Transportation Network Spatial Analysis to Measure Pedestrian Suitability. The Case of Hilly Cities

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Abstract. The current climate and environmental emergency, together with the growing traffic congestion and pollution in urban areas, make mobility and its sustainability a priority in current transport policies. It is essential to change citizen’s behaviour in order to increase the use of less pollutant, economic and egalitarian transport modes, such as walking, combining it with other public transport modes. For this change to happen, it is necessary to provide feasible alternatives to private cars, namely through the offer of high-quality pedestrian infrastructures, adapted to the cities’ specific characteristics and their citizen’s needs. These aspects are particularly important in hilly cities, where traveling by foot requires an additional effort. The present study aims to contribute to the promotion of soft mobility in hilly cities by creating a support instrument to assess the potential of existing pedestrian infrastructures. Three variables are considered in the analysis: trip generation poles, population density and pedestrian network characteristics, with especial consideration of slopes. These variables were processed with spatial and network analysis tools available in Geographic Information Systems (GIS) and combined using a multi-criteria decision analysis to obtain a measure of the pedestrian infrastructure potential. The identification of areas with high pedestrian potential supports the definition of priority intervention programs on the public space and a better allocation of human and financial resources. The proposed instrument was validated through its application to a case study, the hilly city of Covilhã (Portugal). From the results obtained it is possible to conclude that the variable with more impact on the pedestrian infrastructure suitability value is the location of the trip generation poles, influenced by the footpaths’ longitudinal slopes. The instrument also allowed to identify the city’s main expansion areas, corresponding to places presenting a good pedestrian potential and relatively low values of population density.

1. Introduction

The concept of sustainable mobility is increasingly present in the European Union’s (EU) policies and strategies, claiming for itself a central role in the development of the so-called “Smart Cities”. This concept is based on the assumption that citizens have accessibility and mobility conditions that allow
them to travel quickly, economically, comfortably and safely. It also assumes that mobility takes place with energy efficiency and low environmental impacts. In order to achieve these objectives, it is necessary to implement measures but also to educate civil society for this new mobility culture.

The pedestrian soft mode fits perfectly in the sustainable mobility concept, since any journey includes a pedestrian component and trips on foot, in particular those of short distance, represent a significant part of all urban trips. Thus, it is imperative to plan, implement and manage the pedestrian network infrastructure to allow pedestrians to make these trips safely, with comfort and with acceptable travel time. Hence, there is a need to provide authorities with instruments to assess the suitability of the pedestrian infrastructure to support investment decisions and promote the pedestrian mode and, consequently, a sustainable mobility.

The presented work aims to develop a decision support instrument to assess the suitability of pedestrian infrastructures located on hilly cities, where traveling on foot usually requires additional effort. The instrument is based on the characteristics of the existing pedestrian network (road network and footways), with special emphasis on the road hierarchy and slopes (including footways); in the location and attractiveness of the main trip generating poles; and in the population density. These variables are aggregated in a multicriteria spatial analysis performed in a GIS environment to obtain a measure of the pedestrian network suitability. As a proof of concept the proposed approach was applied to a case study, namely, the pedestrian network located in the urban perimeter of the hilly city of Covilhã, in Portugal.

2. Urban mobility strategies in the European Union

European cities are connected by one of the best transport systems in the world. They concentrate around 70% of the population and generate more than 80% of the EU Gross Domestic Product (GDP). However, mobility within cities is increasingly difficult and inefficient, which concerns citizens since most believe that the traffic situation in their residence and/or work area should be improved. Urban mobility still depends a lot on the use of private car, most of which powered by fossil fuels, and the transition to more sustainable modes has been slow [1].

Due to the increase in traffic, major European cities are experiencing a phenomenon of chronic congestion, with several harmful consequences in terms of traffic delay and pollution [2]. According to the European Commission [1], this situation represents an estimated annual cost of 80 billion euros for the economy of many European cities. The choice of how to travel affects not only future urban development, but also the economic well-being of citizens and businesses, and is also essential for the success of the EU's global strategy to combat climate change [3–6].

In 2016, urban transport was responsible for 23% of EU's greenhouse gas emissions [5]. This evidence supports the need for cities to undertake a major effort to reverse the observed trend and contribute to achieve the objective of a 60% reduction in greenhouse gas emissions announced by the EU Commission in its White Book [7]. The EU legislation on air quality and increasingly demanding emission standards for road vehicles, seek to protect people from the harmful effects of exposure to air pollutants and particulate matter. However, most of the state members cities continue to have difficulties in complying with legal requirements [1].

