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AN ENERGY-BASED PEDESTRIAN ACCESSIBILITY INDICATOR

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Abstract *This article presents an approach to pedestrian accessibility based on human effort rather than distance. By measuring effort as the muscular energy required to traverse network arcs with slopes, it is possible to derive an accessibility indicator that takes relief into account. A case study in the city of Coimbra, Portugal, shows that while relief does have a considerable impact on the accessibility thus measured, that impact is global and not local. When accessibility to all types of opportunities are considered, the influence of relief ultimately dilutes due to the geographical scattering of those opportunities.*

1. INTRODUCTION

Walking is the most basic transport mode, used by practically everybody, every day. It connects key city locations among them and provides the basic link to all other modes of transport. There has been, in the last decades, an increasing interest in active travel modes, like walking or cycling, prompted by sustainability worries, traffic congestion and health issues [1]. Indeed, in recent studies dedicated to the evaluation of the performance of European cities, the percentage of journeys to work not done by car was considered a quality of life indicator [2]. The walk mode is favored for small trips, of up to 1 km [3] [4], a distance which is expected to increase if proper infrastructural facilities are provided [5]. It increases physical activity, is non-polluting and socially inclusive, and poses little danger to others. Because walking is also the most basic travel mode, it will always have a considerable share among all transport modes, for people of all ages and social status. It is therefore natural and desirable that municipal decision makers have tools to evaluate how their city stands when it comes to walking accessibility.

The literature is rich in pedestrian accessibility studies, but very few take relief into account. It to fill this gap in the literature, and in a context of rising importance of the walk mode, that the present study is presented, as a prototype of a methodology to help municipal authorities evaluating pedestrian accessibility of their hilly cities. This research was carried out in the context of a case study in the hilly city of Coimbra, Portugal, and used Geographical Information Systems as main calculation tool.

2. METHODOLOGY AND CASE STUDY

There are many ways to define the concept of accessibility in the literature. This study takes the approach of [6], which considers accessibility as a disutility (lower = better). The definition used throughout this study is

$$A(i) = \sum_{j=1}^{N} w_j I_{ij}^{(1)} \qquad (1)$$

where $A(i)$ is the accessibility of geographic location i (trip origin), N is the number of types of opportunities (trip destinations), w_j is a weight assigned to opportunities of type j, and $I_{ij}^{(1)}$ the impedance from location i to the closest opportunity of type j. The formula reads as follows: when people at location i walk to interaction opportunities of a certain type, j (bakery, restaurant, school, etc.), they will look for the closest one (hence the superscript '1'), as walking is time-consuming and can be fatiguing in hilly cities. Weights are assigned to reflect how often a certain opportunity type is sought-after, with higher weights meaning higher frequency and hence higher importance.

To obtain $A(i)$ values it is thus necessary to define locations, indicate where opportunities are, and, more importantly, define the impedance function. In a flat city it is natural to use distance as impedance. In a hilly city, however, the slopes people have to walk through cause significant increases in energy use by the pedestrian. This is valid both uphill and downhill, as high downhill slopes require breaking, a muscular activity which in turn requires energy, albeit less than climbing. For this reason, impedance was taken instead to be human effort, measured in muscular energy to cross the arcs of the streets network. Taking human effort as impedance instead of distance constitutes the main novelty of this study.

2.1. GIS programming

The GIS setup and calculations were carried out in the ESRI *ArcGIS* environment, using data available from previous projects (streets network, public facilities). To define the locations i, a *fishnet* of 50 m × 50 m squares was defined, together with its centroids. Squares whose centroid laid more than 100 m away from a network arc were deleted. This step, which is optional, leads to removal of squares in faraway or deserted locations and prevents distortions due to excessive snapping from centroids to network arcs in the routing calculations of next section. Urban public facilities locations were arranged into sets of type j opportunities and the streets network was endowed with information concerning human effort to cross each of its arcs, in the From-To (FT) and To-From (TF) directions (impedance). To model the impedance, the experimental polynomial regression formula of [7] was used:

$$\frac{E(s)}{\mathrm{kg.m}} = 280{,}5\, s^5 - 58{,}7\, s^4 - 78{,}3\, s^3 + 51{,}9\, s^2 + 19{,}6\, s + 2{,}5 \tag{2}$$

where $E(s)/\mathrm{kg.m}$ is the energy (in J) per SI unit weight and length required to cross an arc of slope (incline) s. Note that the slope can be positive or negative, and the formula caters for that. Small downhill slopes lower the walking effort required, down to a minimum around –15% slope, and higher downhill slopes force the person to spend extra muscular energy for breaking.

