our empirical example we used data collected *after* the introduction of LEZ  
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Centro. However, given a modal split model to project model shares, accessibility  
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indicators, including spatial availability, can be used to investigate changes to the  
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accessibility landscape. Ditto for destination choice. Our empirical example presented  
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but a snapshot of this, and in future research it will be interesting to investigate  
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changes *between* policy interventions. The expansion of Madrid's LEZ to the ring  
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contained by the M-30 orbital presents an excellent opportunity to do so. Given the  
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intuitive and straightforward interpretation of spatial availability scores as fractions of  
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opportunities from the total, relative and absolute changes in the accessibility landscape  
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can be assessed, thus helping to evaluate the implications of policy interventions.  
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Finally, our example dealt with differences in travel by mode only, but it is possible  
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to think of the intersection between mode of travel and different types of travelers. This  
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would expand the number of sub-populations in the analysis from, say,  $m = M$  (modes)  
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to  $m = M \cdot Q$  (modes times population segments), each with their own characteristic  
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impedance function. Evaluations of this kind will be especially relevant as LEZ are  
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implemented in cities globally, and the question of their impact on disadvantaged  
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populations who have become mobility-restricted increasingly come to the fore  
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[40,57,58].  
615

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All work is fully-reproducible and available within this GitHub repository.

## Author contributions

The authors confirm contribution to the paper as follows: study conception and design: AS, JTO, JSL, AP.; data collection: AS, JTO, JSL.; analysis and interpretation of results: AS, JTO, JSL, AP.; draft manuscript preparation: AS, JSL, AP. All authors reviewed the results and approved the final version of the manuscript.

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

Anastasia Soukhov <sup>1</sup> \*, Javier Tarriño-Ortiz <sup>2</sup> , Julio A. Soria-Lara <sup>2</sup> , Antonio Páez <sup>1</sup>

**1** Department of Earth, Environment and Society, McMaster University, Hamilton, Canada

**2** Centro de Investigación del Transporte (TRANSyT), Universidad Politécnica de Madrid, Madrid, Spain

\* Corresponding author: soukhoa@mcmaster.ca (AS)

## Abstract

An increasing number of studies within the domain of transportation planning are concerned with the inequities in accessibility to opportunities. A dimension of these inequities arises from differences in access by mode type (e.g., commuting using a car as opposed to transit). However, methods implemented in current accessibility literature are lacking within the context of multimodal analysis. This paper presents an extension of Recent research has aimed to address the way opportunities are counted in accessibility analysis. In conventional accessibility measures, opportunities are often multiply counted, which leads to values of accessibility that are difficult to interpret. Constraining the 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. A recent effort is spatial availability, a singly-constrained competitive accessibility measure, for the context of multimodal accessibility analysis. We first illustrate the features of spatial availability that lend itself to multimodal analysis. We then demonstrate its use on the case study of Low Emission Zones in Madrid (Spain) and highlight how this policy intervention changes the accessibility of populations using different modes. In summary, spatial availability can be used to create and interpret multimodal policy intervention scenarios unlike previous methods: this creation and interpretation can help regions envision a more sustainable and equitable access-to-opportunity landscape. accessibility measure. In this paper we extend spatial availability for use in the case of multiple modes or, more generally, heterogeneous population segments with distinct travel behaviors. After deriving a multimodal version of spatial availability, we proceed to illustrate its features using a synthetic example. Next, we apply it to an empirical example in Madrid, Spain. We conclude the paper with suggestions for future research.

## Introduction

Implementing urban policies that re-shape cities through accessibility gains (i.e., the potential to interact with opportunities as a result of land-use mix and transport systems as originally defined by Accessibility is a key concept in the analysis of land use and transportation systems [e.g., 1,2,3]) have been widely applied within the

transportation literature and is increasingly discussed by planners<sup>2–5</sup> and too is coming of age from the perspective of planning [see *inter alia*, 4,5–8]. An important challenge in the identification of interventions that equitably transform cities is the effective evaluation of *trade-offs*: cities are complex and dynamic ecologies, and advantaging one component of the city can disadvantage another area, population, or sub-component. In this way, policy evaluation should take a *systems* approach. Beginning with the work of Hansen [61]. One way of considering systems is from the perspective of the *finite*. As an illustration, consider the amount of transport space within a city: the amount is typically finite so re-allocating road space away from one mode directly impacts the performance of the others (see the literature on road space reallocation e.g., accessibility measures have been widely used to evaluate the efficiency of transportation systems when combined with the distribution of opportunities in space [79]). Evaluating policy impacts in the context of *finity* provides a way to contextualize the balance of trade-offs that the citizens of a city should tolerate<sup>9–10</sup>. As such, it is a holistic measure of spatial systems that measures the ease of reaching destinations [10,11].

From the perspective of urban transport systems<sup>11</sup> In practice, the most common form of accessibility measure is based on the gravity model. These measures are sums of weighted opportunities around a focal point (i.e., a potential origin), based on how expensive it is to reach them. Recent research in accessibility analysis has paid attention to the way opportunities are counted in the pertinent calculations. Conventionally, the sums are not constrained, which means that the same opportunity can enter the sum for different origins. Counting the same opportunity multiple times treats it as if it was inexhaustible. But opportunities in general are not inexhaustible, and in fact some of them are by definition exclusive: for example, once a job is taken up by someone in the population, the same job is no longer available for any other person to take. More generally, opportunities are subject to congestion: for example, multiple people can obtain services from the same family doctor, but the more people who do, location-based accessibility measures have been used in the context of policy evaluation. For instance, the more congested the service will be.

The issue of congestion in accessibility measures was the motivation for the development of floating catchment area approaches [812,13] assesses the transit accessibility gains to healthcare and employment opportunities for disadvantaged neighbourhood in Columbus, Ohio, USA after the transit system's re-design and introduction of a rapid bus system. However, a limitation of this study, like others that implement accessibility measures, is they do not calculate results under a *constrained* framework i.e., one of *finity*. The citizens of Columbus should experience quantitative accessibility gains—but is it at the expense of access using other modes? As another example, While these approaches purport to account for congestion, Paez et al. [914] implements a modified cumulative opportunity measure to assess differences between private vehicle and transit system accessibility to jobs in Melbourne, but a similar question remains: does the accessibility afforded to the private vehicle using population come at the expense of accessibility losses to transit users?

demonstrate that in general they do not solve the issue of multiple counting of opportunities, thus leading to biases in the calculation of total demand and supply, sometimes inflating them, other times deflating them. In response to this, recent research has paid closer attention to the way opportunities are counted in accessibility analysis. Paez et al. [814] and, for example, tackle floating catchment area methods and introduce a normalization of the impedance matrix to allocate the population and then the level of service proportionally. More recently, Soukhov et al. [915] both use non-competitive accessibility measures. There is a branch of location-based accessibility measures that do incorporate the effect of competition for opportunities by

the population in the region. However, we argue that these existing methods fall short in acknowledging the *finity* of opportunities. For instance, introduced a singly-constrained measure of accessibility, called spatial availability, that employs a similar, but more sophisticated proportional allocation mechanism. The work of these authors show that floating catchment area methods can be seen as singly-constrained accessibility measures, and improve on existing approaches by guaranteeing that each opportunity is counted only once - in other words, treating opportunities as *finite*. The proportional allocation of spatial availability constrains the calculations to match a known quantity, therefore ensuring 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.

A limitation of spatial availability as introduced by Soukhov et al. [1015] applies a competitive measure, two-step floating catchment approach (2SFCA), for is that it was developed for the case of a homogeneous population, for example for the case of access to healthcare services in Florida for both a multimodal network and a single modal network. While the differences in modal access are discussed, the question of how the advantage in access afforded by one mode over another impacts access for different mode users is unanswered.

This question of how much one mode-using population can access at the expense of another mode-using population is a pertinent equity question in the evaluation of policy scenarios that are multimodal. For instance, consider the impact of a low emission zone (LEZ). LEZ is a policy of spatial and modal discrimination: the circulation of vehicles that are excessively polluting are restricted in specific regions. In the recognition that opportunities are finite, the implementation of a LEZ explicitly reduces the access that the population using polluting vehicles has to opportunities. This restriction allows the population using other more sustainable modes to potentially have a higher level of access than before the LEZ implementation. This evaluation is especially urgent as LEZ are currently in effect in cities globally; their reception has been mixed a single mode of transportation. However, the finite nature of opportunities makes the analysis of heterogeneous populations very relevant. In the case of multiple modes of transportation, people who travel by slower modes (e.g., active modes) can usually reach fewer opportunities than people who travel by faster modes and whose range is typically far wider (e.g., car). This implies that slower travelers will often face increased competition for local opportunities from travelers who can reach said opportunities from farther afield.

The objective of this paper is to address this limitation of spatial availability. Our primary motivation is to extend spatial availability for the case of multimodal accessibility, but it is worthwhile noting that this is in fact just one case of heterogeneous populations (i.e., travel by different modes). The method itself can easily accommodate other forms of heterogeneity, for example variations in travel behavior between older and younger adults [11e.g., 16] and may be having negative impacts on disadvantaged populations who have become mobility-restricted, the propensity of older adults to use different modes of transportation [12, 13e.g., 17]. Measures that evaluate the accessibility of modes given both *constrained* and *competitive* considerations are lacking in the literature, but are needed, to evaluate such policy interventions impact on accessibility.

In, the usually shorter trip lengths of children compared to grown-ups [14e.g., 18], we introduce spatial availability, a type of location-based accessibility measure that is both *constrained* and *competitive*. In this paper, we extend the spatial availability measure into a multimodal framework and explore its use in answering the question outlined: “*given opportunities are finite, how many are available to a given location depending on the mode used?*”. The answer to this question quantifies how many

opportunities can be accessed, considering competition, for different modes. To foreground this exploration, in Section 2, we discuss short falls of a few existing location-based measures in comparison to spatial availability, or the more limited travel ranges of single parents [e.g., 19].

The paper rest of this paper is organized as follows. In Section 2 we provide a brief review of multimodal accessibility. In the following Section 3 we demonstrate the derivation of the new spatial availability expression for multiple modes. In Section 4 we illustrate relevant issues through a synthetic example. In Section 3, the spatial availability of This is followed in Section 5 by an empirical example of the LEZ in the using data from the city of Madrid, Spain is calculated. We demonstrate how the restriction of car circulation could have impacted the spatial availability of opportunities for each sub-population using after the implementation of its Low Emission Zones (LEZ). Data for this example comes from the city's 2018 travel survey. The example shows the differences in spatial availability within and outside the LEZ for travelers using different modes, namely car, transit, cycling and walking modes. In Section 46, we provide concluding remarks on the strengths of the use of spatial availability as a multimodal accessibility measure and, and discuss potential future uses in policy planning scenarios as well as directions for future research.