In order to promote sustainable mobility, several European policies and strategies have emerged to provide state member with guidance instruments for the practice of a more sustainable mobility. Among the guiding documents available it is possible to highlight: the Green Paper [2], the Action Plan on Urban Mobility [3], the Europe 2020 Strategy [8], the White Paper [7], the European Strategy for Low-Emission Mobility [5], the Pact of Amsterdam [4] and the Graz Declaration [6]. Presently, a period of
implementation of these strategies and policies can be witnessed, justifying the development of technical and scientific tools essentials to support mobility interventions in urban areas.

Based on the EU’s policies and strategies, a set of guidelines and measures to promote sustainable mobility were also developed in Portugal. The following projects, plans and documents stand out: the Sustainable Mobility Project [9,10], the Mobility Package [11], the Bicycle and other Soft Modes Promotion Plan [12], the Strategic Transport and Infrastructure Plan 2014-2020 [13], the Green Growth Commitment [14] and the National Strategy for Active Pedestrian Mobility 2020-2030 (under development) [15].

In general, specific guidelines contemplating the orography factor, which is a key factor in hilly cities, are not considered in European and national urban mobility strategies and policies. This reinforces the importance of developing decision support tools that sustain its inclusion in strategies and policies for hilly cities. Some examples of studies that aim to understand and promote soft mobility in hillside cities can be found in the literature [16–19].

3. Methodology for assessing the pedestrian infrastructure suitability in hilly cities
The proposed methodology is based on the consideration of a set of variables that are spatially analysed and combined using a multicriteria approach applied in a GIS environment. To assess the suitability of the pedestrian network infrastructure, three methodological stages are considered. The data collection and organization and the variables selection are performed in the first stage. The second stage comprises spatial analyses carried out using the tools available in a GIS (initial spatial analysis, network analysis and multicriteria spatial analysis). Finally, the model calibration and outcomes analysis are done in the third stage.

Vector and alphanumeric data related to the pedestrian network (roads and footpaths), the municipality administrative limits (urban perimeter, parishes and statistical subsections territorial division), the location of the main trip generating poles, demography data and the digital terrain model (in raster format) are examples of the information collected, processed and organized in the database (first stage). The variables considered to measure the pedestrian network suitability in hilly cities are the location and attractiveness of the main trip generating poles, the population density and the road network characteristics, namely the road hierarchy and slope.

In the second stage, three analyses are performed using the GIS tools available in ArcGIS® (version 10.6). In the initial spatial analysis, thematic maps of the study area’s administrative divisions, location of the trip generating poles, population density distribution, road hierarchy, and footpaths’ and roads’ slope are prepared. For the network analysis, the ArcGIS® Network Analyst extension is used. In this analysis, the pedestrian network data is checked, the pedestrian speed and travel time are calculated based on the road segments’ and footpaths’ slope, the network dataset is built (connectivity, turning and elevation relationships are defined), and finally, the trip generating poles service areas (isochrones) are generated. A point scale method is applied to score the obtained isochrones [20]. In this analysis, isochrones ranges are defined based on trip times declared by a panel of transport experts and the population (surveys) as admissible for walking journeys in a hilly city. Finally, a multicriteria spatial analysis is performed using the ArcGIS® Spatial Analyst tools. Three criteria are considered in the analysis: location and attractiveness of the trip generating poles - Criterion 1 (factor), population density - Criterion 2 (factor) and the pedestrian network infrastructure - Criterion 3 (Boolean restriction). The information related to all criteria is converted to raster format and weights are assigned to the sub-criteria defined for criterion 1. These sub-criteria refer to the facilities’ categories (trip generating poles), such as transportation, health, educational, services, commercial, tourism, culture, recreation, sport and others. To assess its attractiveness, weights are assigned based on the results of a survey carried out with a panel of transport experts and hilly city citizens, asking how long they would be willing to walk, on a
daily basis, in a hilly city and their opinion about the number of people they usually see walking near the facilities. To deal with the overlapping of the isochrones obtained for the different categories of facilities, the weighted sum method (expression 1) is applied to obtain a single score for criterion 1. Then, the values of criteria 1 and 2 are normalized to a 0-100 scale (expression 2) and, through a weighted linear combination of the three criteria, the Pedestrian Infrastructure Suitability is determined (expression 3).

\[ TGP = \sum_{i} w_n x_i \]  

Where \( TGP \) is the trip generating poles criteria value (not normalized), \( w \) is each sub-criterion’s weight, \( x \) is the score assigned to the service areas and \( n \) is the number of sub-criteria.

\[ x_i = \frac{(R_i-R_{min})}{(R_{max}-R_{min})} \times 100 \]  

