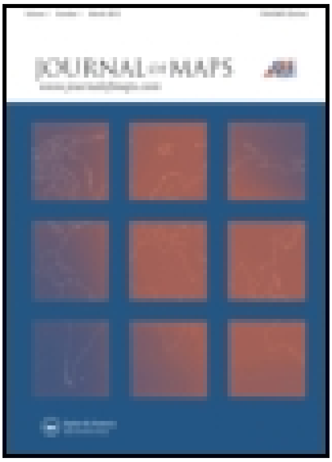

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High levels of mobility have given rise to land-use patterns that are difficult to navigate for non-motorised transport users. Fragmentation in a transport system can be considered as a lack of connectivity (or permeability), as infrastructures reduce the connectivity between places. Fragmentation has been extensively studied in landscape ecology, and can be understood as a loss of connectivity. Connectivity is defined as the degree of permissiveness offered by the landscape for the displacement of organisms, energy flows and dispersive movements. This article presents a map of urban fragmentation for pedestrians using a habitat fragmentation indicator. It represents difficulty for pedestrian mobility as a function the of the accumulative cost distance over a cost surface under the current motor traffic-oriented street/mobility layout. The map is developed for the Chamberí district in Madrid (Spain). The process consists of first developing the resistance matrix of the territory database. The resistance value is the time taken to travel through the streets. The street axis network is converted into pavements, as this is the part of the street used by pedestrians, including pedestrian crossings and traffic lights. The resistance value –travel time – is calculated, including waiting time. Once the resistance matrix has been created, GIS functions are used to calculate the least accumulative cost distance for each origin to a set of attractive locations/destinations for pedestrians.

Keywords: urban fragmentation; GIS; pedestrian mobility; travel time cost

1. Introduction

The analysis of urban fragmentation is a priority for urban designers and planners (Michelutti, 2010). Several disciplines such as sociology, economics, geography, urban planning and transport planning have addressed this phenomenon, but have failed to reach a consensus on the definition of the term. Different approaches can be taken to urban fragmentation; it can be viewed as a social, spatial, political, cultural or economic phenomenon (Deffner & Hoerning, 2011; Harrison, Huchzermeyer, & Mayekiso, 2003; Navez-Bouchanine, 2002; Van Kempen, 1994). Nevertheless, in every approach urban fragmentation is regarded as a threat to social cohesiveness.

This paper considers urban fragmentation from a spatial point of view. It can be defined as a spatial phenomenon resulting from the act of disjointing the pre-existing forms and structures of the city and city systems (Rotem-Mindali, 2012). In terms of the transport system, fragmentation can be seen as a lack of the connectivity (or permeability) enabled by the directness of links and

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the density of connections in a transport network (Victoria Transport Policy Institute, 2013). Urban fragmentation is associated with physical obstacles, and hinders choices and opportunities for social interaction.

Pedestrians are the most vulnerable groups to fragmentation in urban transport systems. High levels of mobility have created land-use patterns that are difficult to navigate for non-motorised transport users. This particularly affects pedestrians with restricted mobility (elderly people, children and people without access to a private car) (Di Giulio, Holderegger, & Tobias, 2009; Hine & Russel, 1996). This issue has recently attracted attention due to the negative environmental impacts of motorised traffic in cities and the ageing of the population, which implies an associated rise in the number of people who are no longer able to drive a car or who have limited mobility (European Commission, 2011). Walking and cycling are positively associated with the number of accessible destinations (Hoehner, Ramirez, Elliott, Handy, & Brownson 2005). The presence of well-maintained footpaths is associated with walking for recreation and for transport (Pikora, Giles-Corti, Bull, Jamrozik, & Donovan 2003).

Some authors consider urban fragmentation and connectivity as concepts inherited from landscape ecology (Rotem-Mindali, 2012). Dunning, Danielson, and Pulliam (1992) consider the landscape as an area composed of a matrix of habitat patches that sustain associated biological systems. The layout and nature of the landscape determines the conservation of its biodiversity (Lindermayer & Franklin, 2002). Habitat fragmentation can be understood as the landscape's loss of connectivity (Serrano, Sanz, Puig, & Pons, 2002); in this framework, connectivity is defined as the degree of permissiveness offered by the landscape for the displacement of organisms, energy flows and dispersive movements (Taylor, Fahrig, Henein, & Merriam, 1993; Tischendorf & Fahring, 2000). Habitat connectivity has often been measured using mapping and spatial indicators as functions of cost-weighted and effective distances, which account of the opposition posed by the landscape matrix to the movements of the organism (Adriaensen et al., 2003; Drielsma, Manion, & Ferrier, 2007; Marulli & Mallarach, 2005; Mancebo, Martín, Casermeiro, & Otero, 2010).