## A brief review of multimodal accessibility

Location-based accessibility indicators are quantitative measures of *potential* interaction with opportunities for locations within a given region: they are a product summary measures of the relationship between land-use and transport systems. Arguably, the most commonly used location-based measured are are measures based on the gravity model [20], of which cumulative opportunity measures and weighted cumulative opportunity measures are particular forms [25]. These measures weight the opportunities that can be potentially interacted with from origin assign a weight to opportunities based on how easy it is to reach them. Given an origin (*i* to destination) and a destination (*j* based on some sort of travel cost function), an impedance function  $f^m(c_{ij}^m)$  converts the cost of travel (e.g., travel time, fare, travel distance) otherwise known as a travel impedance function  $f^m(c_{ij}^m)$ . Many weighted cumulative opportunities (often referred to as the gravity-based measure) originate from the measure proposed by time, money, generalized cost) into a score that represents the propensity for interaction. These measures originate from that proposed by Hansen [1], which can take the following multimodal form form in the multimodal case:

$$S_i^m = \sum_j O_j f^m(c_{ij}^m) \text{ where } m \text{ is a set of modes which have mode-specific travel costs } (c_{ij}^m) \text{ and } (f^m(\cdot)) \text{ and/or travel impedance functions } (f^m(\cdot)).$$

The Hansen-type measure does not consider competition between modes nor is it constrained. As accessibility is not constrained, which is to say it does not consider the opportunities as finite. To cite an example, the work of Tahmasbi et al. [4521] uses the use Hansen-type measure to measure accessibility to assess the potential interaction with retail locations using by three modes: walking, public transit, and car modes  $m$  (i.e.,  $m = w, p, c$ ).  $S_i^m$  is the sum of retail locations  $j$  that can potentially be interacted with reached under the travel impedance as calculated for each  $i$  and  $m$ . In other words, each for each origin  $i$  has three  $S_i^m$  values, one per  $m$  three accessibility scores are calculated. In this work, they demonstrate that the car mode has the highest  $S_i^{m=car}$ . Tahmasbi et al. [21] show that car travel affords the highest  $S_i^m$  values in the majority of  $i$ , i.e., populations using travelers who use a car can potentially interact with the most reach more retail opportunities than populations using other modes. However, the higher  $S_i^{m=car}$  values are not a result of lower higher  $S_i^m$  values for car do not affect the values of  $S_i^m$  values for other modes: it is not assumed that

ear-using populations potentially accessing more opportunities take away potential opportunities for other populations within the measure (no consideration for competition). This measure is also not constrained: there is no global maximum for  $S_i$  or  $S_i^m$  values, they are presented as a population normalized accessibility index. This makes the in effect, each mode is analyzed as if the others did not exist. Since the measure is not constrained, each opportunity is typically counted multiple times within and between modes, and as a result the sum of accessibility is not necessarily a meaningful quantity. The accessibility scores for the modes are often values that are difficult to interpret beyond making statements about relative size. For example, Lunke [22], researching the region of Oslo, reports accessibility scores for car in the order of tens of thousands of employment opportunities. The corresponding scores for transit are lower, but still often in the thousands or tens of thousands. As reported, the ratio of the transit to the car score can be lower than 0.2 (meaning transit gives access to less than 20% of the opportunities than car). But despite the discussion about "sufficient accessibility", it is unclear what the unconstrained scores mean: is having access to but 10.000 jobs by transit insufficient? After all, 10.000 employment opportunities are still plenty of opportunities. These ratios can be found elsewhere in the literature [e.g., 23, and 9,16,19, and 8], and they are useful as relative assessment of when some members of the public are better or worse off than others, but they do not say much about how bad is "worse off".

Besides ratios of accessibility, another way to improve interpretability of scores sometimes seen in the literature is to standardize them to lie in the range [0-1]. This adjustment is only helpful insofar as it facilitates relative comparisons, but interpretation of the 'potentially interacted opportunities' relative to the region, making comparisons of the results across different regions challenging. scores remains challenging because the values are specific to a region and convey no meaning about the magnitude of the scores. In this approach, zones always have values between 0 and 1, but how remarkable is a zone with a low score for pedestrians and a high value for car? And if remarkable, what does the difference in these standardized values mean for planners? By how much should transport systems and land-use configurations be changed to improve conditions? And in what way can these scores be used to track differences over time? Or between regions? These questions lack straightforward answers since certain values will always be relatively 'low' or 'high', but do not track to a quantity that can be intuitively understood. Presentation or discussion of Hansen-type accessibility that has been standardized in this way is not uncommon in the literature [e.g., 24,25].

However, opportunities in a region can be considered finite Once we understand opportunities to be finite, it is possible for an accessibility measure to take on a crisper meaning. As considered in the long tradition of accessibility research, capacity of opportunities is limited and thus is subject to competition by population [12,15,26–30]. There are only so many school-seats, hospital capacity, jobsemployment opportunities, etc., in a region and if one person interacts with an opportunity at a given time reaches an opportunity, it is taken: the supply of an opportunity and the demand for that opportunity are two components of accessibility. These are clear examples of opportunities that are unambiguously competitive. But we would go as far as to argue that every type of opportunity is subject to congestion or capacity constraint, even when the opportunities are conventionally seen as non-competitive. As such

Amenities are a good example of this. For instance, standards for providing green spaces are often stated in the form of *exclusive access*, in units of amenity per capita. A case in point is a the Ile-de-France region, a jurisdiction that suggested in a 2013 planning document that at the municipal level at least  $10m^2$  of public green space should be supplied *per inhabitant* [31]. Green spaces are not evenly distributed, which

means that who has access to them hinges on where they are and how easy is to reach them. This formulation of provision of amenities is not unusual. For example, Natural England, an organization that recommends an Accessible Natural Greenspace Standard such that the minimum supply of space is one ha of statutory Local Nature Reserves per thousand population<sup>1</sup>. Similarly, the World Health Organization [cited in 32] recommends that cities provide a minimum of  $9m^2$  of green area per inhabitant. For our purposes, standards of this type translate into “how much of this resource is available to one individual that has not been claimed by anyone else?”. Green spaces often have large capacities, but they still have a capacity, and it is not the same for a person to have access to  $5m^2$  of *uncongested* green space as  $15m^2$ . This difference is in fact a matter of justice [31], if one person is advantaged and has the ability to reach more opportunities through a lower travel-cost mode, than they have more opportunities to potentially interact with [33]. Constraining accessibility is in this way a useful way to evaluate the congested availability of any type of opportunity. As development of sound standards is emphasized in the planning literature, in particular in regards to fairness in transportation [see 34], spatial availability analysis is a useful way to develop and assess standards.

The relevance of the considerations above is put in sharper relief when we think about the use of multiple modes (or heterogeneous populations). If we return to Oslo for a moment [22], we notice that the places that have high accessibility by transit are also the places that have *very high* accessibility by car (in their Figure 2). Those two populations are going for the same opportunities, and those travelling by transit have fewer to choose from to begin with. More generally, people in a zone who are advantaged with relatively low cost of travel will have the ability to potentially reach more opportunities than other people. From the other perspective, their Due to this advantage, through the perspective of finite opportunities, there are fewer opportunities left to be potentially interacted with for populations using higher travel-cost modes. In this way, populations using modes with a higher travel impedance are at a higher access disadvantage than populations using lower travel impedance modes. This recognition is the motivation behind integrating competition for opportunities within multimodal accessibility measures. Arguably one of the most popular competitive location-based accessibility measures is the two-step for everyone else, especially for those who use modes that are slower or otherwise more expensive.

As noted in the Introduction, competitive accessibility was the rationale for developing floating catchment area (2SFCA) approach popularized by methods (FCA), popularized by Luo et al. [1613] who simplified the approach proposed by reformulated the work of Shen [1712] (with similar considerations for competition into two steps (although similar, and earlier, developments are found in [1830,35] and 19).

The Shen-type accessibility measure's formulation is is formulated as:

$$a_i^m = \sum_j \frac{O_j f^m(c_{ij}^m)}{\sum_m D_j^m}$$
 where  $D_j^m$  is the potential demand for opportunities equal to travel impedance weighted population  $\sum_i P_i^m f^m(c_{ij}^m)$ . In this way, the Shen-type measure and the remaining variables are repeated in the Hansen-type measure. Shen-type modal accessibility ( $a_i^m$ ) can be understood as a ratio of the potential opportunity supply over the potential travel impedance-weighted supply of opportunities for  $m$ -mode in  $i$  over the travel impedance-weighted demand for opportunities. The measure considers competition, but it is *non-constrained*. A score of competitive potential accessibility associated is associated with each location  $i$  for each mode  $m$ , but there are no global maximums. In this way, it considers competition. That said, the measure remains unconstrained, meaning both population and opportunities are multiply counted [see 14]. In other words, it is difficult to interpret

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<sup>1</sup> see <https://redfrogforum.org/wp-content/uploads/2019/11/67-Nature-Nearby%20%99-Accessible-Natur>

the meaning of differences in interpretation of the Shen-type accessibility scores between modes is fraught as it is for Hansen-type measures.

To illustrate, [2036] calculates calculate  $a_i^m$  to jobs for different income-group populations in Shenzhen(China), China using  $m = \text{public transit}$  and  $m = \text{car}$ . They demonstrate that  $i m = \text{car}$ . Their results indicate that zones with low-income populations have lower  $a_i^m$  than  $\neq$  zones with higher-income populations. Further, they demonstrate show that  $a_i^{m=\text{public transit}}$  is lower than  $a_i^{m=\text{car}}$  at many zones, arguing that this may put  $i$  further place those zones with lower-income populations in a further at a disadvantage.  $a_i$  and/or  $a_i^m$  are used to compare relative spatial differences in overall competitive accessibility and modal multimodal competitive accessibility, but because there is no global maximum, making it is difficult to interpret the significance between opportunities were doubly counted (entering the sums of both modes), this makes for uneasy interpretations of the differences in  $a_i^m$  values. Questions such as between modes. Questions that this approach leaves unaddressed include: what is the impact that competition has of competition on the difference in  $a_i^m$  values? How does the impact vary spatially? And what is the interpretation of this difference? are left unanswered.

Spatial availability improves on previous multimodal accessibility approaches as it considers competition in the potential interaction with opportunities in a constrained framework (e.g., finite opportunities) previously discussed accessibility approaches using the Hansen-type measure and the Shen-type measure by constraining the sum of opportunities, that is, by treating opportunities as finite. This is done by considering: 1) competition between means of proportional allocation factors that follow well established principles of spatial interaction and the gravity model [see 37]. In Soukhov et al. [15] these factors consider: the mass effect (e.g., the advantage of sub-populations residing in relatively low population-density and high opportunity proximate areas) and 2) competition between travel impedance size of populations at different origins; and the cost of travel from different zones (e.g., some sub-populations with relatively low travel impedance) through a proportional allocation mechanism face relatively higher or lower costs). The following sub-section demonstrates how spatial availability compares to the Hansen-type and Shen-type measures through a synthetic example section introduces the multimodal form of spatial availability.

## Multimodal spatial availability

In brief, we define the spatial availability at spatial availability at an origin  $i$  ( $V_i$ ) as the proportion of all opportunities in the region  $\Omega$  that are allocated to location  $i$  from all opportunity destinations  $j$ .  $V_i$  is a value of how many opportunities are available to each location  $i$  out of all the opportunities in the region. The general formulation of spatial availability  $V_i$  is shown in Equation (1) [see 15]:

$$V_i = \sum_{j=1}^J O_j F_{ij}^t \quad (1)$$

Where:

- $F_{ij}^t$  is a balancing factor that depends on the demand for size of the populations at different locations that demand opportunities  $O_j$  and as well as the cost of movement in the system  $f(c_{ij})$ .
- $V_i$  is the number of spatially available opportunities at  $i$ ; the sum of  $V_i$  is equivalent identical to the total sum number of opportunities in the region (i.e.,  $\sum_j O_j = \sum_i V_i$ ); in other words, opportunities are dealt with as finite resources.

