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March, 2012

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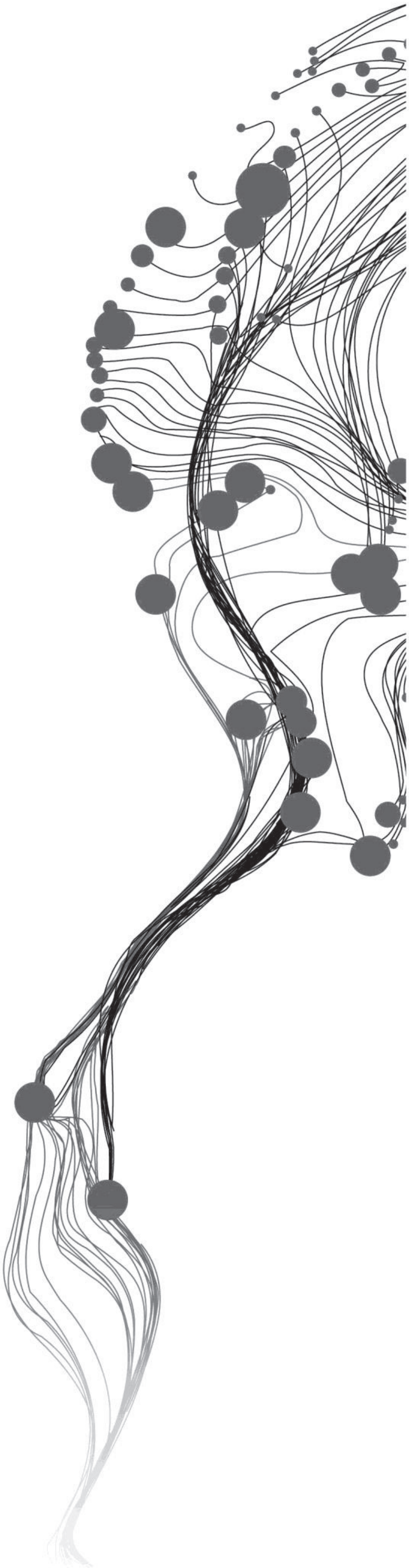

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ABSTRACT

Traffic congestion has become a major issue in recent years, particularly in fast growing cities in developing countries. The negative impacts on people and the environment due to this phenomenon are well known. Cycling represents a handy alternative to cope with this situation while offering many advantages (affordable, healthy, no polluting, etc.).

One of the more important aspects of promoting cycling is the infrastructure provision. However, traditional approaches for cycling networks design does not guarantees the selection of the optimal routes since a variety of technical, social and environmental factors are not considered. In addition, in many cities in developing countries it is not likely to found data on cycling (cyclists' behaviour, OD surveys) and could be existing cycling infrastructure that should be considered if a new design will be implemented.

In this context, the objective of this thesis is to develop a methodology for the evaluation of potential routes within an urban area aiming the optimization of a cycling network in a data scarce environment.

This approach includes a GIS based Spatial Multi-Criteria Evaluation process in which key bicycle trip attractors and their catchment areas along with other relevant spatial factors affecting the suitability for cycling are taken into account to identify the most adequate roads for cycling infrastructure provision.

The methodology was tested through a case study implementation in the Brazilian city of Belém. As a result, the optimal routes to the key attractors were calculated and, based on them and other relevant considerations a cycling network draft is proposed.

This methodology can be used as a decision support tool on upgrading or providing cycling infrastructure in different cities due to their flexibility and ease of implementation.

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1. INTRODUCTION

In the introductory chapter an outline of the research is set up by looking at their background and justification, identifying the research problem and the objectives and questions established to address it.

1.1. *The second chapter includes a review of the literature on different methodologies for bicycle network design that have made use GIS approaches and on the principles that define the basic quality standards of a cycling network. The third chapter continues with a detailed description of the methodology. In the fourth chapter an introduction to the case study can be found, describing the city of Belém and their current cycling activity. In the fifth chapter the methodology is tested through the case study implementation by following the proposed steps. In chapter 7 the results are shown in the way in which the research questions were answered along this thesis. Finally, in chapters 7, 8 and 9 are the discussion, conclusions and recommendations.* Background

Traffic congestion has become a major issue in recent years, particularly in fast growing cities in developing countries. Massive use of private cars, inefficient public transport systems and poor operation and maintenance of infrastructure are among the causes of this problem. The impacts on society are well known: human losses by traffic accidents, increasing air pollution, noise and stress affecting people's health and wellbeing, waste of time and productivity, etc.

The development of an adequate Multimodal Public Transport System integrating (and encouraging) non-motorized means represents a possible solution to lessen traffic congestion. Bicycle transportation, therefore, is an attractive alternative playing an important role in developing a multimodal transportation system, key on the quest for sustainable transport. (Rybarczyk & Wu, 2010)

Among the many advantages that make cycling so attractive, it can be mentioned that it expands the capacity of mobilization of the poorest and more vulnerable groups due to the reduced costs of purchasing and maintenance of bikes, providing basic mobility and, also, access to public transport systems, physical fitness and enjoyment. (Litman, 2010). In addition, cycling is noiseless, produces no emissions, requires a low infrastructure investment and, because bicycles take up less space, alleviates congestion and the need for parking space. Hence, cycling is ideal to be used as a regular urban transport mode and/or to be integrated into the public transport system and, consequently, it should be promoted and encouraged broadly.

One of the key points to achieve this task is to provide infrastructure. As has been well documented, there is a strong relationship between the presence of cycling facilities and the increase of the number of cyclists (Larsen & El-Geneidy, 2009). Nevertheless it is not just a matter of the existence of such services, but also their quality and the fact of being well-connected which will have an impact in the increase of bicycle use (Birk, 2006). In this context, the promoting of massive use of cycling as daily transport mean should be a priority for decision makers and therefore for planners, who, by optimizing the planning and design of the cycling infrastructure will contribute to reduce traffic congestion.

Despite the above mentioned obvious advantages, cycling is still a fragile and hazardous activity as users could suffer serious injuries after an accident. A well designed cycling facility can also help to minimize this drawback by taking into account, beforehand, safety concerns and other factors that have been identified as a basis to achieve high quality facilities.

1.2. Justification

Traditional bicycle network design models are either supply or demand based. The first relies on two theories: a) there should be biking facilities in all main arterials and collector streets, and b) a model calculating the road conditions for cycling, like the Level of Service, should be used prior to the planning (Rybarczyk & Wu, 2010).

The objective of demand models is to estimate the number of bicyclists that will use a road if a facility is present, usually analysing trip generators and attractors. Then, the location of cycling infrastructure that better satisfies the demand is defined.

However, none of these approaches by itself guarantees the selection of an optimal network since a variety of technical, social and environmental factors are not considered: e.g. safety related issues like dangerous crossings and the way bicycles interact with high speed or cargo motorized vehicles; neither the existence of the previous cycling infrastructure are taken into account.

A proper bicycle network design involves the management of many of these factors, sometimes critical and contradicting, so a different approach is needed. Such an approach should be general and multidisciplinary in such a way that the whole range of criteria and priorities involved can be assessed properly. It should also be flexible to the stakeholders concerned and they should be able to involve new criteria that can arise during the planning phase of the project. In this manner the method can be used, with little adjustments, in different cities and conditions.

Given the mix of spatial and non-spatial elements of this kind of design problem, Geographic Information Systems (GIS) can be a very useful tool to deal with this. A GIS is a system (hardware, software and geo-data) designed to collect, store, manipulate, analyse, manage, and present all types of geographically referenced data. Transport is just one of the many possible fields where GIS has been successfully applied.

In the same way, spatial Multi-Criteria Evaluation is a technique developed to analyse a number of alternative possibilities taking into account multiple criteria of spatial nature to assist the decision making processes. It allows considering the 'weighting' in the analysis or in the definition of the level of importance of the involved criteria, according to stakeholders' perceptions, thus generating efficient and tailored solutions to a countless variety of spatial problems.

With this in mind, it is logical that GIS based Spatial Multi-Criteria Evaluation techniques are located at the core of the approach that is needed. It has proven its effectiveness in every field where spatial decisions are required, from environmental impact studies to optimal location finding problems and routing of service networks (Keshkamat, 2007). GIS based tools also have the capacity to deal with a large amount of data in multiple formats and to carry out very useful network analysis applications given the nature of the bicycle facilities system design in which we are interested.