We analyse the issue of urban fragmentation using the methods mentioned above, but substituting the landscape matrix for the street surface and taking into account its opposition to pedestrian mobility from origin to destination, in an equivalent manner to natural habitats.

The aim of this article is to develop a map of urban fragmentation for pedestrians using habitat fragmentation measures, in order to represent the difficulty for pedestrian mobility as a function of the accumulative cost distance over a cost surface under the current motor-traffic-oriented street/mobility layout. The map is developed for the Chamberí district in Madrid (Spain).

2. Method

2.1. *Fragmentation calculation*

The fragmentation of the territory is analysed by studying its connectivity. To assess the connectivity, the selected function calculates the least accumulative cost distance for each origin to a set of destination cells over a cost surface. The calculation is a function of the effective distance, which is the minimum distance between two points, separated by a resistance matrix that models the difficulty encountered by organisms in moving through the territory.

The resulting cost distance grid shows how much it would cost each cell to reach a destination via the least-cost path. The accumulative values are based on the cost unit specified on the resistance matrix or cost surface, and can be translated as the cost to pedestrians in reaching their destinations. Simply put, higher cost equal greater difficulty in reaching the destination and greater the urban fragmentation.

The GIS function used is *costdistance* from ESRI ArcInfo Workstation. The calculation is done as follows (ESRI, 2001). The impedance is derived from the costs associated with the cells from the cost surface and the direction of movement through the cells. The cost of moving from a cell *1* to one of the four directly connected is the cost of cell *1* plus the cost of cell *2* divided by 2. Therefore the accumulative cost of moving from cell *i* to destination *n* is determined by the following formula (Equation (1)):

$$C_{i,j} = \sum_{i+1}^{j-1} \cos t\_\text{cell} + \frac{\cos t\_\text{cell}\, i + \cos t\_\text{cell}\, j}{2} \tag{1}$$

where: $C_{i,j}$ is the cost of moving from cell *i* to destination *j*. The larger the $C_{i,j}$ value, the greater the cost and fragmentation. *Cost_cell i* is the cost of cell *i*. *Cost_cell j* is the cost of cell *j*.

The diagonal movement is also considered. The cost of travelling over the cell is the square root of 2 times the cost of the cell, as this is the distance in the orthogonal link.

This least-cost distance is calculated from each cell to the destination that will be the least costly to reach. In our case, as we want to know the connectivity of each origin to a number of destinations, we need to select each destination and calculate Equation (1). We then apply Equation (1) as many times as destinations. As the number of destinations can be very high, the GIS process has been programmed in the Arc Macro Language (AML). Finally, the total cost value for an origin to the *n* destinations is (Equation (2)):

$$K_i = \sum_{1}^{n} C_{i,j} \tag{2}$$

where: K_i is the cost of moving from cell *i* to *n* destinations. The larger the K_i value, the greater the cost and fragmentation. $C_{i,j}$ is the cost of moving from cell *i* to destination *j*.

The information required to calculate the connectivity is a destination map; a GIS layer of the study area; and a resistance map representing the resistance of the territory to the movement of pedestrians. The necessary databases are compiled as described in the following sections.

The degree of fragmentation is also affected by the urban layout. To remove this effect in the calculations, two scenarios must be considered: the reference scenario, which assumes that pedestrians can move through the streets without any difficulty; and the evaluation scenario, which assumes that pedestrians can only walk on pavements, pedestrian crossings and at traffic lights. The calculation is repeated in each of the two scenarios, making it possible to measure the difference in connectivity between alternatives (*r* and s), K_i^{r-s}, as a percentage with regard to the initial situation (*r*) using Equation (3):

$$K_i^{r-s}\,(\%) = \frac{K_i^r - K_i^s}{K_i^r} \cdot 100 \tag{3}$$

where: K_i^{r-s} is the difference in connectivity of cell *i* to destination *n* between alternatives *r* and *s*. K_i^r is the cost of moving from cell *i* to *n* destinations in reference scenario *r*. K_i^s is the cost of moving from cell *i* to *n* destinations in evaluation scenario *s*.