The spatial availability measure is introduced in 14. Spatial availability's unique feature is the Compared to Hansen-type accessibility:

$$A_i = \sum_{j=1}^J O_j f(c_{ij}) \quad (2)$$

we see that spatial availability is, like the Hansen-type measure, a weighted sum of the opportunities. What makes spatial availability stand apart from other approaches is how the weight used in the sum, balancing factor  $F_{ij}^t$ , implements a proportional allocation mechanisms, that ensures the to ensure that the sum of  $V_i$  calculated for each  $i$  sums, across all  $i$  in the region, to equal is constrained to match the total number of opportunities in the region. As such, spatial availability is a competitive and constrained accessibility measure as  $F_{ij}^t$  handles the number of opportunities in the region in a finite way (proportional allocation) singly-constrained and naturally implements competition or congestion.  $F_{ij}^t$  consists of two components parts. The first part is a population-based balancing factor  $F_i^p = \frac{P_i}{\sum_i P_i}$  and an proportional allocation factor to model the mass effect of the gravity model:

$$F_i^p = \frac{P_i}{\sum_i P_i}$$

This factor makes opportunities available based on demand. Secondly, there is an impedance-based balancing factor  $F_{ij}^c = \frac{F_{ij}^c}{\sum_j F_{ij}^c}$  that, respectively, allocate opportunities to  $i$  in proportion to the size of the population at  $i$  (the mass effect) and the cost of reaching opportunities at  $j$  (the impedance effect). proportional allocation factor that models the cost effect:

$$F_{ij}^c = \frac{F_{ij}^c}{\sum_j F_{ij}^c}$$

This factor makes opportunities available preferentially to those who can reach them at a lower cost.  $F_i^p$  and  $F_{ij}^c$  are calculated for each  $i$  such  $F_{ij}^c$  are designed so that they both equal 1 when summed across all  $i$  in the region (e.g.,  $\sum_i F_i^p = 1$  and  $\sum_i F_{ij}^c = 1$ ). These balancing factors are combined multiplicatively to yield  $F_{ij}^t$  which ensures that a proportion of the opportunities  $O_j$  are allocated to each  $i$  accordingly. In other words, assuming a finite number of opportunities in the region,  $F_{ij}^t$  proportionally allocates  $O_j$  to each  $i$  such that the resulting  $V_i$  value represents the number of opportunities spatially available to the population at  $i$ . This value can be seen to represent spatial availability as it Each zonal value is a proportion of the opportunities in the region (i.e.,  $\sum_j O_j = \sum_i V_i$ ).

The focus of this paper is to extend  $V_i$  for multimodal applications the measurement of multimodal applications (or more generally heterogeneous populations). To do so, the balancing factors are reformulated to yield a proportional value for the set of modes  $m$  used by populations at each need to be reformulated so that 1) the mass effect now accounts not only for the size of the population at  $i$ . As these factors are proportional, but also the size of sub-populations within  $i$ ; and 2) the cost of travel is not only for different zones, but by sub-populations within each zone (e.g., the cost of travel from  $i$  by car, transit, walking, etc.). When we introduce modes (or sub-populations)  $m$ , the proportional allocation factors need to satisfy the condition that  $F_i^{pm}$  and  $F_{ij}^{cm}$  can be summed up across each  $m$  at each  $i$  and then across all  $i$  to equal to 1. They are also similarly combined multiplicatively to obtain their joint effect,

represented as the combined balancing factor  $F_{ij}^{tm}$  similar to that detailed in Equation (3). This factor is given by:

$$F_{ij}^{tm} = \frac{F_i^{pm} \cdot F_{ij}^{cm}}{\sum_{m=1}^M \sum_{i=1}^N F_i^{pm} \cdot F_{ij}^{cm}} \quad (3)$$

Where:

- The population balancing 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
- The factor for allocation by cost of travel balancing factor for each  $m$  at  $i$  is  $F_{ij}^{cm} = \frac{f(c_{ij}^m)}{\sum_m \sum_i f(c_{ij}^m)}$

Implementing  $F_{ij}^{tm}$ , the following Equation (4) demonstrates the multimodal configuration gives the multimodal version of spatial availability  $V_i^m$ :

$$V_i^m = \sum_{j=1}^J O_j F_{ij}^{tm} \quad (4)$$

Where:

- $m = 1, 2, \dots, M$  is a set of modes used by populations in the region  $M$  modes (or sub-populations) of interest.
- $F_{ij}^{tm}$  is a balancing factor  $F_{ij}^t$  for each  $m$  at each  $i$ .
- $V_i^m$  is the spatial availability  $V_i$  for mode each  $m$  at each  $i$ ; the sum of  $V_i^m$  for all  $m$  at each  $i$  is equivalent to the total sum of opportunities in the region (i.e.,  $\sum_j O_j = \sum_i V_i = \sum_m \sum_i V_i^m$ ).

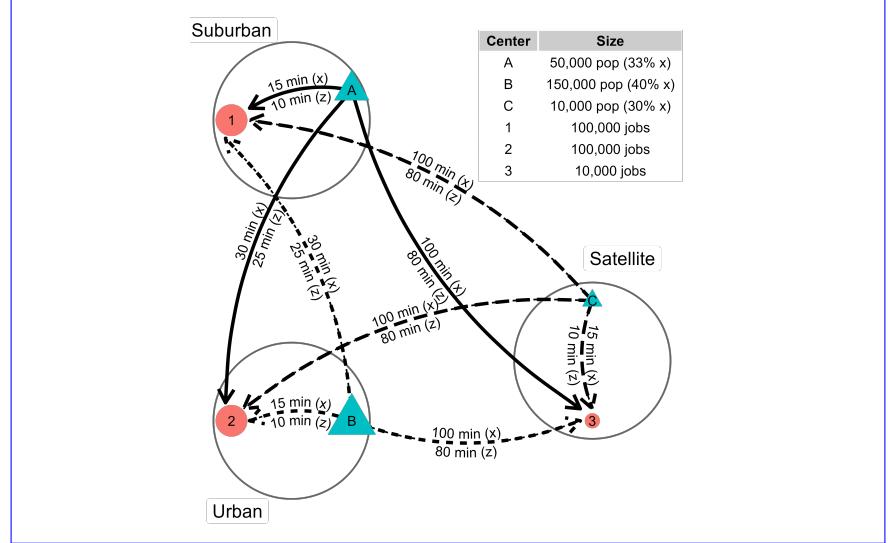
Next we use a synthetic example to contrast multimodal accessibility and spatial availability.

Consider the following. Figure 1 depicts

## An illustrative synthetic example

Consider the simple system shown in Figure 1. The figure shows a region with population and jobs at three population centers ( $A$ ,  $B$ ,  $C$ ) and jobs at three employment centers (1, 2, 3). The population at each population center is divided into origin  $i$  consists of two sub-populations, one using a faster mode  $z$  and another using a slower mode  $x$ , to travel to employment centers. Population center  $A$  is Suburban: it is closest to its own relatively large employment center at 1, close to the Urban's equally large employment center 2, and has a population that is smaller than the Urban  $B$  and larger than the Satellite  $C$ .  $B$  has the largest  $x$ -using population, followed by then  $A$ , then  $C$ . This synthetic example was inspired by the single-mode example used in [1712] and reconfigured in [1415].

From the perspective of access to a finite amount of opportunities in the region (210,000 jobs), the sub-population that is most proximate to jobs (low cost to reach), furthest from densely populated centers, and is using the lowest travel-cost large populations (less competition), and uses the fastest mode  $z$  can potentially access the most job (greater range) can potentially reach the largest number of opportunities. This appears to be the sub-population at  $A$  using mode  $z$ . From the other perspective, sub-populations located in opposite conditions (i.e., further away more distant from jobs, close to dense large populations, and using slow mode  $x$ ) are at



**Fig 1.** Multimodal synthetic example: locations of employment centers (in orange), population centers (in blue), number of jobs and population, and travel times for two modes (slower mode x and faster mode z).

a relative job opportunity access *disadvantage*. From the perspective of inequities, the disadvantage. The competition for opportunities between different mode-using populations matters as it reflects how well the land-use and transport system serves (or doesn't serve) them does not serve certain populations.

**Table 1.** Accessibility values at each origin ( $i$ ) per mode ( $m$ ) at (columns each three origin to five) and aggregated between per modes for (columns each six and seven) for the synthetic example.

$i$	$m$	$S_i^m$	$a_i^m$	$V_i^m$	$a_i$	$V_i$
A	x	27,292.18	0.95	15,696.89	1.36	67,482.61
	z	44,999.80	1.57	51,785.72		
B	x	27,292.18	0.64	38,170.03	0.88	132,638.94
	z	44,999.80	1.05	94,468.91		
C	x	2,240.38	0.68	2,035.86	0.99	9,878.45
	z	3,745.89	1.12	7,842.59		
TOTALS		150,570.22	N/A	210,000.00	N/A	210,000.00

The calculated values calculated for  $S_i^m$  (Hansen-type accessibility),  $a_i^m$  (Shen-type accessibility), and  $V_i^m$  accessibility values (spatial availability) for each  $i$  and  $m$  are shown in the middle three columns and are aggregated for each  $i$  in the final two columns in Table 1. We As in the example in Shen [12], we use a negative exponential impedance function  $f(e_{ij}) = \exp(-\beta \cdot e_{ij})$   $f^m(c_{ij}^m) = \exp(-\beta \cdot c_{ij}^m)$  with  $\beta = 0.1$  for both  $x$  and  $z$  modes for all accessibility measures calculations. Notice that in this example we use the same impedance function but the travel times are different for the two modes. More generally, it is possible to use different impedance functions for the modes, as demonstrated in the empirical example in the following section.

The Hansen-type measure accessibility  $S_i^m$  is presented for each origin and mode in the third column of Table 1 . For all  $i$ , the travel by  $z$  -using sub-population has higher  $S_i^m$  values than the results in higher values of  $S_i^m$  than travel by  $x$ -using sub-populations. Additionally, Lack of competition, or alternatively the assumption of an inexhaustible resource in the calculation of  $S_i^m$  is equal for both mode-using populations in  $A$  and  $B$ . This is the case because  $S_i^m$  does not consider competition, it only relies on reflecting the count of opportunities that may be interacted with as a product of  $f^m(e_{ij}^m)$ . Recall, lead to a curious result. Since the populations in  $A$  and  $B$  have the same travel impedance to employment centers 1, 2 and 3 (either 15, 30, or 100 minutes using  $x$  or 10, 25, or 80 minutes using  $z$ ). As such, these the calculated  $S_i^m$  values, their values of  $S_i^m$  are the same for both  $A$  and  $B$ . Furthermore, the total sum of  $S_i^m$  in the region is equal to 150,570.2. This value is difficult to interpret lacks an intuitive interpretation: it represents the weighted sum of opportunities that may be interacted with reached within the region based on travel impedance . It cannot be interpreted as according to the travel impedance (i.e., the travel behavior and the characteristics of the modes) and does not usefully translate into any sort of benchmark since the measure is non-constrained. To connect this example to the aforementioned literature,  $S_i^m$  is calculated in the work of Tahmasbi et al. [4521]; they compare contrast differences in  $S_i^m$  values between modes in a relative and comparative sense, but make no further interpretation of the  $S_i^m$  values. More densely populated metropolitan regions will tend to have more opportunities and hence large  $S_i^m$  values and less densely regions, smaller values; how much of these differences may simply an artifact of region density?

In the fourth and sixth column columns in Table 1 the results for Shen-type measure is calculated accessibility are reported: first for both origin and mode  $a_i^m$  as well as aggregated by the weighted mean mode-population ( $\sum_m \frac{P_i^m}{P_i} * a_i^m$ ) to represent a value for each origin  $a_i$ . Unlike  $S_i^m$ , this measure does consider competition. For instance, the population travelling by  $x$  -using populations in from  $A$  and  $B$  centers do not have the same  $a_i^m$  values as the values of  $a_i^m$  as those travelling by  $z$ -using. In fact,  $A$  has the highest values  $a_i^m$  and  $a_i$  values since this center has the smallest lowest travel impedance to opportunities (lower than at  $C$ ,  $A$  and  $B$  are equal) and has one of these lowest proximity faces relatively low competition, not being close to a relatively high amount of large population (lower than at  $B$ ).