1.3. Research problem

As discussed in the previous section, to date there is no proper methodology allowing the designing of bicycle networks in a data scarce environment by incorporating relevant factors in a general and flexible manner to provide optimal routing and performance.

The existence of an incomplete or segmented cycling infrastructure that should be integrated into a new network in a given city has hardly been considered before. In many cities where budget constraints are usually common, public investments have been done to build such facilities and they can't be disregarded. Therefore, to look for the best way to integrate existing lanes to the new network ensuring connectivity and the basic quality principles is also necessary.

1.4. Research objective

There are very few methodologies in the literature that make use of GIS based Spatial Multi-Criteria Evaluation (SMCE) for a specific cycling network design. Such a design can be optimized if the factors affecting the quality and efficiency of the system are properly analysed.
Accordingly, the objective of this research is to develop a GIS based SMCE methodology for the evaluation of potential bicycle routes within an urban area, aiming at the optimization of the cycling network, with the city of Belém, Brazil as a case study.
In order to reach this objective, in the following table the sub-objectives and the related research questions are formulated.

1.5. Sub-Objectives and Research Questions

Table 1 Sub Objectives and Research Questions

SUB OBJECTIVES	RESEARCH QUESTIONS
1. To determine which are the more attractive locations for current and potential bicycle users	Q. Which are the main attractors of bicycle trips by purpose (education, recreation, tourism)?
	Q. Where are the attractors located?
2. To estimate the distance people are willing to cycle to get to their destinations.	Q How can the distances people are willing to ride to the different attractors be defined?
3. To define the criteria to evaluate the area based suitability for cycling to be considered in the model.	Q. Which spatial and non-spatial factors influence the suitability for cycling can be included in the model?
	Q. How can these factors be properly formulated in order to be included as input for the analysis?
4. To define the relevant spatial constraints for cycling that can be included in the model.	Q. Which kind of constraints can be considered and modelled?
6. To assess the existing cycling infrastructure and define how it can be integrated within the suitability analysis.	Q. Where is the existing cycling infrastructure located?
	Q. What is its current condition?
	Q. How the existing cycling infrastructure can be ranked or weighted?
7. To develop an SMCE based model to determine the suitability for cycling in urban space.	Q. How can the previous items be weighed to perform the analysis?
8. To identify the optimal routes for the cycling network.	Q. How can the best possible roads within the suitable areas be prioritized?
9. To assess the developed cycling network	Q. Which indicators can be used to evaluate the network?

2. LITERATURE REVIEW

2.1. GIS approaches for bicycle network design

Although the use of GI techniques has been analysed in the literature, the majority of studies dealing with transport planning are focused on networks for motorized means.

For example Keshkamat (2009) developed a method aiming for the identification of routing alternatives for a highway project, which include the definition of suitable areas (SMCE) based on specific criteria, and the prioritization of existing routes to define the more appropriate ones under four different visions.

Nevertheless, some research, although very few, has been performed lately aiming to take advantage of these methods for a bicycle network design.

For instance, Larsen and El-Geneidy (2009) describes a method to identify locations for new cycling facilities using a Geographic Information System (GIS) within the city of Montreal, Canada as case study.

In their model they include current cyclists' trips and short car trips (as potential new bike users) based on Origin Destinations (O-D) surveys, as well as suggested routes for new facilities from a survey of local cyclists and records of bicycle crashes. They make use of a grid cell analysis in GIS with data derived from the above criteria to identify high demand corridors within the city.

As a result, they recommend general areas in a region where facilities are needed. However, the location of the network is not defined. A method to prioritize the roads within the high demand corridors is also missing.

Moreover, this approach is based on the existence of many data on cycling behaviour that is not always available in cities in developing countries.

In another relevant research, Rybarczyk and Wu (2010) have described a multi-criteria evaluation analysis intended to integrate the supply and demand-based criteria for bicycle facility planning. They performed analysis at network and neighbourhood level exploring the spatial patterns of the facilities for bicycling in the city of Milwaukee, WI. U.S.A. Their results "suggest that a combination of GIS and MCE analysis can serve as a better alternative to plan for optimal bicycle facilities…"(Rybarczyk & Wu, 2010).

However, their aim is not to design a cycling network but assess the current conditions of an existing infrastructure based on the spatial patterns and road network characteristics. So they are able to make suggestions, like on which roads it is necessary to improve the Bicycle Level of Service (BLOS) or which neighbourhoods have qualities that make bicycle facilities attractive.

The previous examples show, with different approaches, how GIS based tools can be applied in the planning and design phases of bicycle networks with an efficient handling of the available data. However, in the approaches described above an optimal location for the network elements is not provided as a direct result of the methodology.

In contrast, a multi-criteria approach study where feasible bicycle tracks were identified was made by Thambiraj (2003). Although it is just a preliminary study within the campus of the National University of Singapore, the methodology is well defined and the objective of identifying suitable routes is accomplished.

There are, however, a number of factors influencing the quality of the design that, due to the scale (a university campus), are much less than those in an entire city. For instance, in the study, she defines a safety parameter to keep the bicycle tracks away from roads as far as possible; this works within the campus but in a city where many tracks usually go along main roads, different safety parameters must be considered. Due to the same scale issue, factors and constraints like existing cycling infrastructure, roadways' and cyclists' characteristics and many more that affect the quality of a network design are not considered.

Moreover, as she recognizes, the constraints and objective function used in the project were derived from research articles of foreign countries, where local perception and the influencing factors to pick up cycling may differ significantly. Nowadays new research on the topic is available (Providelo & Sanches, 2011; Rybarczyk & Wu, 2010) and it is possible to make use of information from environments with similar, when not the same, cultural and socio-economic characteristics, which can improve the research results significantly.

2.2. Bicycle networks design criteria

Since this study is dealing with the design of cycling networks it is essential to take into account the elements that through research and experience have been identified as basics to ensure the facilities' quality.

Bicycle network design aims to improve mobility for bicyclists by providing appropriate facilities to meet their needs. Such needs can be summarized under the main principles that define the requirements that a cycling network must satisfy to comply with the basic standards (Godefrooij, Pardo, & Sagaris, 2009) Modern cycling network planning and design are based on these core principles.

Below a general description of them can be found, followed by a description of the specific section of the methodology where such principles will be considered in this study.

Coherence

Coherence refers to a continuous network, connecting all the origins and destinations, with minimal quality changes, in an easy to follow way and including the integration with other transport means.

The integration of existing facilities with the new design and the definition of key attractors in the methodology we are developing are directly related to complimenting the Coherence principle.

Directness

Directness means the possibility for the user to take a route to the desired destination with the minimum possible detour. Travel time and distance are key concepts for cyclists.

To identify the optimal routes in the analysis this principle will be considered, but not before compliance with other requirements is ensured, (i.e. those recognized by users as crucial to decide to make use of cycling facilities e.g. safety.)

Safety

Due the characteristics of this transport mode and the inevitable interaction with motorized traffic the cyclist is vulnerable. Thus, Safe facilities are a basic need, which means that the risk must be minimized.

The mentioned interaction with motor vehicles, other cyclists and pedestrians, as well as technical conditions of the route (geometric design, obstacles, lighting, etc.) have to be considered while designing networks. The fact that the infrastructure must be *perceived* as safe is equally important in the design phase.

By defining the proper constraints according to local conditions and by the evaluation of roads conditions like surface material, street lighting, crossings and roundabouts among others, the safety factor will be taken into account in this methodology.

Accessibility

Accessibility makes reference to a network connecting key origin and destination points, by means of routes as direct and quick as possible. Key destinations must include integration points with different public transport means, major educational and employment centres and those considered as important in a given community.

An attractor's based methodology like the one that is intended to be developed here can ensure a basic accessibility to users by defining catchment areas and proper criteria to allocate cycling facilities inside them. Bus stops and different kinds of transport terminals can be also included as attractors in this methodology which will enhance the overall accessibility.

Attractiveness

An attractive environment in terms of appearance, landscaping, public space design, safety, cleanness, presence of resting places and utilities, etc., that makes the facility propitious to be used is the core of the attractiveness principle.