2.2. *Developing the resistance matrix of the territory database*

Normally in a GIS, the city streets are represented by polylines in vector format. The process of creating the resistance matrix requires these polylines to be transformed into surface elements and include the cost of travelling through them.

2.2.1. *Creating the network*

The Chamberí district has a population of nearly 150,000 inhabitants and an area of 4.69 km^2 (31,043 inh./km^2). The district is primarily residential, and the percentage of people aged over 65 is 25 points higher than the average for Madrid (Banco de Datos Munimadrid, 2014). Chamberí also continues to have a largely traditional commercial offering with a range of public amenities. The district consists of six neighbourhoods, linked by large – wide and long – avenues, which act as barriers to pedestrians and attract motor-traffic-oriented mobility, which are among the reasons pedestrian mobility is so important in Chamberí.

The original database represents the streets in the Chamberí district of Madrid and corresponds to 2012 (Instituto de Estadística de la Comunidad de Madrid, 2013) (Figure 1). The network is formed by polylines, and each street is shown by a line representing the axis of the street (including the road and pavements).

The network must represent pavements – as they are the part of the street used by pedestrians –, and so the first phase consists of transforming the axis polylines into pavement polylines. This is done by classifying the streets into three types based on their width: 8, 16 and 24 metres. This information is included in the network database.

A copy of the database is made taking each of these three street types separately and displacing this copy by the corresponding 8, 16 and 24 metres (Figure 2).

As the calculations are made based on the difference between scenarios, two networks will be used. The reference scenario refers to the original network representing the street axis; and the evaluation scenario refers to the pavement network (see also Figure 2).

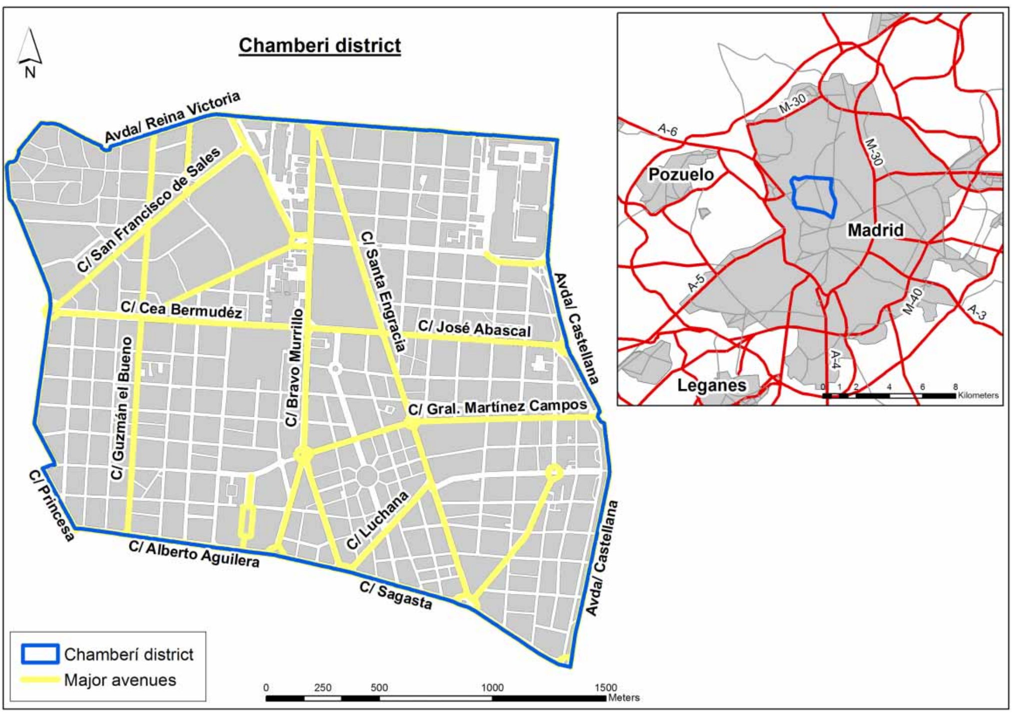

Figure 1. Location map.

Figure 2. Transformation of the axis polylines into sidewalks polylines.

2.2.2. *Correction of topological errors in the pavement networks*

The original street network is extremely precise; however the duplicate process described above introduces a large number of topological errors (Figure 3). There is a lack of continuity between sections of the same pavement, and two pavements sometimes fail to meet up. This leads to errors in computing the minimum paths when calculating travel time, as there are gaps in the network. The connectivity errors were identified using GIS topological tools and corrected manually, thereby substantially reducing the errors (Figure 3).