However, the Shen-type measure is non-constrained calculations of  $a_i^m$  are not constrained: the total sum of  $a_i^m$  or  $a_i$  is practically meaningless since it represents a sum of ratios. For instance, the population travelling by  $z$  -using sub-population at from  $A$  has a value of 1.57 potential jobs per potential jobs per job-seeking population compared to 0.95 for users of mode  $x$ -using sub-population. What is the significance meaning of these values? The difference between these modes is equal to 0.62, but 0.62 of what? How many more job opportunities are  $z$  users interacting with than can users of  $z$  reach compared to user of  $x$  users? When  $a_i^m$  is aggregated to  $a_i$  as shown in the sixth column, the values face similar interpretability issues. The Shen-type measure is implemented in the previously discussed work of Tao et al. [2036] to calculate modal  $a_i^m$  values and the aggregated  $a_i$  is implemented in the work of Carpentier et al. [2138]. However, similar to the Hansen-type measure accessibility, these works discuss relative and spatially comparative differences in values, they do not make further interpretation of the but veer from interpreting the values of  $a_i^m$  or  $a_i$  themselves. This may be because the Shen-type measure is non-constrained, this is no benchmark or global maximum to which comparisons can be drawn from. In fairness, interpretation is complicated by the multiple counting of opportunities between zones and modes.

By In contrast, spatial availability  $V_i$  considers competition and is constrained such

that the total sum of values is equal to the total number of opportunities in the region (i.e., 210,000 jobs). Seen in fifth column of Table 1 , ~~the values of  $V_i^m$  for the same mode-using populations~~ in  $A$  and  $B$  are not the same ~~within each mode~~ (as this measure considers competition). In fact, at  $A$ , ~~the users of mode  $z$  -using sub-population captures capture~~ 36,088.84 more spatially available jobs (of the 210,000 jobs in the region) than the sub-population ~~using mode~~-travelling by  $x$ . The numerical difference ~~has a practical interpretation~~is clear since it refers to opportunities out of the total.

Furthermore,  ~~$V_i^m$  values for an~~ the proportional allocation mechanism also means that the values of  $V_i^m$  for any origin  $i$  can be aggregated across  $m$  and compared ~~across t-between zones~~ ( $V_i = \sum_m \sum_i V_i^m$ )~~as a result of the proportional allocation mechanism~~. This aggregation,  $V_i$ , is shown in the seventh column in Table 1 . Again looking at center  $A$ ,  $A$  is allocated 67,482.61 spatially available opportunities for both modes. 77% of this spatial availability allocated to  $A$  is assigned to ~~the users of mode  $z$  -using population~~despite representing 66% of  $A$ 's population.

Spatial availability can be further aggregated to better interpret competition between modes. Across the entire region, 130,000 people use  $z$  (62% of the region population). However, ~~the users of  $z$  -using population accounts account~~ for 73% of the region's total spatial availability - ~~the rest while the remaining 27%~~ is allocated to ~~the users of mode  $x$  -using population (who are~~ 38% of the total population). Notably, the ~~population who uses  $x$  -using population captures have 11% less spatial availability to fewer spatially available opportunities than its population proportion. This understanding can lead share in the population. This realization leads~~ us to ask normative questions such as, how unequal should ~~opportunity access for the two mode-using populations be availability of opportunities be by mode? What intervention could help to redistribute spatial availability to sub-populations commensurate with their proportion of the total? Can the lower travel cost populations spare some spatial availability if a policy of modal restriction (like a LEZ) was introduced?~~

Since spatial availability is constrained and has an interpretable meaning as a proportion of the total opportunities in the region, the values at  $i$  have a ~~new significance~~straightforward interpretation. Inequality in  $V_i^m$  values can be explored through a variety of approaches. For instance, consider travel times. The ~~population of travelers who use  $z$  -using population~~accounts for 67% of the potential travel time traveled in the region: this is 7% less travel time than the proportion of spatial available opportunities that is allocated to them. In other words, the  ~~$z$ -using population travels less population of users of  $z$  travels fewer minutes overall and has more spatial availability of opportunities than the  $x$ -using population using the users of the slower mode  $x$ .~~

Alternatively, inequities in spatial availability between ~~mode-using populations modes~~ can be explored through proportional benchmarks. A spatial availability per capita  $v_i^m$  ~~as is~~ presented in Equation (5):

$$v_i^m = \frac{V_i^m}{P_i^m} \quad (5)$$

The  ~~$v_i^m$  values~~ values of  $v_i^m$  for  $A$ ,  $B$ , and  $C$  for ~~the users of  $x$  -using sub-populations~~are 0.95, 0.64 and 0.68 spatially available jobs per capita, respectively. The ~~values of  $v_i^m$~~  for ~~the users of  $z$  -using sub-populations~~are much higher, with values of: 1.57, 1.05 and 1.12 respectively. ~~The Users of  $x$ -using population, especially especially those~~ at  $B$  and  $C$ , are directly impacted by the jobs that are spatially available to ~~the users of  $z$  -using population~~in addition to the mass effect (occurring at  $B$ , high population density) and high travel impedance (occurring at the Satellite  $C$ ). If, ~~lets let us~~ say, the planning goal ~~is~~was to have one spatially available job per

mode-using population, a policy intervention ~~can be put in place~~ could be devised, to reduce the  $v_i^z$  values and increase  $v_i^x$  values. This values of  $v_i^z$  (making it slower or more expensive) and increase he values of  $v_i^x$  (making it faster or less expensive). The purpose of this simple demonstration is to show how simply the  $V_i^m$  framework can be manipulated spatial availability can be used to quantify the competitive (dis)advantage in a multimodal application. In what follows, we further explore competition between multiple modes demonstrate the use of multimodal spatial availability through an empirical example.

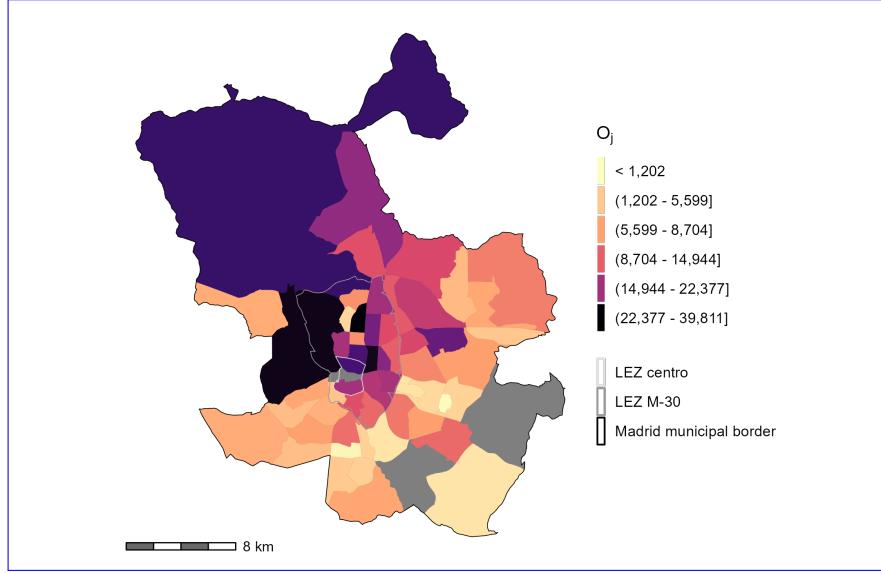
## Empirical example

### Context

~~Low emission zones~~ The context for the empirical example is Madrid, Spain. This city implemented a Low Emission Zone (LEZ) ~~have~~ in 2017 to: pursue goals set out in the national climate change agenda, cut nitrogen dioxide levels, and to prioritize people's movement in the city. LEZs elsewhere have similarly been implemented as ~~a climate change policy intervention interventions~~ to reduce GHG emissions, improve air quality, and support sustainable mobility ~~in many countries~~. Though rules vary [39, LEZ-40]. Though the rules of exclusion vary by city, LEZs aim to deter/reduce traffic in designated zones under threat of penalty (e.g., fines, seizure of vehicle). ~~From the perspective of restriction for passenger transport, LEZ are a policy~~ In other words, LEZs implement a form of geographic discrimination as they change how people access can reach opportunities by making the travel impedance it more costly for car-mode users. If seeing some forms of travel, typically cars, to circulate in predetermined zones. When considering opportunities as finite ~~in a region~~, this discrimination allows populations to access opportunities by other modes more readily than before. In this way, LEZ change the multimodal competitive reduces the competition of one mode and opens up opportunities for other modes to better thrive. At their core, LEZs operate by changing the accessibility landscape of a city ~~from the perspective of multiple modes~~.

Spain is one of a few countries with active LEZ and plans to expand their implementation as specified in their climate-change-related plans: *Plan Nacional Integrado de Energía y Clima 2021-2030* 22 and *Plan Nacional de Control de la Contaminación Atmosférica* 23. Specifically, the national Spanish law 7/2021 (*Ley de Cambio Climático y Transición Energética*) will require all municipalities to implement LEZ by 2023 if they meet at least one of the following requirements: (i) municipalities >50,000 inhab.; (ii) islands; and (iii) municipalities > 20,000 inhab. when air quality exceeds limits specified in *RD 102/2011 de Mejora de Calidad del Aire* 24.

In 2017, LEZs were implemented in the Spanish capital city of Madrid following the goals set out in the national agenda. In geographic scope, the 2017 boundaries of the LEZ ~~were relatively small (covering in Madrid were relatively modest, covering only approximately 4.72 km<sup>2</sup>(2)) and within the center (i.e., <sup>2</sup> of the central business district of the city (the so-called LEZ Centro). These boundaries were expanded in 2023 to inside of As of this writing, there are plans to expand these boundaries to the area inside the M-30, a an orbital highway in proximity to the city center (i.e., LEZ M-30) and the city has plans to further spatially expand the LEZ. Within the 2017 LEZ Centro implementation, all cars, motorcycles and freight with environmental label vehicles with environmental labels A or B (higher polluting classification, associated with older make and model older makes and models of fossil fuel internal combustion engine vehicles), are not permitted to enter the area were disallowed from entering the zone unless they are used by residents or meet other exemptions. This restriction~~



**Fig 2. Jobs  $O_j$** —Distribution of jobs taken by people living and working in Madrid as reported by in the 2018 travel survey. Grey TAZs has no jobs. Ranges of values in the legend are quintiles.

impacted approximately half of all car trips that were typically made into used to travel into what is now the LEZ Centro [2541].