From these, some elements according to local conditions can be taken into account in the proposed methodology, for example the promotion of attractive places for cycling like waterfronts; to consider wide avenues, open spaces or the presence of trees along roads as factors that increase the suitability for cycling, etc.

Other elements related with the attractiveness principle will depend on the operation and maintenance phases that mainly are responsibility of the cities' administration, and are out of the reach of this study.

Comfort

Comfort makes reference to a convenient infrastructure in terms of surfacing, gradient and width,, minimal stops and no obstructions that avoid nuisances to the user. In general, all the characteristics that make the user feel comfortable while cycling.

In the proposed methodology, in the optimal selection of routes the consideration of factors like slope (where applicable, a slope map can be used to define such constraints) and the roads' bicycle friendliness (speed of motorized traffic, wide, road surface etc.) can be included and evaluated to ensure that a level of comfort is achieved in the resulting network.

Many of the elements under these principles can be considered given the flexibility of the model by a proper definition of constraints and suitability criteria during the initial phase. The users perceived importance of each one of them, however, must be identified to ensure a balanced weighting assignment during the suitability analysis.

2.3. Factors influencing quality perception of cycling networks

There are many factors that, based on the characteristics (cultural, socioeconomic etc.) of users, can vary in importance when assessing the cycling networks quality. For instance, Providelo and Sanches (2011) conducted a study on Brazilian medium-sized cities with the aim to describe the roadway and traffic characteristics that are prioritized by users in the evaluation of the quality of roads for bicycling.

From the attributes representing quality characteristics that were identified, the most important to the participants of the study are: (1) lane width; (2) motor vehicle speed; (3) visibility at intersections; (4) presence of intersections; and (5) street trees (shading), so, to promote bicycle use, they suggest that these attributes must be prioritized.

Also, developing a Level of Service model for applications in U.S. metropolitan areas, Landis (1997) identified the pavement surface conditions and striping of bicycling lanes as very important factors in the quality of service.

Thus, a flexible methodology to design cycling networks must allow the inclusion and evaluation of these key quality factors.

2.4. Bicycle Network Design in Data-Scarce Environments

From the traditional bicycle network design models above mentioned, those based on the demand for the cycling estimation to define the location of facilities are normally developed founded on cycling behaviour data like counts and surveys.

However, to forecast the demand for cycling where this kind of information is not available there are methods that, even with some limitations, can provide acceptable results.

For instance, the comparison study method makes a prediction of the demand of a facility by comparing its current use, neighbouring population and land use distribution of similar cycle facilities in other places where the data is available. One type of comparison method that is applicable for new developments just compares an existing facility and its surrounding population with those of the proposed facility. Such a method was used in the Central Massachusetts Rail Trail Bikeway, U.S.A. (McDonald, Macbeth, Ribeiro, & Mallett, 2007)

The methods advantage is its minimal input requirements and the easy application. Its major limitation is that the number of compared situations is generally very few as well as the number of examined variables, allowing misinterpretation of the results depending on the ability to analyze them and the quality of the information used. (McDonald, et al., 2007)

Even if this is a relatively simple method and not always requires bicycle counts; the data of surrounding population must be available which is not easy to obtain in many cases. Moreover, by its characteristics, it is applicable only for sections of cycling facilities, i.e. to design an entire cycling network based on this method is not feasible.

2.5. Spatial Multi-criteria Evaluation

As can be seen in the conceptual diagram, this is a central component of the model to be developed. So it is relevant to give a brief description to have an idea of the advantages it can offer regarding to the evaluation of the suitability for cycling.

The objective of the SMCE analysis techniques is to analyze a number of alternative possibilities taking into account the multiple criteria of spatial nature and their often conflicting objectives. SAME allows generating alternatives and ranking them according to their attractiveness to support the decision making processes.

In a SMCE, criteria are usually classified into factors and constraints, based on the type of impact. A factor can be a benefit or a cost:

A benefit is defined as a criterion that contributes in a positive way to the output; the higher the value, the better it is. A cost is defined as a criterion that contributes in a negative way to the output; the lower the value, the better it is.

A constraint is a criterion that defines which areas in the study area are considered as completely not suitable.

In the SMCE, each criterion is represented by a map. If there are different units of measurement, standardization of all criteria should be carried out according to the given factor and data characteristics. As a result, the input maps are normalized to utility values between 0 (not suitable) and 1 (highly suitable). (Farkas, 2009) So, a series of raster-based maps are generated showing how the criteria are evaluated over the entire area according to the perceived weights. The values of each pixel will represent how appropriate is the proposed use for this area.

At the end of the SMCE analysis, the maps that represent the different criteria and weights are combined to prepare a final suitability map, where it is possible to visualize the possible alternatives.

3. METHODOLOGY

Since in many cities in developing countries available data on cycling travel behaviour is limited, the use of traditional cycling networks design methodologies can imply costly and time consuming additional tasks (surveys, counts).

Accordingly, the methodology of this research is based on the selection of key bicycle trips attractors, their catchment areas, and a series of factors according to the available data that by the integration and evaluation through GIS software will help to identify the spatial distribution of the suitability for cycling within an urban area. Based on such suitability the routes forming an optimum cycling network will be identified

The suitability maps for cycling based on the area of influence of the attractors, the factors influencing cycling and the constraints will be standardized and weighted through an SMCE process to define a final combined suitability map, which will be overlapped with the road network.

The next step will be to analyse those segments of the road network that falls into the suitable areas and to evaluate the best potential routes for cycling among them. Then, the existing cycling infrastructure's connectivity with the new one must be checked and the network must be reviewed as a whole.

A description of the main steps, as shown and numbered in the **conceptual diagram (**figure 1) can be found below. The minimum data requirements and its possible sources are also pointed out after the relevant steps.