2.2.3. *Updating the networks*

This phase consists of updating the information in the travel time database. Each arc must include information on its length, travel speed and travel time. Walking speed has become a subject of research in the literature (Cera, Corazza, & Di Mascio, 2008; Gates, Noyce, Bill, & Van Ee, 2006; Knoblauch, Pietrucha, & Nitzburg, 2007; Laplante & Kaeser, 2004). In the network there are two arc types: normal arcs, and arcs representing crossings. In normal arcs the travel speed is calculated as 4 km/h –i.e. 1.1 m/s– and the corresponding travel time is also calculated. Walking speed has become the subject of research in the literature. This speed is consistent with the walking speed values found in the literature (Gates et al., 2006; Knoblauch et al., 1996; Laplante & Kaeser, 2004).

In crossing arcs the travel time comprises two partial times: the walking travel time; and the waiting time associated with the type of crossing. There are three different crossing types: those with no a pedestrian crossing or a traffic light; those with a pedestrian crossing; and those with a traffic light. The corresponding walking travel time is calculated for them all based on 1.1 m/s. If there is no a pedestrian crossing or a traffic light, the total travel time is the walking travel time alone; and if there is a pedestrian crossing or a traffic light, the waiting time is added to the walking travel time.

The waiting time was measured after visiting all the crossings in the study area, a total of 814. Once all the data were collected they were included in the pavement database and the total crossing arc travel time (walking travel time plus waiting time) was calculated.

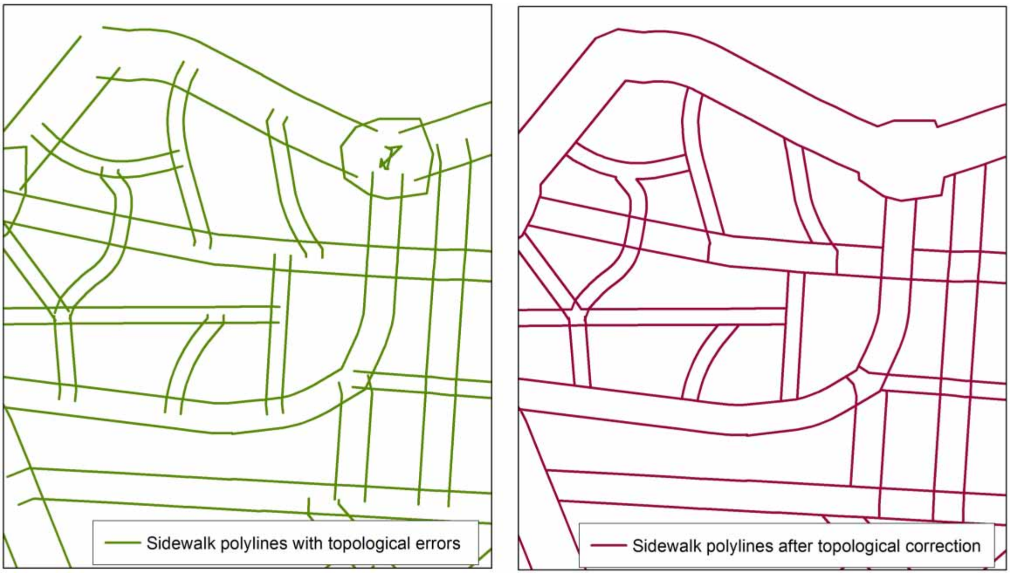

Figure 3. Correction of topological errors.

2.2.4. *Developing a territorial resistance matrix*

The territorial resistance matrix represents the cost for the displacement of the individuals. This cost is measured in time units. As this is quantitative information, it is usually represented in raster format. The polyline vector networks are then transformed into raster. This process also provides a better representation of the real layout of the streets for pedestrians as it takes account of the width of the pavement. The pixel size selected is 4 metres as it is a multiple of 8, 16 and 24 and adequately represents the width of the pavements in the area.

The process varies depending on the network considered. In the case of the axis street network, it is assumed that the pedestrians are allowed to walk everywhere; however in the case of the pavement network, the pedestrians can only walk on the pavements.