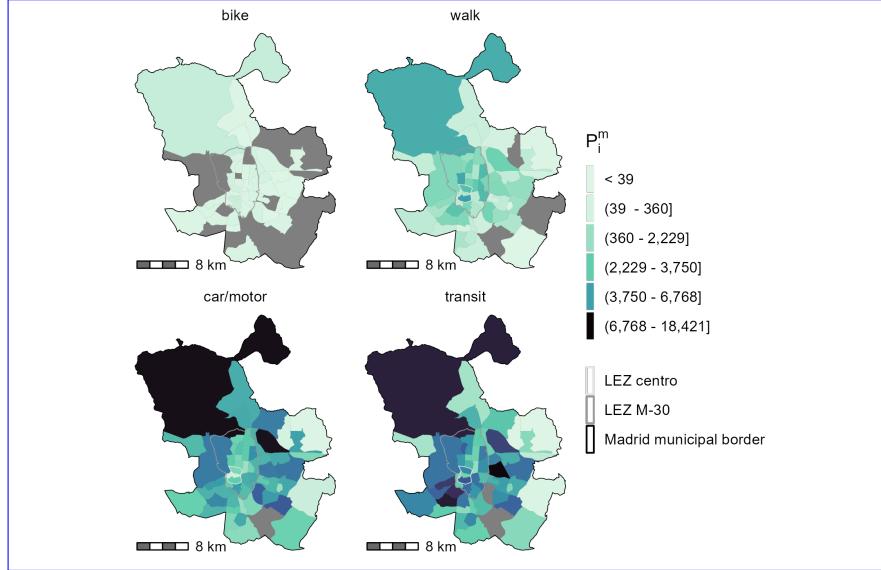
For this case study, we use  $V_i^m$  to quantify the competition of spatially available opportunities between modes after the LEZ Centro implementation spatial availability to quantify access to opportunities by different modes in Madrid. Particularly, we demonstrate how  $V_i^m$  can be used to speculate on derive insights into how the restriction of car mobility in areas around/within the LEZ Centro allowed the other, more sustainable but often with higher travel impedance modes, may have allowed more sustainable (but often slower or more costly modes) to become more competitive.

The

## Data

The source of data for our empirical example is the 2018 Travel Survey of the Community of Madrid travel survey ([2642]) is the source of data for this empirical example: it is. This is a representative survey that reflects offers a snap-shot of the travel patterns for one typical day of the working week (e.g., n=a typical weekday in 2018. The survey collected 222,744 trips with representative population elevation factors) from a representative sample of 85,064 households across the traffic analysis zones (TAZ) in the Community of Madrid. For context, the population older than 3 years in the Community is 6,507,184.

In this example, we use all home-to-full-time-work trips, by all modes. In this paper, a sample of the travel survey is used, namely the residential home origin to work destination tripsof all modesand those that originate and end in the city of Madrid. These totals are displayed in Figure 2 and Figure 3 . Both figures are displayed at the level of traffic analysis zones ( $i$  and  $j$ ) that correspond to the survey. The red The trips are expanded using population weights. Figures 2 and 3 show the number of workers and the distribution of full-time jobs in the City of Madrid by TAZ. The light grey boundary represents the LEZ Centro in effect in 2017 and thus those travel patterns of ear restriction reflected in the survey . The cyan 2017. The survey was conducted



**Fig 3.** Population living and working in Madrid, by four summarized modal categories,  $P_i^m$ , mode of transportation as reported by in the 2018 travel survey. Grey TAZs have no population. Ranges of values in the legend are quintiles.

after the introduction of LEZ Centro. The dark grey boundary represents the LEZ that will be within planned for the boundaries of the M-30 highway in 2023 and is present in the plots as a spatial reference for areas in proximity to the LEZ Centro.

The total sum of jobs  $O_j$  that are held are shown in Figure 2 and the populations that go to a work destination by four modal categories  $P_i^m$ , is reflected displayed in Figure 3. The modal categories represented shares in Figure 3 are summarized for the following trip mode types calculated based on those measured in the survey. The modal categories and the mode types within each category are reported as follows:

- Car/motor: all cars and operating modes (e.g., cab, private driver, company, rental car, main driver, passenger, etc. of a private car, passenger in a private car) and all public, private or company motorcycle/mopeds.
- Transit: all bus, trams, and trains
- Bike: all bicycle trips (e.g., private, public, or company bike trips) and “other” types of micromobility options
- Walk: walking or by foot

Some aggregation of modes is necessary to calculate the travel impedance functions by mode. From Figure 2, it can be seen that the largest concentration of jobs are within, near, and to the north of the LEZ Centro. The population that is accessing populations with access to those jobs by mode (Figure 3), appear are spatially distinct. Car and transit trips Travel by car and transit represent 37% and 47% of the modal share respectively. The population that travels using transit is more spatially distributed than those using cars - particularly near and within LEZ Centro. This distribution could be a result of a is likely caused by a variety of factors including: transit coverage and service within with city, effective car infrastructure outside of the M-30, and/or the impact of the Central LEZ itself.

LEZ Centro itself. From Figure 3, it can also be seen that biking and walking trips are active travel is less common than motorized trips at 1% and 15% respectively. Noticeably for cycling and walking respectively. Noticeably, there is a positive trend between the populations of walking and biking trips in zones and populations of

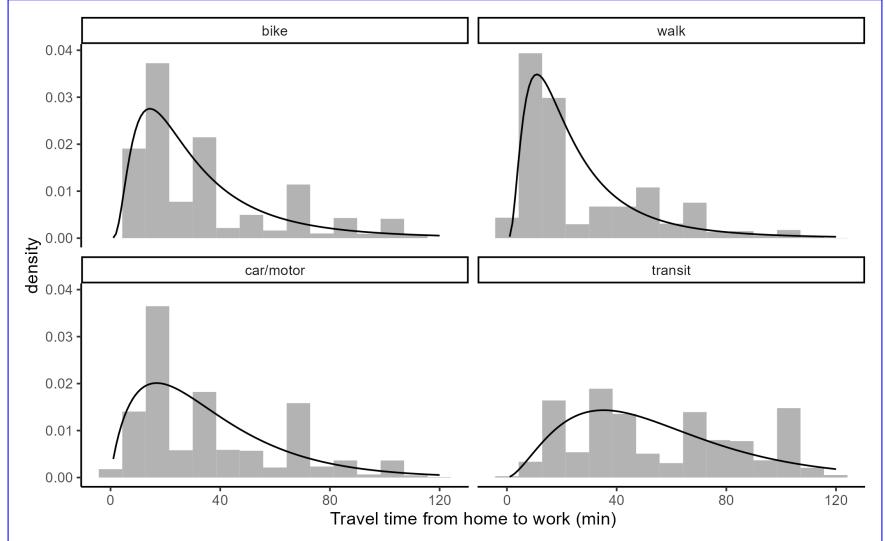
~~transit trips~~walking and cycling in zones where transit is also present. This positive trend is higher than for car trip populations.

~~The travel time for each trip is~~ Travel times are provided within the survey. ~~These travel times, per modal category, are~~ travel survey by mode. This information is used to calibrate mode-specific travel impedance functions  $f^m(c_{ij}^m)$ . To illustrate the modal differences in travel ~~lengths, summary descriptive times, the following descriptive statistics~~ per mode are ~~detailed~~ presented:

- Car/motor: ~~mean~~ 36 ~~min.~~minutes (min: 0 ~~min.~~minutes, Q2: 15 ~~min.~~minutes, Q3: 55 ~~min.~~minutes, max: 120 ~~min.~~minutes)
- Transit: ~~mean~~ 55 ~~min.~~minutes (min: 1 ~~min.~~minutes, Q2: 30 ~~min.~~minutes, Q3: 80 ~~min.~~minutes, max: 120 ~~min.~~minutes)
- Bike: ~~mean~~ 34 ~~min.~~minutes (min: 5 ~~min.~~minutes, Q2: 15 ~~min.~~minutes, Q3: 40 ~~min.~~minutes, max: 115 ~~min.~~minutes)
- Walk: ~~mean~~ 27 ~~min.~~minutes (min: 1 ~~min.~~minutes, Q2: 10 ~~min.~~minutes, Q3: 45 ~~min.~~minutes, max: 119 ~~min.~~minutes)

~~To calculate Impedance functions  $f^m(c_{ij}^m)$  from the survey travel times, a concept known as the~~ are calibrated from the travel times in the survey via the empirical trip length distribution (TLD) ~~was used. A TLD represents~~. An empirical TLD is given by the proportion of trips ~~that are taken at a specific travel cost such as travel time (i.e., probability density distribution of trips taken by travel cost)~~ at various travel cost bins. This distribution is then used to derive impedance functions (e.g., done in the accessibility works of estimate the parameters of a function for the travel impedance [27as done in 43,44,45],28, and 29). To fit the impedance functions, we use the Maximum likelihood estimation and the Nelder-Mead method for direct optimization available within the R {fitdistrplus} package [30,46] is used to fit the impedance functions. As shown as shown in Figure 4, based. Based on goodness-of-fit criteria and associated diagnostics, the gamma and log-normal probability density ~~function (line curves)~~ functions are selected as best fitting curves for the motorized and non-motorized modes respectively. The selection of functional ~~form~~ forms aligns with empirical examples in other regions [14,31,32,15,47,48]. Overall, the plots in Figure 4 display the probability of travel. The shape and rate parameters for the gamma functions (motorized modes) are 1.8651852 and 0.051468 for car/motor and 2.7566235 and 0.0499193 for transit; for the log-normal functions (non-motorized modes), the mean and standard deviation parameters are 3.2372212 and 0.7575986 for bike and 2.9918042 and 0.7575986 for walk.

Figure 4 includes four plots to visualize the calibrated impedance functions (represented as black lines) superimposed on the empirical TLD. The impedance functions can be interpreted as the propensity to travel (y-axis) given a trip travel time, ~~based on trip flows from the survey. These 'probability of travel' at each travel time for each mode are realized observations that reflect the land-use,~~ (x-axis). The functions reflect a combination of possibilities and preferences: the travel behavior given the transportation technologies available. For example, trips shorter than 5 minutes do not occur frequently for any mode; this reflects the spatial separation between places of residence and places of work commonly seen in many cities. In terms of the transport system, ~~and~~ non-motorized modes, there is a preference towards walking trips around 15 minutes in duration, as seen from the highest value of  $f_{walk}(c_{ij}^{walk})$ . With respect to travel by bicycle, longer travel times are more common; although the highest value of the impedance also corresponds to approximately 15 minutes, the curve has a longer tail and values decrease less rapidly at longer travel times than is the case of  $f_{walk}(c_{ij}^{walk})$ . A similar trend can be observed for the population travel behaviour in Madrid ~~motorized modal options where transit mode is~~



**Fig 4.** Fitted impedance function **curve (line)** against empirical TLD (bars) corresponding to the **home-to-work origin-destination** **home to full-time work origin destination** flows **from** **for** the **City of Madrid** **from the** 2018 travel survey.

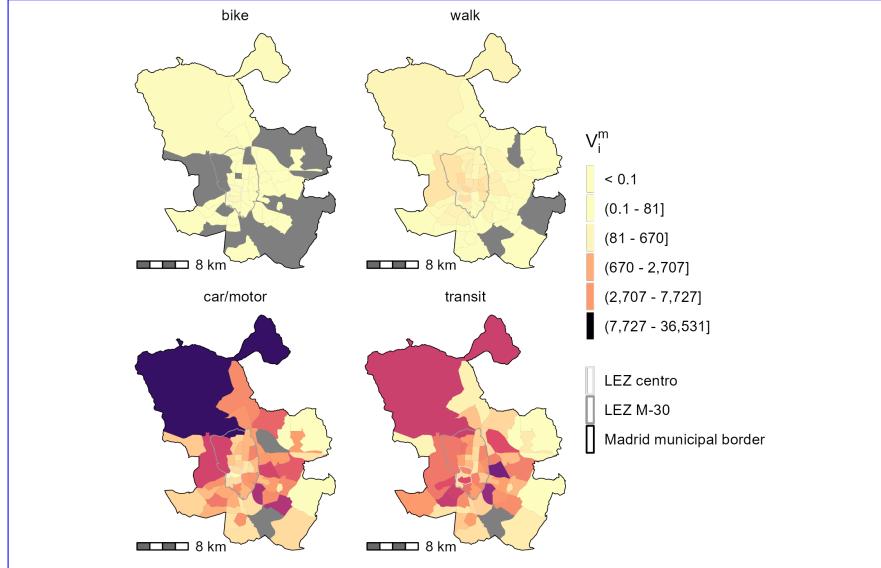
more spread out than car/motor mode. All in all, these functions represent the propensity of travel by mode by duration of trip, and are used to calculate the proportional allocation factors  $F_{ij}^m$  for  $V_i^m$ .