3.1. Conceptual Diagram

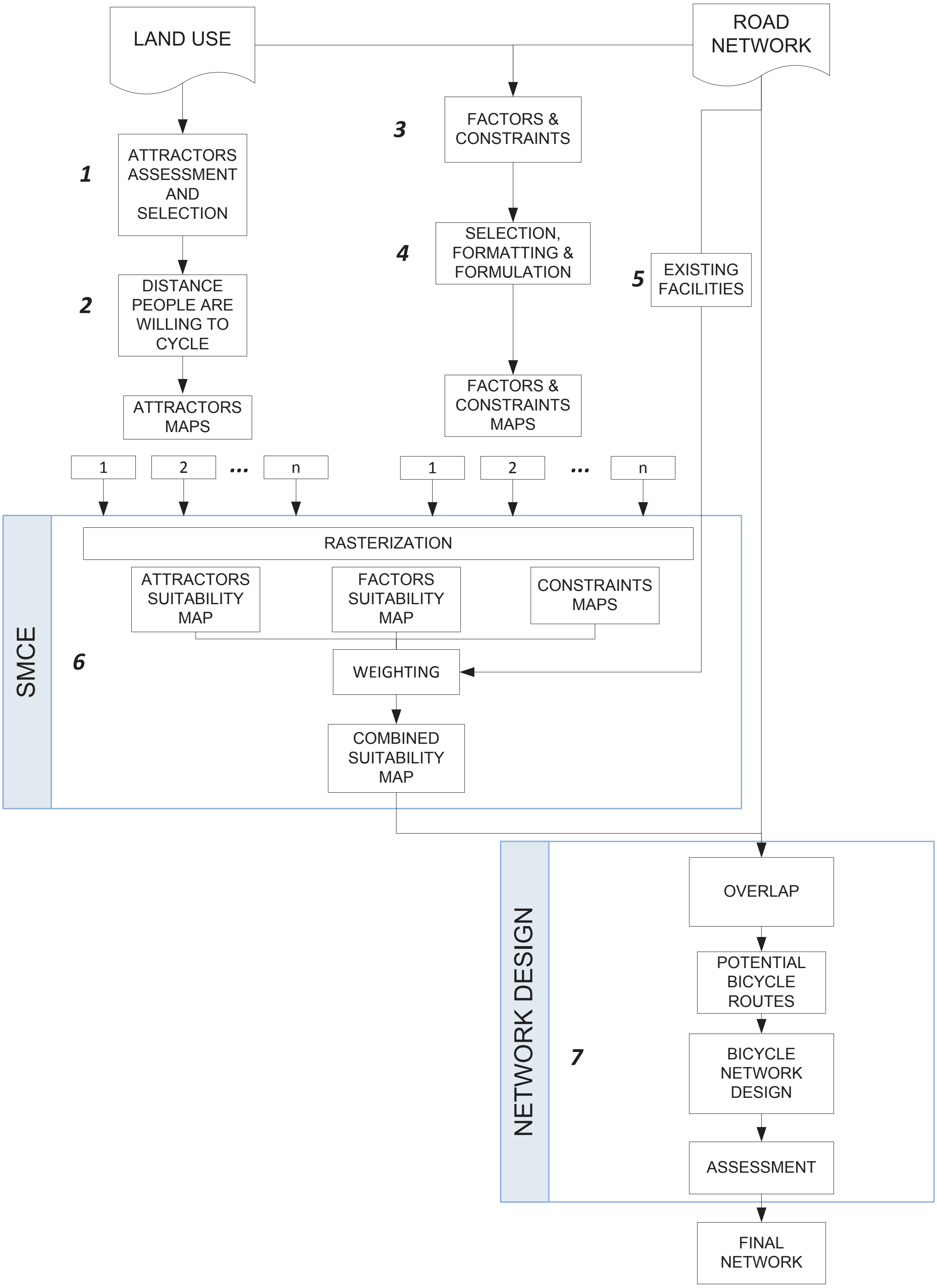


Figure 1 Conceptual Diagram of the Methodology

3.2. Identification of key bicycle trips attractors (1)

Key bicycle trips attractors in a given city can be identified based on local conditions, local knowledge, planning policies and field observations. However, a review of the literature can give a preliminary idea about the more visited places by bicycle users.

The educational institutions and major employment centres can be considered the most important potential destinations for **utilitarian** bicycle trips (Providelo & Sanches, 2008). Educational institutions must be crucial for bicycle facility planning because they generate a large amount of bicycle trips. For example, estimations indicate for the United States that cycling involves approx. 15 to 30% of trips to schools and remains at 10 % year round near college campuses (Huber, 2003).

On the other hand, the main potential destinations for **leisure** bicycle trips within an urban area can be recreational areas and parks, where the public has access to open spaces and public events (Rybarczyk & Wu, 2010). Depending on the local context, touristic sites also can be significant bicycle trip attractors to be taken into account in the design process.

Therefore, in principle, the analysis will be focused on universities, parks and touristic sites as major attractors that should be accessible to bicycle users. Local knowledge or policies, however, can influence this selection later on. Bus stops or transport hubs (waterway, train) for instance, may be interesting points to be accessible by bike, so some flexibility is possible after the final selection.

Sources of information on touristic attractors can be the city administration and the tourism office, which should keep statistics on the topic. Information on educational institutions by size and location and recreational areas can be obtained from discussions with local people and confirmed during field visits.

Data collection: Since at universities many people, (current and potential users) are gathered it is easier to get relevant information through group discussions, workshops and small surveys. There it is also possible to get some insight in the local conditions that define the distance people are willing to cycle to destinations and different points of view about constraints and criteria weights.

3.3. Distance people are willing to cycle (2)

On the basis that, particularly in developing countries, available data in cycling travel behaviour (O-D surveys) is limited and its collection implies a lot of time and resources to be consumed, the approach of this work will be attractors based, i.e. key attractors' catchment areas will be considered as the first approach to find the more suitable zones to allocate bicycle facilities.

The extent of such areas depend on several factors: It has been stated that the distance between origin and destination affects cycling more radically than it does for motorized means (Woldesemayat, 2009). Also, local conditions (socio-economic level, public transport tariffs, slope, weather, etc.), gender and trip purpose influence the maximum distance the users are willing to cycle. (Iacono, Krizek, & El-Geneidy, 2008)

For instance, from a study in Canada, cyclists are generally willing to travel greater distances for work than for other purposes (Larsen, El-Geneidy, & Yasmin, 2010). Therefore, if in the design approach zones inside the catchment area of each attractor will be considered as the more likely origin of bicycle trips, it is necessary to identify the appropriate distances for cycling according to the trip purpose (work, education, leisure).

The distances people usually ride described in the literature vary considerably given the influence of local conditions mentioned above.

E.g. for Montréal, Canada a study shows distances travelled for work purposes are less than **5 km** while leisure trips are less than **3.5 km** long (Larsen, et al., 2010).

In the Twin Cities Region, Minnesota U.S.A., recreation trips reach **30** to **40 km**. followed by work trips, most of them falling within a range of about **20 km** (Iacono, et al., 2008)

The difference is notable compared with an African country: in Dar es Salaam, Tanzania "…cyclists are generally making very short trips for education, social and work purposes; but business trips are slightly longer and reach **20 km**" (Woldesemayat, 2009)

Therefore, to get the most reliable estimation of the distance people are willing to cycle in a given environment the following alternatives can be explored: (if there is no data available)

- It is possible to consider information of a comparable city as reference,
- To work with average distances from different studies in the literature.
- Adjust values from the previous alternatives based on local experience.

Interviews with key local people can be very useful at this stage, and can be carried out without many time and resources consumption. A land use map and the literature review are also crucial in the definition of the distances people are willing to ride to their destinations.

After the identification of the proper distances according to the trip purposes, a network distance based service area will be calculated in ArcGIS to define the catchment areas.

This methodology is based on the assumption that the origins of the bicycle trips leading to a given attractor are located inside of the catchment area defined by the distance described above. Due to the fact that it is not viable to provide cycling infrastructure in every road of the city, to define the optimal routes it is required to prioritize the origins or to select a representative one based on some criteria. It is reasonable to consider the residential areas as the origin of most of the cycling trips. Since an infrastructure serving the highest amount of people is desirable, the most densely populated zones among residential neighbourhoods inside catchment areas can be considered as representative origins of the trips.

3.4. Factors and Constraints influencing suitable areas for cycling (3)

Diverse factors, as local conditions vary for each city, influence the suitability of spaces to the cycling infrastructure allocation. They can be grouped into the following categories according to its nature:

Safety: Regarding to the users interaction with motorized transport causing accidents (roads with high traffic of trucks, high speed highways) and technical characteristics of the infrastructure like slopes, crossings, narrow or no-paved roads, traffic signals, etc.

Multi-lane crossings for instance have been identified as places where severe bicycle accidents occur more frequently due to the direct interaction with motor vehicles. In the same way, multi-lane roundabouts can significantly increase risks to cyclists (Reynolds, Harris, Teschke, Cripton, & Winters, 2009).

A safety measure can be considered to avoid such points and to prefer a little detour to cross the main roads where less traffic is present. To do so, in a road map major crossings and roundabouts can be identified and considered as constraints. Based on a report of the British Medical Association (1992) which concludes that two-thirds of all cycling accidents occur at or within 20 meters of a junction, this distance can be used to define the constrained area.

Safety:: in many cities there are zones where the risk of robbery and other crimes is higher for cyclists. Street lighting and landscaping may help to reduce it but it certainly is a social problem that needs additional measures by the city's administration. A controversial but practical approach having the users' safety in mind, could be to avoid allocating facilities in such areas

Environment: Green zones and parks are fundamental for the wellbeing of citizens. Recreational areas, flora and fauna reserves and other clean air sources are crucial in urban environments. Even some of them are attractive and propitious for cycling rides; there are some others that must be protected from any detrimental intervention since they are sources of crucial resources like water or home of endangered species. So, the last should be defined as hard constraints while the first can be promoted as suitable in this methodology.

Social: As any urban infrastructure, a cycling network should be designed to benefit the highest amount of people, so, denser populated neighbourhoods and places where public transport system's users are concentrated every day should be prioritized. The first as potential high demand origins to all destinations and the latter as places where the provision of cycling infrastructure will improve the accessibility of those living far from transport routes while promoting multimodal integration.

The most dense industrial/work places areas also represent a high potential demand of cycling infrastructure. Census and land use maps can be used to identify these zones to include them in the analysis.

Administrative – Economic: Existing facilities, operation and maintenance, streets surface material, length, land use, upgrading or changing needs, etc., have a direct impact on the budget assigned to cycling facilities. The efficiency of the design will be based on the appropriate selection and analysis of these factors.