Where \( x_i \) is the normalized pixel value, \( R_i \) is the pixel value and \( R_{min} \) and \( R_{max} \) are the criterion minimum and maximum values.

\[ PS = (p_{TPG} \times TPG_n + p_{PD} \times PD_n) \times PNS \]  

Where \( PS \) is the pedestrian suitability of the network segments on a 0-100 scale (0 denotes segments without pedestrian suitability and 100 denotes segments with high pedestrian suitability), \( p_{TPG} \) is the weight to be assigned to the trip generating poles criterion, \( p_{PD} \) is the weight to be assigned to the population density criterion, \( TPG_n \) is the trip generating poles criterion normalized value, \( PD_n \) is the population density criterion normalized value and \( PNS \) is the pedestrian network segment value (0 for the road network not compatible with pedestrians usage or 1 for the road network compatible with pedestrians usage).

In the third and last stage of the methodology, the criteria weight calibration for the weighted linear combination is performed. The results are then represented in suitability maps where the network segments with different degrees of pedestrian suitability can be identified (very high \((80<PS\leq100)\), high \((60<PS\leq80)\), medium \((40<PS\leq60)\), low \((20<PS\leq40)\) and very low \((0<PS\leq20)\) pedestrian suitability).

The flowchart of operations and tools used in each stage of the methodology is detailed in figure 1.

### 4. Case study

#### 4.1. Study area and data collection

The municipality of Covilhã comprises 21 parishes spread over a territorial area with 555.60 km². The study area focuses on the municipality’s urban perimeter (parishes of Covilhã and Canhoso, Boidobra, Tortosendo, Cantar Galo and Vila do Carvalho, and Teixoso), where the population density is highest and the main facilities are located.

To apply the proposed methodology to the case study, first it was necessary to collect alphanumeric data related to the population and geographic data concerning the parishes and statistical subsections boundaries (vector), the road and footpath networks (vector), location of trip generating poles (vector) and the digital terrain model (raster). All data was processed with ArcMap® in PT-TM06/ETRS89 coordinate system.
4.2. Initial spatial analysis
Maps in figure 2 show the location of the trip generating poles (Variable 1), the spatial distribution of population density (Variable 2), the road hierarchy (includes the road network, stairs, elevators, funiculars, footpaths and pedestrian bridges and tunnels) (Variable 3) and the spatial distribution of the network segments' longitudinal slope.

4.3. Network analysis
After checking the pedestrian network (road and footpaths), the network analyst extension was used to calculate the trip generating poles service areas (isochronous). This analysis was performed for each considered facility category (see table 1). Based on a survey carried out with 275 inhabitants and 15 experts, it was decided to define, three service areas for each facility category representing three pedestrian travel time ranges: 0 to 10, 10 to 15, and 15 to 20 minutes (maximum travel time declared as admissible for a journey on foot). The corresponding travel distance was computed using the Tobler's
Hiking Function model [21] considering the road/path slope, pedestrian speeds at stairs [22, 23] and city elevators’ and funiculars’ (vertical and oblique connections) speed calculation. Figure 3 shows two examples of service areas (isochronous) maps obtained for the health and educational facility categories.

![Thematic maps](image)

**Figure 2.** Thematic maps: a) Trip generating poles, b) Population density, c) Road hierarchy and pedestrian paths and d) Pedestrian network slope.
4.4. Multicriteria analysis
The score assigned to the service areas for each travel time range, as well as the weights assigned to each facility category (defined according to the survey’s results), are shown in table 1. Expression (1) was used to combine the service areas’ scores with the facilities weights.

Table 1. Criterion 1: Service areas (isochrones) scores and sub-criteria weights (facility category)

| Travel time (min) | Score (0-100) | Facility category | Weight |
|------------------|---------------|-------------------|--------|
| 0 – 10           | 90            | Transportation    | 0.71   |
| 10 – 15          | 60            | Health            | 0.68   |
| 15 - 20          | 30            | Educational       | 0.75   |
| > 20             | 1             | Services          | 0.62   |
|                  |               | Commercial        | 0.63   |
|                  |               | Tourism           | 0.6    |
|                  |               | Culture           | 0.54   |
|                  |               | Recreation        | 0.65   |
|                  |               | Sport             | 0.58   |

The results obtained for criteria 1 and 2 were normalized through a reclassification of values on a scale from 0 to 100 (using expression 2). The value normalization aims to enable their combination in the multicriteria analysis (see figure 4).