## Results

At this point, it is worthwhile reiterating that the empirical example is a snap-shot of spatial availability by mode using data from the 2018 travel survey. Our purpose in this empirical example is to investigate the trends in availability of employment opportunities by mode, and illustrate how spatial availability can be used in discussions about the competitive advantage of various modes within Madrid Centro. The spatial availability of jobs  $V_i^m$  is calculated for each of the four modal categories modes  $m$  at the level of traffic analysis zones  $i$  in Madrid and demonstrated displayed in Figure 5.

In the figure,  $V_i^m$  is a proportion of the total number of the 847,574 jobs in the region and is visualized in Figure 5. Since  $V_i^m$  is calculated based on the likelihood of travel from observed home-to-work journeys population of workers and the distribution of jobs, the values can be understood as the number of full-time jobs that are spatially available to the full-time working population workers at that  $i$  and their associated traveling by mode  $m$ , relative to all the jobs in the city.  $V_i^m$  is the number of jobs that are spatially available to a  $m$ -using population located at  $i$ , relative to the travel impedance and size of all populations in the region.

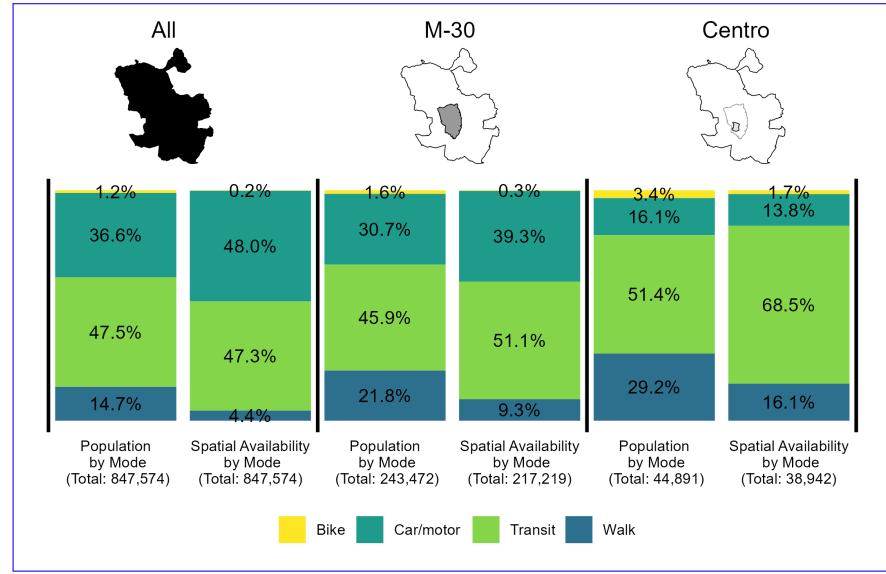
Notable are the There are noticeable differences in the magnitude of  $V_i^m$  between modes as seen in Figure 5. The majority of  $V_i^m$  (which is to say of spatially available jobs) are allocated to workers travelling by car and transit. In a way, this is allocated to car- and transit- using populations. This is to be expected, as the population that commutes using these modes represents since users of these modes represent 84.1% of the total population. Differences However, the ability to travel at greater speeds also impacts these results. Furthermore, differences in  $V_i^m$  values within mode-using populations also exist : car-using populations modes also exist in space: car users outside of the M-30 region appear to have greater  $V_i^m$  values enjoy greater spatial



**Fig 5.** Spatial availability of job opportunities jobs per origin and mode  $V_i^m$  in Madrid. Calculated using Grey TAZs have no population. Ranges of values in the home-to-work origin-destination flows from the 2018 travel survey legend are quintiles.

availability, while some  $i$ -areas zones inside the M-30 appear to have higher  $V_i^m$  values for the transit-using populations to have greater spatial availability for transit. Overall, the magnitude of  $V_i^m$  values for the bikers and walkers cyclists and pedestrians are lower than for car and transit but the highest values of  $V_i^{bike}$  and  $V_i^{walk}$  values tend to be allotted to is found in zones within the M-30 and is that have higher  $V_i^{transit}$  values origins with higher spatial availability by transit.

The differences between the mode-using population and their mode-specific spatial availability shares of modes and their shares of spatially available opportunities highlights the competitive advantage offered to certain modes in certain spatial extents. As summarized of certain modes, although this effect is not geographically uniform. As seen in the left-most columns in of Figure 6, the users of 'car/motor' and 'transit' populations represent a combined together can avail 95.3% of the total spatial availability all jobs in the city (Spatial Availability by Mode). However, the 'car/motor' using population is allocated disproportionately more users have a disproportionate share of  $V_i^m$  than its size compared to the transit using population. The car-using and transit using population relative to the population of users of this mode (Population by Mode), compared to opportunities that are spatially available to transit users. The combined population of car and transit users is 36.6% and 47.5% respectively, but is these populations are allocated 48.0% and 47.3% respectively, of the city's spatial availability jobs. When treating the number of opportunities that can be reached as a finite value (total: 847,574 opportunities), fewer opportunities are spatial availability to the lesser competitive modes using populations, in this case spatially available to slower modes (i.e., walking and cycling), even taking into account that their share is smaller overall. These modes are less competitive at a disadvantage as a result of: their lower travel impedance values at longer travel times the travel impedance for longer trips (see Figure 4at travel times beyond ~30 minutes); their low population values values overall; and higher populations present larger populations in origins with high motorized mode commuting shares of travel by motorized modes. These factors all contribute to the the car/motor mode being most advantaged in capturing spatially available job opportunities overall.



**Fig 6.** Displays the proportion of the working population by mode and spatial availability of job opportunities by mode aggregated for three spatial areas. From left to right, the city of Madrid (All), the area within the M-30 highway (M-30), the area within the Centro region (Centro).

There are spatial variations in the competitive advantage of the car-using populations. The proportion of car-using population in the Centro is smaller and has higher travel impedance values relative to the inputs in other areas and mode-using populations. The LEZ Centro implementation further restricts the car advantage as it shifted more than half of all car trips into the LEZ to another mode<sup>25</sup>. This restriction decreased the number of car-using population from 16.1% going into the LEZ Centro (an area with The big picture demonstrates how car is the most advantageous mode, however it is interesting to notice that this advantage appears to be blunted by the LEZ. Unlike the results for the whole city and even within the M-30 ring, the proportion of car users in Centro is larger than the proportion of opportunities spatially available to them. The restriction on cars in effect reduces competition by this mode, and leads to a relative increment of the mass effect of the modes allowed within the LEZ, which also contains a large number of jobs overall, (see Figure 2), thus increasing the mass effect for non-car modes and resulting in proportionally higher  $v_i^m$  values for non-car modes. As such, the lower amount of access to opportunities by ear-mode allows more opportunities in the LEZ to be available by populations using other modes.

As summarized in the two right-most columns in Figure 6, the proportion of spatial availability allocated to the car-using population in the Centro jobs spatially available to car in Centro is (13.8% or 5,373 opportunities). As a comparative reference, this is less than the proportion of the car-using population in the car users in Centro (16.1%), evidently less than the proportion of car-using population car users in the city, and is the opposite of the trend overall overall trend (left-most columns) and within the M-30 (middle columns). More opportunities are spatial availability

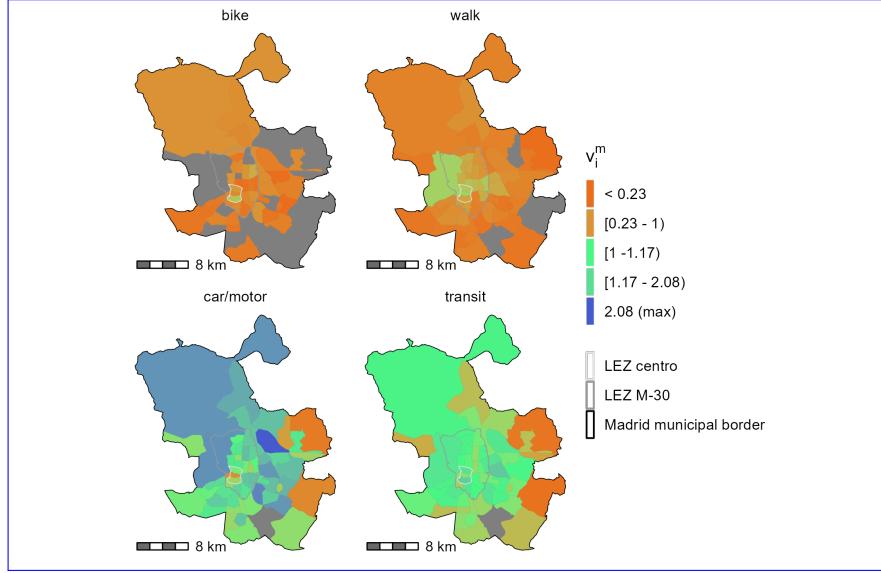
It is also clear that more opportunities are spatially available to non-car using populations within the Centro, particularly transit-using populations (68.5% of spatially available jobs in the Centro despite representing 51.4% of the population in the Centro and 47.5% in the city overall).

From users within Centro. In the case of active travel, the proportions of cyclists

and walkers within LEZ Centro still exceeds the proportions of jobs spatially available to them — however, the disparity is drastically reduced compared to the rest of the city. As seen in Figure 6, it is also summarized that there is a higher proportion of opportunities that are spatially available to walking and cycling populations in the pedestrians and cyclists in Centro than in the City overall and in all areas within the M-30. Notably, within the Centro, 1.7% and 16.1% of opportunities are spatially available to bike and walk modes respectively, while their populations represent smaller proportions of 1.2% and 14.7% of the population overall. Though the proportion of spatial availability for these mode-using populations is still lower than the proportion of mode-using population located in the Centro, these modes are more competitive within the Centro than outside of the Centro. By restricting the more competitive car mode through the LEZ, the advantage in the spatial availability of opportunities afforded to the otherwise lesser competitive modes is made apparent. By restricting the ability of cars to enter Centro, the LEZ seems to contribute to leveling the playing field for slower modes, in particular cycling and walking, but also transit. As seen in the Figure 6, transit users are generally close to parity across the region, with nearly as many spatially available jobs as transit users. Still, this mode has the greatest advantage in LEZ Centro with 68.5% of spatially available jobs in Centro for 51.4% of transit users in Centro. This result makes intuitive sense: after car, it is the mode with the greatest range, and unlike car it is unrestricted in the LEZ Centro.

The spatial differences in the competitive disadvantage of spatial availability between modes can also be visualized per origin at a finer level of granularity. Figure 7 visualizes shows  $v_i^m$ , the spatial availability  $V_i^m$  divided by the mode-population population of users of  $m$ . Values of  $v_i^m$  values above 1 are represented in increasing red shades, values below 1 are represented in increasingly green shades, and values equal to 1 are white. These plots illustrate the discussion of the disproportionately high over-allocation of spatial availability relative to the mode-using population in many of the origins for the car/motor mode below one are shown in shades of orange, and indicate TAZs with less than one spatially available opportunity per capita for the mode. Values above one are shown in shades of green, and indicate TAZs with more than one spatially available opportunity per capita for the mode. The highest spatial availability per capita (shown in blue) is for car users in a zone northeast just beyond the M-30. These plots illustrate in unambiguous fashion, and in a quantity that is comparable over space and time, the advantage in terms of spatial availability of car for most of the city (bottom left plot, areas denoted with green  $v_i^m$  values above 1). These plots also visualize areas that disproportionately capture lower spatial availability (under 1), represented in shades of red. It can be observed that the transit-using population's spatial availability to spatial availability of jobs is relatively balanced well balanced for transit users over most of the regions (i.e., many zones are white), while the light orange or light green). Spatial availability of jobs for non-motorized modes  $v_i^m$  values are, in contrast, is low (under 1) overall, although less so within LEZ Centro.