On field data collection and local knowledge (research groups, planning office, transport authorities, etc.) can give more insight on this topic for a given city.

3.5. Selection, formatting and formulation (4)

According to the local conditions and data availability a selection of the factors and constraints must be done carefully. Since they possibly may differ in nature or extent and even in the format of the files when secondary data is available, it is necessary to homogenize it (projection, origin etc.) and to establish the proper evaluation function that will be used in the analysis. Once these tasks are accomplished the maps can be created with the needed attributes and be ready to the next phase.

3.6. Existing facilities (5)

For the existing cycling facilities, an analysis of their location must be carried out to define the way to ensure their integration and connectivity with the new network without disregard of the overall system quality.

It is necessary to explore the best way to include these facilities within the analysis:

A buffer zone around them can be included with high weights in the SMCE process which will increase the suitability values of the nearby roads. By doing so, and assuming existing facilities are well located, there will be routes through suitable areas connecting old and new infrastructure.

Also, after the selection of optimal routes, each existing bike lane can be treated separately to be integrated to the network. The upgrading of existing facilities should also be considered when a new network is implemented to ensure the coherence and the basic safety standards of the system.

3.7. Spatial Multi-criteria Evaluation (6)

At this point the different criteria and constraints identified are weighted and combined to prepare a final suitability for cycling infrastructure allocation map. In such a raster based map, the areas where the location of facilities will produce the biggest positive impact will be identified as described above in the key concepts section.

3.8. Bicycle Network Design (7)

From the "suitable road network", i.e. road network that falls into the suitable areas recognized in the SMCE process, the optimal routes for cycling must be identified. (Prioritization if there are many suitable roads in the same area)

To do so in the best way, an exploration on the criteria to select the routes should be conducted and therefore it was defined as a sub objective of this research.

Among the possible alternatives, an evaluation and ranking of how appropriate for cycling are the roads of a given city can be used to prioritize the routes. However, it implies that information on traffic and road specifications must be available. Since one of the characteristics of this methodology is that it can be used in data scarce environments, the decision on such alternative will depend on specific local conditions, data availability and budget.

Another option that fits better with the data scarce environment assumption of this methodology is the Line Weighted Mean method. Such method was used by Keshkamat (2009) in his routes alternatives analysis for the Via Baltica Express Way Project, and, in short, it assigns a weighted value to each segment of the network based on their underlying cell values of the raster suitability maps.

A network analysis can then be conducted by the proper assignment of impedances to the roads and the identification of the more likely origins of the bike trips leading to each attractor, so the optimal routes can be identified.

4. STUDY AREA DESCRIPTION

4.1. Background

Belém is the capital city of the state of Pará, in the north of Brazil. This city is located at the banks of the Pará River, which is part of the Amazon River system. (Figure 2)

Figure 2 Belém Location

The population of the metropolitan area is near 2 million and the municipality covers an area of 1070 Km^2. It is the 10^{th} biggest city in Brazil, concentrating a large amount of commercial, services and educational institutions operating in the Pará state. It is considered the gate to the Amazon due its condition of main fluvial port at the mouth of this river on the Atlantic Ocean.

The metropolitan area of Belém (*Regiao Metropolitana de Belém* – RMB-) consists of the municipalities of Belém, Ananindeua, Marituba, Benevides and Santa Bárbara.

There, the urban growth was developed with the setting of a central space and a subsequent expansion to peripheral areas at the north and north-east direction.

This is due to the special location of the city, constrained by the Pará River in the west, by the Guamá River in the south, and the existence of an environmental protected area at the east side, as can be seen in the figure 3.

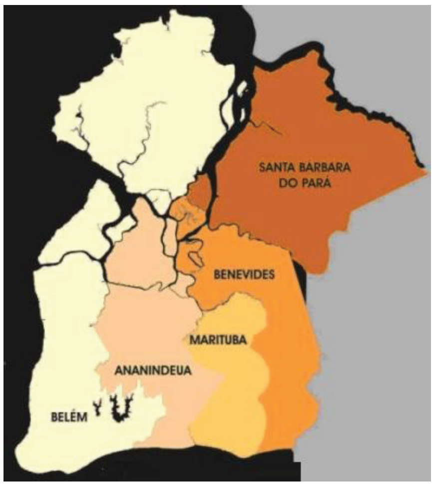


Figure 3 Metropolitan Region of Belém

Source: Adapted from Google Earth

Figure 4 City of Belém

The metropolitan region of Belem had undergone a transformation due to the population growth, which occupied the available urban space in a disorderly manner as is shown above: the low- and middle-income groups were occupying the designated areas for expansion in the periphery, while the higher incomes are concentrated in the central region, where the availability of commerce and services is higher. The density continues to increase in vertical direction with the construction of tall buildings.

This traditional centre is the main destiny for urban public and private transport trips, originating mostly in the expansion area. The characteristics of the road network in the city define the behaviour and effectiveness of public transport to try to meet this demand that generally points towards the centre in the morning and towards the periphery at the end of the afternoon. The following section provides a brief description of the road network in Belém.

4.2. Road Network

In the area where the territorial occupation of Belém began, the so-called historic centre and its surrounding areas there is a dense road network that offers good accessibility to transport. However, the streets are narrow, making it insufficient for the amount of traffic. This leads to congestion, which particularly, at peak times, has become an everyday thing. In areas with high commercial activity there is a large presence of street vendors, informal trading posts, pedestrians, cyclists and illegally parked vehicles,

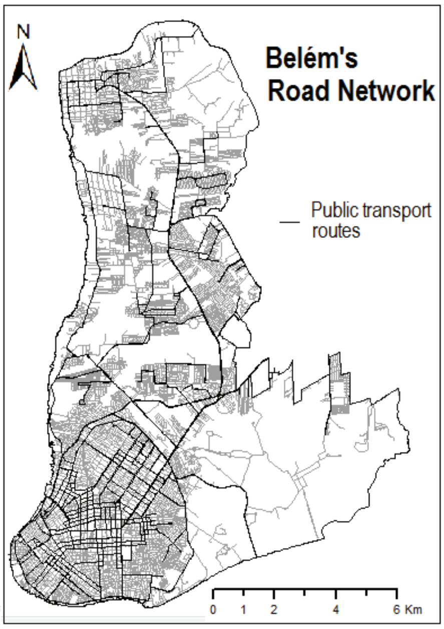


Figure 5 Belém's Road Network

interrupting the traffic. As the distance increases from the centre you can see wider streets that in certain sectors have a modern neighbourhood development, while in others, toward the southeast, less developed neighbourhoods were established where you can even find unpaved roads.

This central area is connected to the periphery by means of two main roads that form the backbone of public transport in the city: Almirante Barroso Avenue in the east and in the west the Pedro Alvares Cabral Avenue. It is important to note the existence of an intermediate zone between the centre and the periphery, which is mostly used for military purposes, causing the discontinuity of occupation and the main road system, thus hindering the movement of people between the main trip generators and attractors.

In the periphery, the region north of Belém is connected to the Avenida Almirante Barroso on the highway Augusto Montenegro. This two-lane road has great movement of public transport in each direction, which gives an idea of the number of people who depend on it daily to reach their destinations. Beyond the expansion area, at the urban municipalities of Ananindeua, Marituba, Benevides and Santa Barbara, the main focus is on highway BR-316, which is the continuation of the Avenida Almirante Barroso but is in the hands of the national government.

4.3. Cycling in Belém

Cycling in the city has increased considerably in the last years. By 1990, cyclists' population was just 1% of the Metropolitan Region of Belém's total population, while by 2000 this percentage increased to 5.69%. (M. S. G. Tobias, et all, 2007b). Socio-economic conditions and public transport system characteristics are the cause of this phenomenon as it is explained below.

During the 90's the population of Belém significantly increased (2.3% annual average) while the average income declined. This created a strong pressure on public transport demand, which was still financially unaffordable for many people. In response to this situation there was an increase in the supply of bus lines on the main roads of the city.

However, no investments were made in the new road infrastructure or in the maintenance of existing roads, which even today are not in a fair condition and cause several discontinuities for motor vehicles.

As a result, road congestion increases travel times, giving another reason for users to find alternative transport solutions.

By the year 2000 the average travel time by bus per capita increased by 16.3%, while in the case of the bicycle meant a 0.7% decrease in travel time, making transportation by bicycle becoming a strong competition for the public transport.