To program of this formula in *ArcGIS*, use was made of altimetric information already available in the streets network shapefile for each individual arc, namely average uphill and downhill slopes (s_{up}, s_{down}) (both marked as positive quantities in the network associated table) and respective 3D length (l_{up}, l_{down}), in the FT direction. Using tool *field calculator*, human effort necessary to cross each arc, as defined by (2), was calculated for FT and TF directions via the formulas:

$$\begin{aligned} E_{FT} &= \left[E\left(s_{up}\right)l_{up} + E(-s_{down})l_{down}\right]\times 80\,\mathrm{kg} \\ E_{TF} &= \left[E\left(-s_{up}\right)l_{up} + E(s_{down})l_{down}\right]\times 80\,\mathrm{kg} \end{aligned} \tag{3}$$

The 80 kg factor (average weight of pedestrian) was inserted so that the formula returns energy units. This multiplication is not strictly necessary, as 80 kg is just an overall multiplicative factor affecting all arcs. The minus signs reflect the fact that what is uphill in the FT direction becomes downhill in the TF direction, and vice-versa.

Finally, arcs with uphill or downhill slopes higher than 50% were restricted. This allows pedestrians to use stairways, whose slopes are circa 45%, but no higher inclines, which may be too cumbersome to step through. This completed GIS programming.

2.2. Pedestrian accessibility indicator map

With the network programmed, it was possible to calculate the $A(i)$ accessibility indicator. For this purpose, the following methodology was used. The public facilities feature class was divided into the opportunities types shown in table 1 below, together with their respective weight.

Table 1. Opportunities types and weights.

Opportunity type	**Weight**	**Opportunity type**	**Weight**
Cultural associations	1	Shopping centers	2
Sports halls	1	Entertainment places	2
City Hall	1	Secondary school	2
Post offices	1	Pharmacies	2
Higher education faculties	1	Restaurants	2
Police squads	1	Grocery stores	3
Churches	1	Bakeries	3
Civil parish	1	1st cycle primary schools and kindergarten	3
Elderly care centers	1	2nd and 3rd cycle primary schools	3
Primary health care	2		

To obtain the individual $I_{ij}^{(1)}$ impedances, the *ArcGIS network analyst* tool *closest facility* was used to generate shortest routes from each centroid of square i to the set of opportunities of type j, with walking energy as impedance. The procedure was repeated for the N = 19 opportunities types, leading to 19 walking energy values stored in new fields of the feature class of 50 m × 50 m squares. Then, using *field calculator*, formula (1) was implemented in a new field of this feature class, leading to the final value $A(i)$ for each square. The result, visualized as a map in GIS, is shown in figure 1 below, together with the topography of Coimbra, for comparison. The same color scale was used to indicate min/max values for both altitude and accessibility. Since the accessibility index is expressed in weighted units, its absolute value is arbitrary and this is why the scale presented is merely qualitative.

2.3. Discussion

The maps evidence considerable discrepancies between altitude and pedestrian accessibility, which was to be expected because the pedestrian accessibility index $A(i)$ is affected by both distance to opportunities and city relief, not just the latter. The main observation concerning accessibility is that the city center evidences the best index values, reflecting the effect of centrality, with many nearby opportunities of each type. The hill-top of

Olivais (center-top right) in particular displays very good pedestrian accessibility despite its high altitude. This is however a very densely populated and well serviced area.