Interestingly, as also represented in Figure 6, Incidentally,  $v_i^m$  for car/motor values for car within and near the LEZ Centro is near or below 1 (white/red) close to or below one in Figure 7, while all non-car modes have relatively higher  $v_i^m$  values. Though the spatial availability from before the LEZ Centro implementation is unknown Since these values are comparable across regions and over time, Figure 7 potentially provides a benchmark for quantifying potential LEZ implementations changes in LEZ policies in the future(given 2018 travel conditions). As Figure 7 also shows that, many areas within the M-30 have high (white/green)  $v_i^m$  values for car mode, signaling that the car, but the results for LEZ Centro give reasonable grounds to speculate that a spatial expansion of the LEZ Centro stands to include



**Fig 7.** Spatial availability Distribution of job opportunities spatially available jobs per mode using capita by mode of transportatin ( $V_i^m$  per origin in Madrid). Calculated using Grey TAZs have no population that use the home-to-work origin destination flows from mode. Ranges of values in the 2018 travel survey legend are quintiles.

all areas within the M-30 would likely increase the spatial availability of jobs for non-car mode using populationstransit users, cyclists and pedestrians.

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## Discussion and conclusions

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Location-based accessibility measures like the Accessibility measures are an important tool in transportation research [9] and are increasingly seen as valuable for planning purposes [4–8]. They boast a long history of development, beginning with Hansen-type  $S_i^m$ , Shen-type measures, with other developments like Shen's  $a_i^m$ , and spatial availability to account for competition/congestion. The more recent spatial availability measure  $V_i^m$  measures share a commonality; they are a has in common with these accessibility indicators that it is a weighted sum of opportunities assigned to each spatial unit  $i$ –the opportunities in a region –from the perspective of a determined origin  $i$ . Aggregations of opportunities embody principles of gravitational/spatial interaction modelling that date back to at least H.C. Carey [49], and are part of a line of research that includes the work of Ravenstein [50], Reilly [51], Stewart [52–54], Zipf [55,56], Wilson [37], and many others. In this way, they all  $S_i^m$ ,  $a_i^m$ , and yes,  $V_i^m$  can be interpreted as a score of how many opportunities can be potentially interacted with by the population at  $i$ . How the weight and sum of the potentially interacted with opportunitiesis considered is what defines the type of accessibility measure. scores of the potential for interaction with opportunities in space.

Within this paper, the location-based singly-constrained and competitive accessibility measure, known as spatial availability  $V_i$ . Different accessibility indicators are characterized by how they weight and aggregate opportunities. Spatial availability's contribution to the literature is to incorporate a proportional allocation mechanism that essentially constrains the sums to match the number of opportunities in the region; in this way it is a singly-constrained accessibility measure that naturally accommodates congestion and competition. The effort with spatial availability is in

line with previous research on proportional allocation by Paez et al. [14], is extended.  
As initially introduced by Soukhov et al. [15], spatial availability was designed for a  
homogeneous population traveling by a single mode of transportation. In this paper,  
we extended spatial availability for the case of capturing multimodal accessibility to  
opportunities  $V_i^m$ . A synthetic example and then an empirical case of LEZ in Madrid  
are detailed to demonstrate this multimodal extension. heterogeneous populations.  
We discussed this in terms of multiple modes of transportation, but the framework can  
accommodate equally well variations in travel behavior by population segments.

The spatial availability measure is capable of capturing a new interpretation of  
multimodal competition that previous accessibility measures have not yet done.  
Competitive measures hypothesis that populations using modes with lower travel  
impedance, when competing for a finite set of opportunities, will capture more  
opportunities. With spatial availability, the An empirical example using data from  
Madrid helped to illustrate the potential of multimodal spatial availability analysis,  
including its ability to account for competition for opportunities within and between  
modes. Particularly relevant is the fact that spatial availability scores relate directly  
to the total number of opportunities that are captured (of the total opportunities in  
the region) by each mode can be individually calculated. From there, the difference  
between how many spatially available opportunities one mode captures versus another  
can be investigated. This is the advantage of the spatial availability measure,  
particularly its multimodal extension.

The flexibility and need for an accessibility measure such as spatial availability is  
pertinent in policy scenario evaluation. As showcased in the empirical example of the  
LEZ in Madrid, competition for job opportunity availability varies spatially as well as  
between modes. The car and transit modes have the highest spatial availability, with  
the car-mode having highest availability with exception to the areas within the LEZ  
Centro. Since car travel has been highly restricted within the LEZ Centro, fewer  
car-using people potentially interact with jobs within the LEZ Centro, leaving more  
*spatially available* jobs for non-car-using populations. This makes it possible to  
compare the results to intuitive benchmarks, such as opportunities per population, in  
ways that other accessibility measures cannot or tend to obfuscate. This comparability  
is preserved between regions and over time. The example suggests that once that  
opportunities are treated as being finite, restrictions to travel by car leave more  
spatially available opportunities for non-car-users. This difference in car-using  
populations in locations accessing jobs for car travel in locations within and  
immediately outside around the LEZ Centro increases the competitiveness of seems to  
increase the number of opportunities spatially available to transit users (transit being  
the transit-using population (the second most competitive mode), as well as the spatial  
availability from the perspective of non-motorized modes. In effect, a policy such as  
Low Emission Zones help to improve the accessibility situation of active travel and  
transit in the parts of the city where it is implemented.

Spatial availability  $V_i^m$  can also be divided by the mode using population at each  $i$   
to yield mode-population normalized values. These values, reflected in Figure 7, can  
be used as a benchmark to investigate existing conditions and plan future LEZ  
implementation (i.e., target areas with exceptionally high car spatial availability such  
that more opportunities are available to other mode users). The purpose of the  
empirical example is to illustrate the kind of insights that can be derived from the  
application of multimodal spatial availability. But there are some intriguing  
opportunities for future research. Accessibility indicators are not designed to work as  
modal split models, and yet, in the case of policies that alter the relative cost of various  
forms of transportation, one can reasonably expect to see some shifts between modes.  
In our empirical example we used data collected after the introduction of LEZ Centro.

However, given a modal split model to project modal shares, accessibility indicators, including spatial availability, can be used to investigate changes to the accessibility landscape. Ditto for destination choice. Our empirical example presented but a snapshot of this, and in future research it will be interesting to investigate changes between policy interventions. The expansion of Madrid's LEZ to the ring contained by the M-30 orbital presents an excellent opportunity to do so. Given the intuitive and straightforward interpretation of spatial availability scores as fractions of opportunities from the total, relative and absolute changes in the accessibility landscape can be assessed, thus helping to evaluate the implications of policy interventions.

In summary, conventional *non-constrained* accessibility measures are difficult for planners to operationalize for a variety of reasons including issues of computation and interpretability. Finally, our example dealt with differences in travel by mode only, but it is possible to think of the intersection between mode of travel and different types of travelers. This would expand the number of sub-populations in the analysis from, say,  $m = M$  (modes) to  $m = M \cdot Q$  (modes times population segments), each with their own characteristic impedance function. Evaluations of this kind will be especially relevant as LEZ are implemented in cities globally, and the question of their impact on disadvantaged populations who have become mobility-restricted increasingly come to the fore [240, 57, 58]. With spatial availability, the magnitude of opportunities that are available as a proportion of all the opportunities in the region is equal to  $V_i$ . As a result of its proportional allocation mechanism,  $V_i$  can be naturally extended into multimodal applications. This flexibility is helpful to modelling policy scenarios in our cities that are increasingly multimodal. The interpretation of  $V_i$  allows for manipulation of  $V_i^m$  values to investigate differences of availability between neighbourhoods, modes, and regions, generate per capita benchmarks, and/or generate average values per population group.

From a spatial equity perspective, spatial availability measure can provide researchers, policy makers, and citizens a new-found interpretation of accessibility measures. With a plot of spatial availability values, one can begin asking, how much is enough and what level may be too much. These interpretations were difficult to be made with accessibility measures in the past.

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All work is fully-reproducible and available within this GitHub repository.

## Author contributions

The authors confirm contribution to the paper as follows: study conception and design: AS, JTO, JSL, AP.; data collection: AS, JTO, JSL.; analysis and interpretation of results: AS, JTO, JSL, AP.; draft manuscript preparation: AS, JSL, AP. All authors reviewed the results and approved the final version of the manuscript.

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# PLoS ONE submission: Response to reviewers

2023-11-09

Thank you for the time and care taken by the editorial team and reviewers in providing feedback to this manuscript. No doubt, the revised version submitted is more articulate than the first. Our responses to all comments from each reviewer are shown below in blue.

## Reviewer #1:

The article extends the concept of spatial accessibility and applies it to a fairness analysis of different modes of transportation. The article uses travel data from a week in Madrid as an example to analyse spatial accessibility in the city. However, the article has the following issues:

We appreciate your effort reading our submission and respond in detail to your comments below.

1. Lack of Innovation: The article's improvement on spatial accessibility mainly involves incorporating the ratio of travel frequencies as weight in travel costs. This improvement is relatively minor and the method used does not demonstrate superiority over traditional accessibility approaches.

Thank you for this comment. We would like to bring to your attention the editorial philosophy of PLoS ONE, according to which editors "make decisions on submissions based on scientific rigor, regardless of novelty," (see <https://journals.plos.org/plosone/s/editorial-and-peer-review-process>). Nonetheless we wish to respond to this comment.

In this paper we extend our earlier work on spatial availability (<https://doi.org/10.1371/journal.pone.0278468>) for the simultaneous analysis of multiple modes of transportation. You appear to be under the misapprehension that the main difference with accessibility measures is to incorporate "the ratio of travel frequencies as weight in travel costs". This statement is not correct. The main difference is the proportional allocation mechanism that we introduced for spatial availability, and that is extended in this paper to allocate opportunities based on the proportion of travelers by different modes. This is not the same as "weighting the travel cost". In fact, each mode is modelled using its own impedance function, as shown in our empirical example, where we use origin-destination data by mode to estimate travel impedance functions specific to each mode.

While this enhancement may appear minor in your opinion, it is not plainly obvious how spatial availability applies to multiple modes, which is why we believe this paper is needed. We do not dispute that this is an incremental step in the development of a more general method, but it is a step that considerably expands the range of potential applications. Further, we contend that the method has been rigorously developed and demonstrated this using an open, transparent, and reproducible example.

In response to this comment we have edited the paper to more clearly describe the advantages that multimodal spatial availability offers when considering the accessibility to opportunities by different modes. In particular, proportional allocation of opportunities using mode-specific impedance functions means that the travel-cost-advantage of each mode can be analysed. Further, this mechanism ensures that the sum of all spatial availability values for all modes sum up to the total number of opportunities in the region, which is not true for any other type of accessibility measure.

With respect to the "superiority" of the method, a reader of our earlier paper would already be aware of what limitations of accessibility analysis spatial availability aims to address. In this paper we also try to demonstrate throughout the manuscript what our measure does that others can't. Since spatial availability values result from proportional allocation, each value is a proportion of the total number of opportunities. Put another way, we can compare the proportion of opportunities available to users of each mode, to users at

each zone, to users of each mode by zone, and so on, and the values relate directly to the total opportunities in the region. This also allows us to calculate values per capita that serve as benchmark values, as shown in the empirical example.