In the axis street network, the steps are as follows. The three polyline street types based on width (8, 16 and 24 metres) are considered independently. For each type, the polyline is converted into a polygon according to its width. The three polygons representing the streets are merged and converted into raster format. Each pixel will have a cost value of 3.6 s, the time needed to travel 4 metres – the pixel size – at a speed of 1.1 m/s. The space occupied by buildings is given a value of 9999 in order to discard them in the fragmentation calculation.

The case of the pavement network is more complex (see Figure 4). It must consider normal pavements, pedestrian crossings and traffic lights independently. The normal pavement polyline is converted into raster (4 m in size) and the time cost is calculated as above.

For the pedestrian crossings and traffic light polylines, the running speed is calculated in each arc according to the data – length and travel time (walking travel time plus waiting time) – calculated in section 2.2.3. In this case the pixel size is also 4 metres. In order to calculate the value of each pixel, the length – 4 metres – is divided by the arc running speed. The three polyline layers – normal pavements, pedestrian crossings and traffic lights – are then converted into raster, with each pixel representing the time taken to move through it. Finally, they are merged into one layer, each pixel with its corresponding type (normal, pedestrian crossings or traffic lights) and its corresponding crossing time. The space occupied by buildings is given a value of 9999.

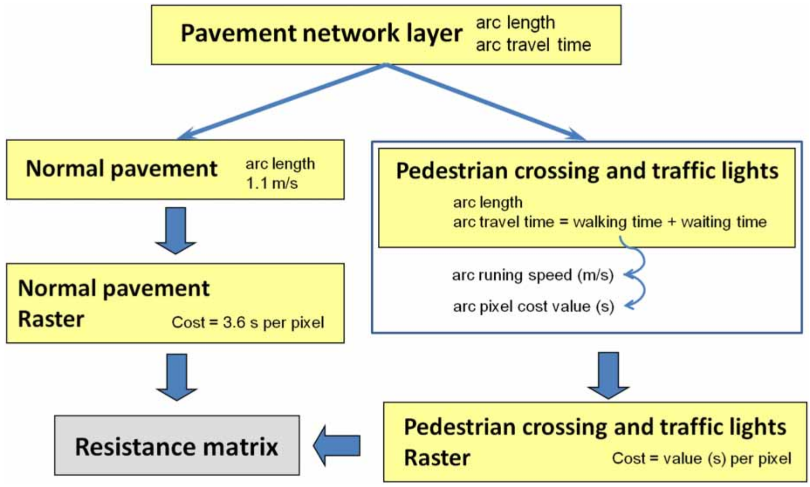

Figure 4. Resistance matrix creation process. Sidewalk network.

Figure 5 shows the two resistance matrices. On the right – in the resistance matrix that assumes that pedestrians can walk freely – all the pixels represent the same cost. On the left there are values only on pavements, and the pixels represent a different cost depending on whether they are streets, pedestrian crossings or traffic lights.

2.3. *Selection of origins and destinations*

Origins and destinations must be defined in order to evaluate the fragmentation. In ecology, the origins and destinations are natural areas with common characteristics. In our case, we can take any location in the study area. The origins consider the whole of the study area – i.e. all the pixels – so we have values every 4 metres.

The choice of destinations was decided according to their importance or attractiveness for pedestrians. Thus public education centres, health services, government offices, parks, cinemas, theatres and museums were considered as destinations. The locations layer from the Instituto de Estadística de la Comunidad de Madrid (2013) (Madrid Region Institute of Statistics) showing 132 public facilities was used for the destinations within the study area.

The facilities layer (destinations) does not exactly match the networks layout. In order to correct this problem, the facilities were displaced until they coincided with the nearest street axis or pavement respectively, using a snapping GIS tool. This displacement is only a few metres, to the nearest perpendicular point on the arc.

3. Resulting map representation of urban fragmentation

Based on the resistance matrix and destinations, the connectivity indicator (K_i) is calculated using Equation (2) in each scenario. To calculate Equation (2), Equation (1) must be calculated 132 times –the number of destinations. The AML script developed calculates Equation (1) 132 times, and Equation (2).