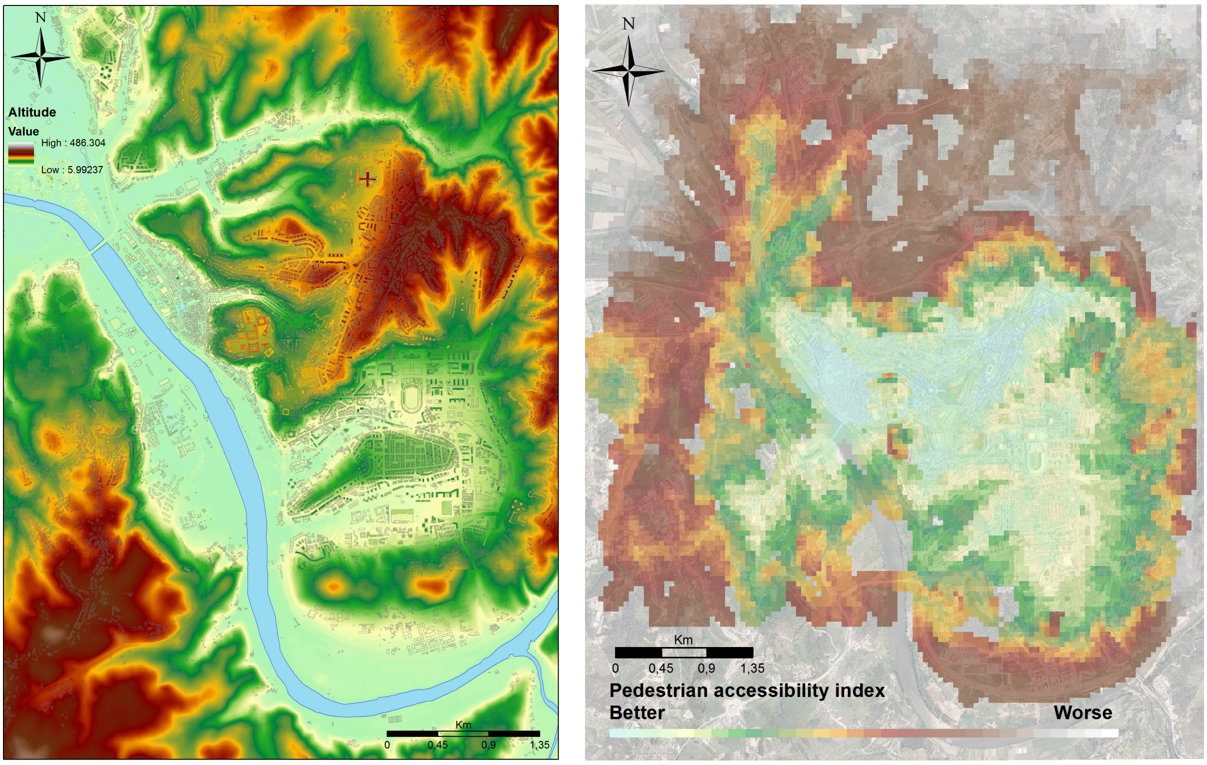

Figure 1. Topography of Coimbra (left) and effort-based walking accessibility map (right).

The geographical dispersion of the opportunities throughout the city also contributes to the good performance of the indicator: indeed, while some opportunities require climbing, others require descending. In the end, the index for central locations is not excessively penalized by relief effects. On the other end of the spectrum lie the faraway regions of the outskirts. These have worse indexes, but this is essentially related to lack of close opportunities rather than relief effects.

The relief effect is however not negligible: it is present as a background value throughout the study area and becomes more explicit for some higher locations within the central area. For instance, the University campus ‘Polo I’ zone (center of map, near the river) exhibits slightly lower accessibility, owing to being on the top of a hill. The same happens in a few other central locations, which would show better indexes if their altitude were lower.

3. CONCLUSIONS AND FUTURE WORK

The methodology proposed here shows that for the hilly city of Coimbra, Portugal, centrality, more than relief, is the chief factor determining a location’s pedestrian accessibility. This methodology, based on classic definitions of accessibility as disutility and using on human effort (as measured by muscular energy spent to walk the streets network) as impedance, is general and can be applied to any city. Since human effort rises considerably with slope, it especially adequate to hilly cities.

For hilly cities, effort/energy-based pedestrian accessibility maps are, in principle, more accurate than maps based purely on distance. Therefore, these maps should be preferred by municipal authorities when planning for changes to public transportation routes. For the case of Coimbra, busses from the outskirts into the (high accessibility) riverside downtown are frequent, but this is not the case for the Olivais area, whose high pedestrian accessibility indexes indicate it should perhaps be better serviced. Such maps also indicate the best zones to improve sidewalks and crossings, thus providing people with adequate infrastructure for exerting their choice for the pedestrian mode, which is key to foster that choice.

As future work, it would be interesting to apply the methodology to other hilly cities and compare altitude charts with the resulting pedestrian accessibility map, so as to check to what extent the conclusion that centrality dominates over relief effects holds. Another possible line of research would be to set all slopes to zero, recalculate the pedestrian accessibility index and create a ‘flat vs real’ differential map. This map would identify the geographic locations i for which relief is more relevant. The impedance function can also be refined by including sidewalk availability and pavement condition, both of which can influence effort. The effort/energy-based approach also allows for construction of other types of pedestrian accessibility indexes, such as e.g. number of opportunities within standard walking distances (say 600 m), converted into energy equivalent. Finally, since long trips can induce tiredness, to validate the accuracy of the hypothesis that human effort is cumulative, real experiments can be carried out, that involve volunteer pedestrians carrying out a smartphone and a wearable health device to log energy expenditure. (Doing this for short trips would only reproduce the results of [7].)

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