The results of the survey of the perception of transport service quality in the city also support this statement: there, the demand of transportation by bus was considered as “unfavourable” by 40% of the population, whereas 44% of the population perceived travelling by bike as "favourable". (M. Tobias S. G., et all, 2007a)

From the studies it was also possible to notice that the number of households that owned bicycles in 1990 was 13.1% and that this rate increased to 51.16% for the year 2000, which is an increase of more than 300 %. This constitutes a change in social behaviour towards this transport mean which must be properly cared for and encouraged within the city.

In addition to this unexpected growth of cycling as a means of transportation, there are certain factors that may influence its development. In the peripheral neighbourhoods, where the population of regular cyclists is higher, the low income of the people makes this an ideal transport mean, which can grow further if the infrastructure is provided to ensure safety and connectivity to the user. As there is a predominantly flat topography in the city that also facilitates this activity, it is clear that it has great potential to have the bike as a means of transportation in the metropolitan region of Belém.

4.3.1. Existing Cycling Network

At present there are about 60 km of cycling routes within the city that were built by different public services in the recent years. They are found along the two main motorways connecting the transition area (figure 12) with the north of the city, and along two midsized transversal roads also in the transition area, connecting the mentioned motorways. There are other isolated sections that are not interconnected. Because they were not designed as an integral part of a network the roads are not uniform in their physical characteristics and maintenance conditions.

In terms of distribution, in any of the streets of Belém centre there are cycling routes. In the four-lane arterial road connecting the centre to the periphery, the Av. Almirante Barroso, there are biking paths that vary between 1 and 1.5 meters wide, located mostly along a central divider. (See Figure 6)

On the highway Augusto Montenegro, which connects the Av. Almirante Barroso endpoint with the Icoarací district at the northwest, and on the BR-316 highway, which is the continuation of the Av. Almirante Barroso outside the Belém municipality, there are biking paths along the central divider on both sides, with a 1.40 m width. On the same road there is the motorized traffic, the two roads being separated from each other by painted lines and auxiliary devices such as a strikethrough, which is not sufficient to prevent the invasion of motor vehicle on the biking paths, resulting in great uncertainty for the cyclists.

Figure 6 Cycle Path Av. Almirante Barroso

In some secondary roads there are small sections that are in good condition although isolated, as described above.

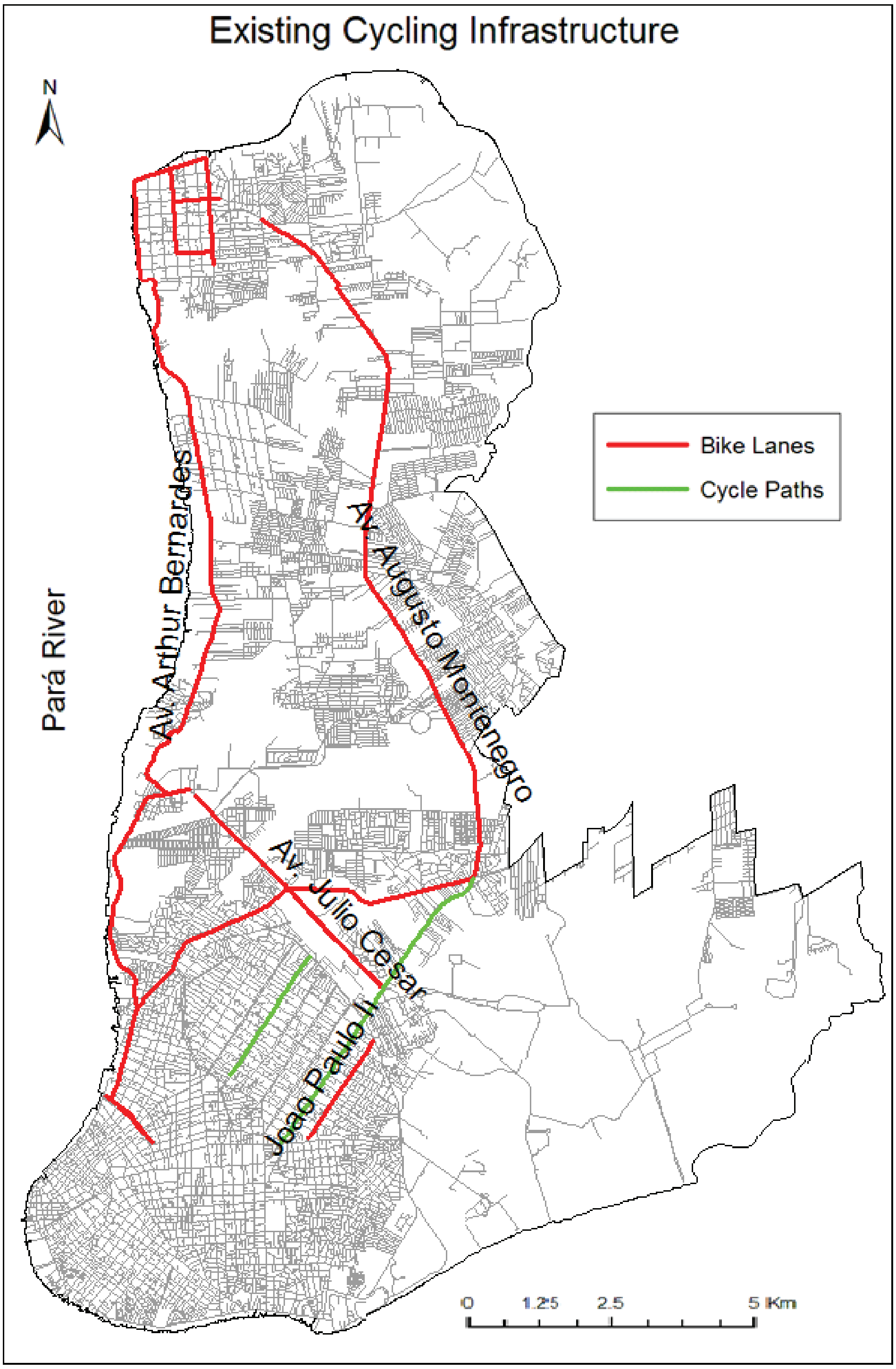


Figure 7 Existing cycling infrastructure

The map in Figure 7 shows the location of these cycle paths and bike lanes in the city. As can be seen, in the city centre there is very few infrastructure; some sections were built insulated, i.e. no connection with other infrastructure; in main streets linking north and south areas there are bike lanes which, as mentioned before, the users' safety is compromised.

In Table 2, a list of the existing bike lanes within the metropolitan region of Belém with ther respective length can be seen.

Table 2 Existing Cycling Infrastructure in Belém

Road	Length (km)
Bike Lanes	
João Paulo II	2.00
Júlio Cézar	4.80
Orla de Icoaraci	1.30
Visconde de Souza Franco	1.80
Av. Arthur Bernardes	15.00
Augusto Montenegro	13.00
Total	**37.90**
Cycle Paths	
Almirante Barroso	6.00
Independência	4.00
Orla de Mosqueiro	1.00
Av. Marqués de Herval	3.20
Av. Pedro Alvares Cabral	6.00
Total	**20.20**
Total:	**58.10**

4.3.2. Cycling interaction with motorized vehicles

During the fieldwork, from interviews held with taxi and private car drivers and the experiences of public transport, it was possible to identify the points that are considered crucial in the interaction between cyclists and motor vehicles in the city:

Bicycle traffic is disordered. In roads without a cycling infrastructure you can encounter cyclists that do not obey the regulations, risking their own lives by cycling along fast transit avenues, even where public transport buses and cargo trucks are mixed.

Especially crossings and popular commercial areas are congested; there are not enough pedestrian overpasses and the traffic lights' timing is not very efficient. Cyclists cross anywhere as soon as they see a chance, as can be seen in the image in figure 3, taken in the BR 316 highway at the north of the city.

Figure 8 Uncontrolled street crossing by cyclists and pedestrians

As shown in figure 9, some streets are narrow and motorized traffic has to share the road with informal vendors' carts, cyclists and pedestrians. Such situation mainly occurs close to popular markets and fairs operating every day.