The urban fragmentation is obtained as the difference between scenarios using Equation (3). However the problem is that the pixels do not match, as the reference scenario represents the whole street and the evaluation scenario represents only pavements. This is resolved by creating

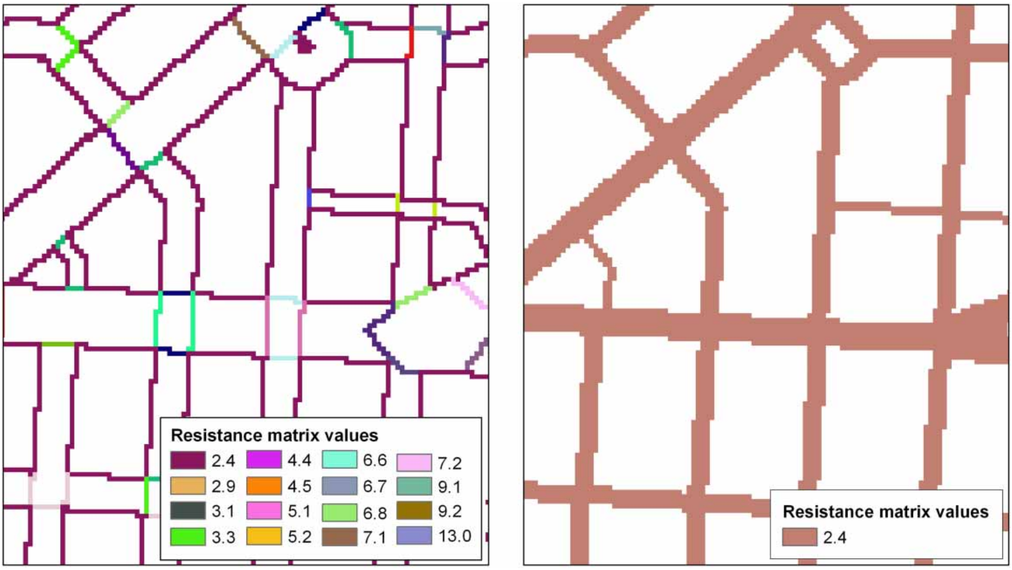

Figure 5. Resistance matrix.

a buffer with a width that includes the pixels of the two situations. Topological errors were amended by means of a manual edition process. This buffer represents each street, thereby obtaining a layer in vector format. For the graphic representation, the mean of the cost value of the pixels in each street is calculated, followed by Equation (3), to give the map of urban fragmentation.

4. Conclusions

The fragmentation map of Chamberí (Main Map) presented here shows the difficulty for pedestrian mobility as a function of the accumulative cost distance under the current motor-traffic-oriented mobility layout. The results show that the cost – measured as travel time – in the movement of pedestrians is 25% higher, because of the current motor-traffic-oriented street/mobility layout. This is because pedestrians cannot move freely through the streets and are forced to prolong their route by having to use pedestrian crossings and traffic lights.

Areas with higher fragmentation values are concentrated in the southeast and southwest (Almagro and Gaztambide neighbourhoods, respectively). These are neighbourhoods with high traffic levels. The origins located in these areas involve a high percentage of travel to destinations through these high-cost areas, and therefore have higher fragmentation values. The north – on the opposite side – although still subject to considerable fragmentation, has lower values. In these areas, there are fewer difficulties in the form of pedestrian crossings, traffic lights and waiting times, and the average values for travel time are reduced. If each neighbourhood is considered independently and the destinations are only those inside the neighbourhood, the results point to the same conclusion: the southwest is the most fragmented and northwest the least.

The presence of major avenues also influences the results. When one or more major avenues have to be crossed between destination and origin, the cost increases. There are few places to cross on these avenues and the waiting times are usually longer than in narrower streets.

The methodology has been validated by applying it to a specific case study, and proved to be a useful tool for measuring urban fragmentation in large areas with major avenues and high motor-traffic-oriented mobility. To replicate it only requires a model of the streets in a GIS database and the collection of time data at crossings. The size of the study area does not make the method any more complicated to apply; the only limitations are the resources for collecting the field data at the crossings.

As a final conclusion, both the results and the map highlight the impediment to pedestrian mobility, which can affect people's quality of life as well as representing a very high cost in time and money (when translated into monetary units). The map also identifies zones with high urban fragmentation. These are priority areas for improvements by mobility planners seeking to provide high-quality networks for pedestrians. This goal can be achieved by considering both motor traffic and pedestrians, and efficiently designing traffic light timings and allocating pedestrian crossings oriented to greater non-motorized mobility. The method can be used to improve the current functionality of the network, to study the impact of new urban developments on pedestrians, and as part of project appraisals and environmental impact assessments.

Software

ESRI ArcGIS 9.X and ESRI ArcInfo Workstation were used as the analysis platform for this project. ESRI ArcGIS 9.X was used to create the maps.

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