2. Insufficient Experimental Data: The article uses questionnaire data from a week in Madrid, but lacks basic descriptions of the questionnaire data. Additionally, the daily travel data of approximately 30,000 trips is significantly limited, and there is no description of the criteria for selecting the dates. The typicality of the experimental data is questionable.

Thank you for this comment. To clarify, the empirical data used is not experimental. It is observational, since it is collected using a travel survey conducted by the City of Madrid. Travel surveys are a standard instrument in transportation planning and research, and are conducted in cities around the world. The data we work with represent the most recent and most complete travel survey conducted for the region to date. We are not completely sure where you got the figure of "30,000 trips" (which you consider significantly limited); presumably you are citing the maximum 'opportunity' or 'population' numbers in Figures 2 or 3. The most job-rich TAZs have 30,000 jobs while the least have 1,000 or fewer (Figure 2). In fact, there are 847,574 jobs in the city, which is also the sum of the total spatial availability in our analysis, as well as the number of potential trips to work.

With respect to The "typicality" of the data, travel surveys are designed to provide information about personal travel on a typical day, usually during a period of maximum demand (i.e., not during the summer vacation). This is standard practice for these surveys, and the one for Madrid is no different in this respect.

3. Lack of Data-Driven Analysis: In the analysis section, a large amount of data is used to analyse people's travel behavior in different areas. The analysis of spatial accessibility only considers the differences in the modes of travel mentioned earlier. The analysis results are somewhat one-sided, and examining the indicator from multiple perspectives would provide a more objective view. It is recommended to expand the dimensions of the analysis.

Thank you for this comment. It is somewhat puzzling that "30,000 trips" would be significantly limited (as per your comment #2), and at the same time be "a large amount of data". We find that this comment in particular is not actionable due to its vagueness. There are no meaningful responses to "somewhat one-sided" when "somewhat" and "one-sided" do not quantify or refer to a particular side. We studied the modes available in the region, and examined the results from the perspective of each mode. What other perspectives do you suggest? What dimensions should be explored?

Despite this comment being nonactionable, we believe that with the additional detail added to the manuscript to address your and other reviewers' comments, that overall clarity has been improved.

4. Disorganized Format: The article's methodology section contains numerous formulas and variables, but the definitions of these variables are unclear and difficult to read. There are also numerous formatting errors, and Table 1 is disorganized and unappealing. It is recommended to revise these issues.

Reviewer #2 identified some specific formatting issues and we fixed them. Otherwise we proofread the paper and hopefully did not leave a typo behind. We also made sure Table 1 starts on a new page, when it runs across pages the formatting resulted in some disorganization.

Thank you again for your efforts trying to review our submission.

## Reviewer #2:

This paper has sound mathematical foundations and allows to answer its research question in an elegant way (how to measure competition for e.g. jobs based on spatial accessibility?). I also really appreciated the fact that the paper was very didactic. Still, I have concerns about the relevance of the paper for future research.

Thank you for your thoughtful review of our paper. Your comments were very helpful to improve the clarity of the research.

More specifically, the new measure proposed by the authors has clear limitations: i) it focuses on the competition for jobs and is not useful for studying access to non-competitive or semi-competitive resources such as amenities.

Thank you for this comment. We would begin by noting that there are many types of opportunities that are mutually exclusive due to competition. For this paper we focused on jobs, but there are many others, such as beds at hospitals, seats at schools, and so on. Thus, even if the measure was applicable only to exclusive opportunities, there are numerous applications to choose from.

That said, we have grappled for some time with the question of what types of opportunities are best analysed using spatial availability. Our current thinking on this matter, after much consideration, is that in practice every type of opportunity, even when not clearly exclusive, is subject at least to congestion or capacity constraint. For instance, green spaces are often considered non-competitive, however, standards for the provision of such amenities are provided in the form of units of amenity per capita. For example, a case could be the Ile-de-France region, a jurisdiction that suggested in a major planning document of 2013 that at the municipal level at least  $10m^2$  of public green space should be supplied per inhabitant (Liotta et al. 2020). But green spaces are not evenly distributed, which means that who has access to them hinges on where they are and how easy is to reach them. Formulating the provision of amenities in these terms is not rare. For example, Natural England recommends an Accessible Natural Greenspace Standard such that the minimum supply of space is one ha of statutory Local Nature Reserves per thousand population<sup>1</sup>. Similarly, the World Health Organization (cited in OECD, 2013) recommends that cities provide a minimum of  $9 m^2$  of green area per inhabitant<sup>2</sup>. For our purposes, standards of this type translate into "how much of this resource is available to one individual that has not been claimed by anyone else?". Green spaces often have large capacities, but they still have a capacity, and it is not the same for a person to have access to  $5m^2$  of *uncongested* green space than to  $15m^2$ . This difference is in fact a matter of justice (Lara-Valencia and García-Pérez 2015; Liotta et al. 2020). Constraining accessibility is in this way a useful way to evaluate the congested availability of any type of opportunity. As standards are emphasized in the planning literature, in particular for fairness in transportation (see Martens and Golub 2021), spatial availability analysis can be used to assess standards. We are convinced that as other researchers discover this new approach to measuring accessibility many other applications will be found.

- ii) it doesn't allow to study absolute gains or losses in accessibility from public transportation infrastructure improvements or changes.

Great point. Spatial availability can certainly be used to capture absolute gains and losses. In fact, logically, the gains and losses produced by using a competitive and constrained measure allows for a clear interpretation. This would require the analyst to estimate the accessibility before and after some change to the land use or transportation system. In this paper our empirical application is a single scenario to serve as proof of concept, but in future research we intend to use spatial availability to analyse changes in the size of Madrid's Low Emissions Zone implementation from a modal and socio-economic equity perspective.

- iii) the authors do not allow for modal shifts: they assume that the transport mode choice of households is fixed and cannot evolve due to e.g. transport infrastructure changes.

This is an excellent point. Accessibility measures, including spatial availability, are not meant to function as modal split models, but they are certainly amenable to analysis of changes in the accessibility landscape

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<sup>1</sup>see <https://redfrogforum.org/wp-content/uploads/2019/11/67-Nature-Nearby%20%99-Accessible-Natural-Greenspace-Guidance.pdf>

<sup>2</sup>see <https://doi.org/10.1787/9789264191808-en>

if different modal shares are used as inputs. This is similar to the case of destination choice: accessibility measures do not model this, but changes in destination choices can be incorporated via how they affect the impedance function. In terms of how this could be implemented, the process can be sketched as follows: the results of a modal split model are used to estimate new modal shares, which in turn are used to recalculate spatial availability. The new values then can be compared to the baseline scenario. In other words, the framework for spatial availability is sufficiently flexible to take in not only mode-specific travel impedance functions, but also the proportions of the populations using each mode.

These points limit the relevance of the new accessibility measure. The authors should, at least, specify these limitations early in the paper. The introduction should start by stating the precise research question the new accessibility measure is seeking to answer as well as its limitations). They should also justify, based on the literature, that competition for jobs is a key determinant of job market outcomes, and that there is strong inertia in mode choices.

Your comments have been very helpful to improve the clarity of the paper, as well as the scope of what we do, as well as directions for future research. For example, we now note in the "Discussion and conclusions" that "our example dealt with differences in travel by mode only, but it is possible to think of the intersection between mode of travel and different types of travelers. This would expand the number of sub-populations in the analysis from, say,  $m = M$  (modes) to  $m = M \cdot Q$  (modes times population segments), each with their own characteristic impedance function. Evaluations of this kind will be especially relevant as LEZ are implemented in cities globally, and the question of their impact on disadvantaged populations who have become mobility-restricted increasingly come to the fore (De Vrij and Vanoutrive 2022; Verbeek and Hincks 2022; Liotta 2023)."

Finally, the writing of the paper, and particularly of the abstract and introduction, should be improved. The abstract could state the broader relevance of the topic and summarize the results of the case study on LEZs. The introduction should start more directly by introducing the research question and its relevance and describing the new measure and its limitations.

We have now done this. In the original version of the abstract and introduction we gave the misleading impression that we would analyse changes in the system, when in reality our intent was to demonstrate the application of the measure in an empirical example. We do plan to study changes in the system, but this requires more work than can be presented in a single paper, partly for the reasons that you identified above (modal shifts and the calculation of spatial availability for two different scenarios, as well as the analysis of the differences between them). We plan to do this in a future paper focused on the policy instead of the presentation of a new method.

Thank you again for your thoughtful comments and suggestions to improve the paper.

Minor comments:

- i) what are the summary statistics p10 (car: 36 min, transit: 55 min,...)? I assume they correspond to the mean.

Updated! Apologies, car: '36 min' corresponds to a mean of 36 minutes and then within the brackets additional descriptive statistics (minimum value, maximum value, etc.).

- ii) I also have identified a few formatting issues (e.g. Fcij p10 and 4.72km<sup>2</sup> p 8).

Fixed! Thank you.

### **Reviewer #3:**

This manuscript extended the authors' previous work spatial availability measure, which is a type of location-based accessibility measure that is both constrained and competitive compared to Hansen-type measure and Shen-type accessibility measure, into a multimodal framework. The new measure, multimodal spatial availability, strengthened the constrained (or finite) nature of opportunities, and the competitive nature among multimodal accessibility resulting from this constraint through a synthetic example and an empirical example of the LEZ in the city of Madrid. In conclusion, the authors demonstrated one restriction had impacted the spatial availability of opportunities for other modes using and proposed potential future uses in policy planning scenarios.

In general, the manuscript was logical and well-structured. The research problem was well defined. The data were available and quite supported the conclusion. The statistical analysis performed appropriately.

However, there are some issues:

Major issues:

Please demonstrate whether "car/motor & transit" and "bike & walk" are comparable or whether they are in an actual competitive relationship? For example, if I work 3km from where I live, maybe I will never choose to take a transit, I will always walk or ride. But if I work 20km from where I live, walking or riding to work seems impossible for me, I have to drive or take public transportation. Car/motor and transit can be in competitive relationship and people can choose which one they prefer, but not choose between motor and walk. This issue will also have an impact on the results of the research.

This is an excellent comment. The short answer is that whenever a destination can be reached by more than one mode, users of those modes are in competition for the opportunities there.

In this revision we tried to improve the discussion to make this point more clear. The impedance functions for all four modes are not the same. They describe the travel behaviour of commuters as informed by the 2018 travel survey. To follow your example, someone who cannot walk to work because their job is 20 km from where they live, will not compete for that job against people from their same origin who do walk. However, if the place where their work is can be reached by anyone who can walk from other origins (say, someone who lives closer to that destination), they would be in competition for the same opportunity.

Furthermore, average travel times for car/motor and transit are longer than bike and walk. All people don't have access to all options - completely true. But the travel impedances reflect this real travel at an aggregate based on all the trips for a mode. And on average, it is assumed that people at each origin that take a mode to a destination are in direct competition for opportunities (as opportunities are finite) – and a part of the competition is defined by the mode-specific impedance function (the second part is the population balancing factor). This assumption, that all populations, no matter their mode, are competing for the same finite set of opportunity, is part of spatial availability. We've made an effort to make this more clear in the text.

Minor issues:

1. As for Fig 2 and Fig 3, please indicate the meaning of the gray color blocks in illustration.
2. Please change the color scheme of fig 2. The red color scheme makes the LEZ centro area boundary, which is also in red, not visible.

We have updated the captions of the figures to reflect the meaning of grey colour blocks and the colour scheme of all Figures. We've also updated the labels on the legends to make them more interpretable.

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