Figure 9 Congestion in narrow streets

Presence of Cycling Infrastructure

In the few roads where segregated bicycle facilities are present the traffic conditions are better. However, where there are biking lanes that are just demarcated (see figure 10) the users safety is seriously compromised due the speed of motor vehicles, the drivers' disrespect for cyclists' space and also by the irresponsible behaviour of the cyclists.

Figure 10 Cycle lane along Av Augusto Montenegro. The speed of vehicles compromises user's safety

For instance, along one of the main avenues of the city, the Almirante Barroso, there is a bike lane on the left side (separated cycle path along some sections) but it is common to find cyclists riding on the right side and even between the car lanes when the vehicles speed decreases due to congestion.

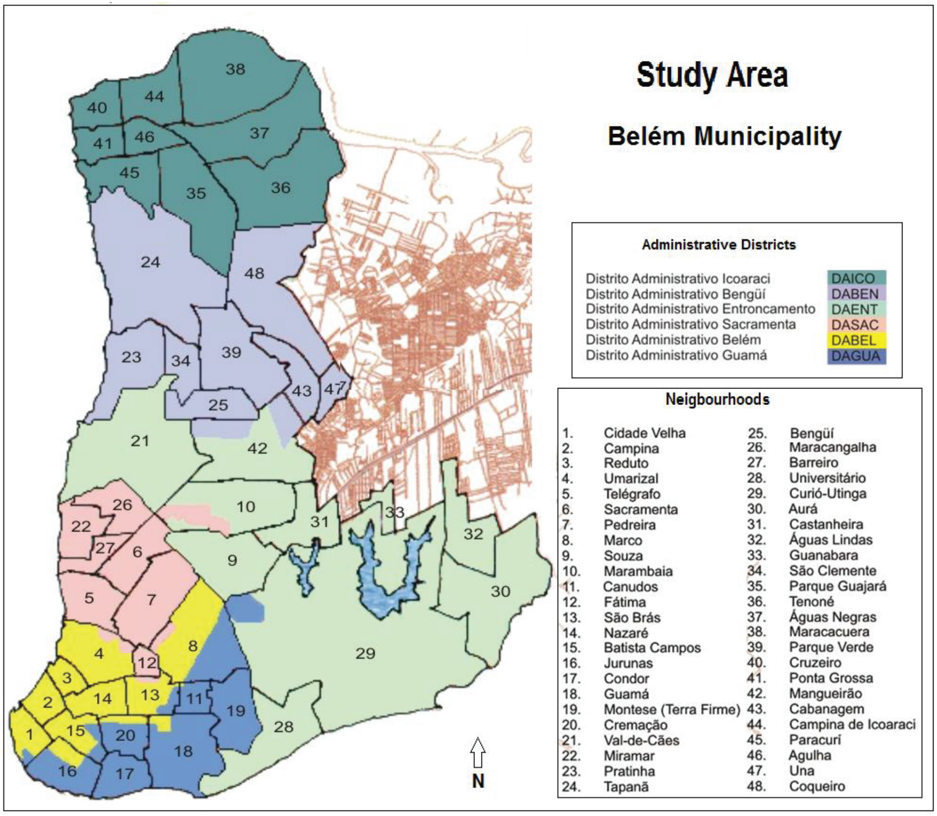
The situation described above shows that user's safety is a very important factor to take into account when designing or upgrading cycling infrastructure in Belém. Even cultural factors influence the people´s cycling behaviour; the provision of facilities designed considering safety issues will reduce accidents and gradually will influence positively users' performance.

The increasing number of accidents involving cyclists, the rising of the vehicle fleet, of 12% just from 2009 to2010 (DETRAN 2010), the inefficient public transport system, and the evident and continuous growing of bicycle users in Belém (M. S. G. Tobias, et all, 2007a) shows also that the city needs a proper cycling network urgently.

5. CASE STUDY IMPLEMENTATION

5.1. Study Area

Due to the quality and coverage of the available data, the study area for the present case was defined as the extent of the continental area of the municipality of Belém, which is composed of 48 neighbourhoods grouped in 6 administrative districts, as shown in figure 11 below.



Source: Adapted from CODEM, 2008

Figure 11 Study Area map, Belém

5.2. Data Collection

A set of secondary data in different formats was collected during the fieldwork thanks to the collaboration of people from diverse public and private institutions in Belém.

A description of the data as well as the way it will be used in the analysis can be seen in the table 3 below:

Table 3 Summary of the collected data

ORIGINAL NAME (português)	CONTENT	DATE	SOURCE	USE IN THE METHODOLOGY
Lotes	**Plots, lots**	2008	CODEM	
Uso do solo	Land Use			To sketch potential bicycle routes between selected trips attractors and their respective generators
Logradouro	**Roads**			
Ilum Publica	street lights: yes / no			Soft constraint, prioritization of suitable roads
Tipo Pav	Street Surface			Soft constraint, prioritization of suitable roads
TranCol	Public Transport: yes / no			Identific. Public transport coverage. Uncovered zones, distances
Mapa-Belém-12 pontos.dwg	High bicycle use Points- survey	2011	UNAMA, UFPA	Attractors: Hot spots bicycle-bus integration
Limite de bairros	Neighborhoods	2009	UNAMA, UFPA	Reference map,
Rede de transporte publico	Public transport routes by company	2009	UNAMA, UFPA	To define coverage and accesibility
Ciclovias e Ciclofaixas	existing cycle paths and lanes	2011	UNAMA, UFPA	Existing infrastructure to be integrated to the new network.
RMB-Porto	City ports	2011	UNAMA, UFPA	Attractors to be connected with the network for Bicycle-Boat transport integration.
RMB.AutoCad	Belém Metropolitan Region	2009	UNAMA, UFPA	Road network, Attractors' Influence Areas definition. Network analysis.
Acidentes RMB RUA	accidents involving cyclists, by road	2010	DETRAN	Most dangerous roads for cyclists, need to instal or Upgrade infrastructure
Areas da Região Metropolitana de Belem	municipalities, islands, population, area, building units, lots	2008	CODEM	Reference map, Population, density
Areas do Municipio de Belem	(by Neighborhood) population, area, building units, lots	2008	CODEM	Reference map,
Mapa Belém	Administrative districts, Tax sectors, Neigborhoods	2008	CODEM	Reference map,

DETRAN: Departamento de transito do estado do Para; **CODEM**: Companhia de Desenvolvimento e Administração da Área Metropolitana de Belém
UNAMA: Universidade da Amazoni **UFPA**: Universidade Federal do Pará

5.3. Assessment Criteria Selection

In a given city it is possible to find many factors and stakeholders views that influence the degree of suitability to build cycling infrastructure in a road. For instance, the municipality budget can force changes in the design regarding to length, specifications, protection elements and even the selected routes. Also nearby residents and commercial premises owners and private or public transport drivers may feel affected by such infrastructure. Also, different aspects like terrain slope, roads and traffic conditions, land use, ecological based constraints, population density and income, among others, may determine the overall usefulness of a cycling facility according to the road where it is allocated.

The flexibility of the proposed methodology allows including the relevant factors by formulating them in a proper way to serve as input for the analysis.

Thus, based on the special local conditions influencing the cyclists' behaviour at Belém identified during the fieldwork (local knowledge, own experience) and the available dataset, the following attractors, factors and constraints have been selected to be included in the analysis.

5.4. Bicycle Trips Attractors

As mentioned in chapter 3, the methodology will be based on the key bicycle trip attractors and its influence area. After informal interviews with local people and discussions especially with Dra. Maisa Tobias, at Universidade Federal do Pará, previous ideas about popular attractors described in literature had to be reviewed and the more relevant for the local context were considered. For sure there must be many places that can be considered as bicycle trips attractors within the city and, the more are included in the analysis the better the result that could be could be expected; however due to the data availability and time constraints only a few were selected, seeking a evenly distribution over the study area. So, the attractors identified at Belém can be grouped in two classes: Points with current/potential high demand of cycling (Markets and Universities), and attractors related with multimodal integration (Fluvial ports and Main bus stops). Below is a description of each one.

5.4.1. Markets & Fairs

The highest amount of bicycle trips made in the city is concentrated inside of each of the three homogeneous zones in which the city has been divided in, based on management and research purposes that can be seen in the figure 12. Around 97% of the trips originated in the central and expansion areas are short and local, i.e. trip destinations are inside of the same area. For the transition area this figure is a little lower: 75% (Viana, 2003).