Criterion 3, regarding the road hierarchy, is a constrain considered in the multicriteria analysis as a binary variable. For a given segment to be considered in the analysis, it must satisfy the logical condition: roads’ hierarchical class = NOT arterial. This means that only major collector, minor collector, access roads and footpaths (including elevators, funiculars, stairs, city garden and parks paths and pedestrian bridges and tunnels) are considered in the analysis.
After criteria 1 and 2 normalization and verification of criterion 3, all criteria were converted to raster maps and combined through expression (3) to obtain a measure that reflects the pedestrian suitability of the pedestrian network segments. Three weight combinations were tested in expression (3) for $TGP_n$ and $PD_n$: $p_{TGP} = p_{PD} = 0.5$, $p_{TGP} = 0.6$ and $p_{PD} = 0.4$ and $p_{TGP} = 0.7$ and $p_{PD} = 0.3$.

![Figure 4](image1.png)

**Figure 4.** Criteria 1 and 2 maps: a) Attractiveness of the trip generating poles (normalized) and b) Distribution of the population’s density (normalized).

### 4.5. Results

Table 2 presents the results for the three analysis carried out with different weight combinations.

| Suitability | Analysis 1 70% $TGP_n$ and 30% $PD_n$ | Analysis 2 60% $TGP_n$ and 40% $PD_n$ | Analysis 3 50% $TGP_n$ and 50% $PD_n$ |
|-------------|-------------------------------------|-------------------------------------|-------------------------------------|
|             | Pedestrian network length (km)      | Pedestrian network length (km)      | Pedestrian network length (km)      |
|             | Pedestrian network length (%)       | Pedestrian network length (%)       | Pedestrian network length (%)       |
| Very high   | 0.29                                | 0.18                                | 0.08                                |
| High        | 41.42                               | 10.62                               | 1.96                                |
| Medium      | 58.07                               | 76.29                               | 60.15                               |
| Low         | 60.95                               | 63.23                               | 78.77                               |
| Very low    | 289.17                              | 299.58                              | 308.94                              |
|             | 64.27                               | 66.59                               | 68.67                               |

Based on results, literature review and the opinion of the Covilhã City Council representatives, the combination of 70% for $TGP_n$ and 30% for $PD_n$ was chosen as representative, since the $TGP$ criterion has, in general, more influence on the trips made on foot (see figure 5). The results’ analysis for this combination showed that 22.18% of the network has a medium to very high pedestrian suitability and 64.27% has a very low potential. The lowest suitability values are found essentially in the pedestrian network located outside the trip generating poles service areas and in the city areas with low population density.
5. Conclusions

The increased use of the private car as the main transport mode contributed to the increase of greenhouse gas emissions, deteriorating the urban environment quality and expanding the current climate emergency. To help reverse this situation, it is necessary to promote a more sustainable urban mobility, restricting the free use of private car to the detriment of soft modes such as walking.

From the end of the first decade of the 2000s, the EU paid particular attention to sustainable mobility. The definition of various policies and strategies, as well as the emergence of air quality legislation establishing greenhouse gas emission limits, provided the state members with guidelines for the practice of a better urban mobility. Like other EU members, Portugal has already started to transpose these policies to the national scene. However, although soft modes are beginning to gain expression, the private car continues to be the most used transport mode in Portuguese cities.

In order to promote more sustainable mobility and increase the use of soft modes, it is necessary to provide transport infrastructures with adequate characteristics adapted to the citizens’ needs and cities’ specificities, especially in hilly cities where, due to orography, walking requires an additional effort. It is therefore essential to create instruments that assist urban space managers in the allocation of resources.
to improve the pedestrian infrastructure and encourage citizens to consider walking as their main transport mode for short daily trips. In this view, the present study aims to contribute to the promotion of soft mobility through the creation of an instrument that allows the assessment of the pedestrian suitability of the existing pedestrian infrastructure.

The proposed methodology was validated through its application to a case study, the hilly city of Covilhã. The multicriteria analysis was performed for 3 combinations of $TGP_n$ and $PDn$ weights, resulting in three network pedestrian suitability maps. The results allowed to obtain, for the considered combinations, the length of the network per pedestrian suitability level (very high, high, medium, low and very low). The city centre areas, where most of the population and trip generating poles are concentrated, have a pedestrian network suitability level between medium and very high, while the more peripheral areas of the city, with less effect of the $TGP$ criterion and less population density, have low or very low suitability. It was also possible to identify the expansion areas of the city. These areas currently have good pedestrian network suitability but still relatively low population densities.

As future work, it is suggested to complete the information on the pedestrian network, namely with data on the existence and width of sidewalks, the existence and location of pedestrian crossings, conditions for reduced mobility pedestrians and assessment of the pedestrian level of service. This information can then be added to the proposed pedestrian suitability analysis to help locate pedestrian networks needs.

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