A high portion of these intra-zones bicycle trips actually occur near local markets or fairs, where all kinds of supplies are sold. There are around 20 big markets spread over the city, varying in size and importance, with an intense daily activity throughout the year.

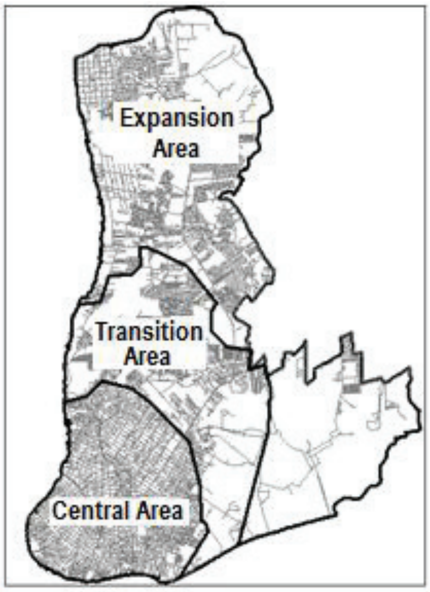


Figure 12 Belém's homogeneous zones division

The main purpose of the trips made within the surroundings of such markets is for errands for formal and informal businesses. (Fig 13) It is possible to see the bikes carrying any sort of products along the crowded streets.

Figure 13 Bicycle use for errands and delivery in markets and fairs

For such bicycle trips a 10 minutes ride can be assumed as the mean travel time since the narrow and crowded streets affect the cyclists' mobility and most of the trips are within a network distance of 1 Km. from each market. (Viana, 2003)

Based on this special current bicycle use distribution in the city, the approach to find the better location for a cycling network should include such high bicycle use zones. Influence areas will be demarcated in a kind of high bike use suitability map.

5.4.2. Universities

Due the specific local conditions of Belém (ranging from weather conditions, safety and travel distances to population income and motorcycles prices) universities do not attract as many bicycle trips as expected.

However, in a more generic approach intended to fit in different cities, educational institutions are important attractors of bicycle trips (estimations indicate bicycling involves approx. 15 to 30% of trips to schools and remains at 10 % year round near college campuses (Huber, 2003)), and should be taken into account when designing cycling networks. With this in mind, and the possibility that the existence of cycling infrastructure encourage people to use them, Belém's major universities and their catchment areas will be used to generate an attractors based suitability map.

Major universities were selected based on the amount of enrolled students, as can be seen in the table 4 below, which shows 2008 higher education census data. Universities were georeferenced and a network distance of 3 Km was used to define its influence area. This distance was selected based on the of the study on characteristics of Belém's bicycle users (Viana, 2003), which concludes that this is the mean distance of the cycling trips made on the city with educational purposes.

Table 4 Belém's Major Universities

Acronym	Name	Enrolled Students
UFPA	Universidade Federal do Pará	31,069
UNAMA	Universidade da Amazônia	13,172
UEPA	Universidade do Estado do Pará	12,141
CESUPA	Centro Universitário do Estado do Pará	4,339
FACI	Faculdade Ideal	3,917
ESAMA	Escola Superior da Amazônia	2,779

Source: Censo da Educação Superior 2008, Ministério da Educação, Brazil.

5.4.3. Fluvial Ports

The integration of cycling with other forms of transport within the city is considered an important goal for the short and medium term transport system development, so, for the present study some fluvial ports were identified as attractors that should be accessible through the cycling network and will be included in the analysis.

Actually, through Belém´s ports many workers come every day from the nearby islands where there is no public transport at all. A portion of these workers make the first stage of their trip by bike in their islands; then, carrying their bikes by boat they reach the city ports in a second stage, and finally they ride from the ports to their workplaces. A proper cycling infrastructure will also encourage those workers from the islands that make use of public transport in the last stage to switch to cycling since is a cheaper way offering a door to door trip. In figure 14 images of the described on boat stage of the trip can be appreciated.

In table 5 are the number of passengers registered on the greater movement days in selected dates both in low and high seasons (July and September, respectively). Such ports are the points of embarkation-disembarkation of passengers whose origin or destination are the islands of the region and where potential users are concentrated as previously mentioned.

Table 5 Counts of passengers arriving to Belém’s ports, for greater movement days in low and high seasons.

Port	Num. Of Ships	Capacity	Passengers	Start	End
Icoaraci					
20/07/2008, Sunday	145	12.228	10.807	06:40	18:26
23/07/2008, Wednesday	54	4.828	4.096	06:50	18:30
25/07/2008, Friday	72	5.92	5.237	06:45	18:27
6/08/2008, Wednesday	43	3.65	2.558	06:53	18:50
10/09/2008, Wednesday	29	2.4	1.342	06:58	18:30
Porto da Casa Silva					
23/07/2008, Wednesday	26	1.4	166	09:25	18:30
10/09/2008, Wednesday	26	1.3	291	06:39	18:35
Porto da Palha					
25/07/2008, Friday	68	3.4	644	06:00	17:50
9/09/2008,Tuesday	37	1.85	460	06:30	18:25
Porto do Açai					
23/07/2008, Wednesday	21	1.05	147	06:38	18:20
Praça Princesa Isabel					
20/07/2008, Sunday	53	1.654	960	08:00	18:34
7/08/2008, Thursday	59	2.95	868	07:45	18:27

Source: D-Fluvial Project – Relatorio Final (2007b)

Source: M. Tobias

Source: M. Tobias

Figure 14 Current integration of bicycle and-boat transport at Belém

These ports were then georeferenced and their catchment area was defined based on a network distance of 4 Km, pointed as the mean distance travelled by cyclists for work purposes in the Viana (2003) study. Even the highest passenger's movement is registered on Sundays, having in general different motivations like food suppliying or religious activities, the potential bicycle users coming from the islands on weekdays are the main target of the multimodal integration plan and almost all of them come with work purposes. They are usually headed to main secondary type of work places like industrial zones, which, given the configuration of the city, fall into the influence area defined by the 4 Km distance.

5.4.4. Hot Spots -Main Bus Stops-

Regarding to the main bus stops, a research, aiming the development of a methodology to implement cycling systems integrated into the public transport in Brazilian cities, is currently being developed with Belém as one of the case studies (Tobias, 2011). As part of these results, main convergence points of traffic flows were identified, (i.e. places where high public transport demand and large concentration of bicycle use was empirically observed). Consequently, in the present study these Hot Spots are considered the most probable Bicycle–Public Transport integration points and therefore potential important bicycle trips attractors.

Hence, the extent of the catchment areas of the hot spots based on the reported cycling travel time and an assumed cyclist's mean speed in the city was defined follows:

The potential users of hotspots as bicycle - bus integration points are those making long trips to work that will look for the hot spots where their bicycles can be safely parked. Probably their homes are far from the main public transport routes like the Av. Almirante Barroso, where buses leading to the farthest points of the city are available. So, the bicycle is a good option for them

The average travel time calculated to bicycle trips to work and to educational institutions in Belém is around 15 minutes (Viana, 2003). This time is relatively short compared with other cities averages described in literature so, for the first stage in a multimodal trip this can be assumed as the time people would be willing to ride to these special bus stops.

Furthermore, since the majority of the reported mean cyclists speeds in the literature are between 12 and 20 km/h (El-Geneidy, Krizek, & Iacono, 2007) a 12 km/h speed can be safely assumed here given the Belém's roads and traffic conditions, mainly narrow and poorly maintained streets, daily congestion and encroachment in some sectors. So a network distance of 3 Km, (the distance that a cyclist can travel in 15 minutes at a mean speed of 12 Km/h) was used to define the catchment areas of the hotspots.

5.5. Attractors Distribution on the Study Area

As can be seen in the map of Figure 15, the spatial distribution of the selected attractors fits with the characteristics of the city as follows:

- In the central area (Figure 12), where the population density is higher (a population density map can be seen in figure 19), the services, commercial and institutional activities are concentrated and therefore the demand for bicycle infrastructure is higher. The amount of attractors there also demonstrates this fact.
- In the transition area, where the population density is the lowest, there is one hot spot directly related to the meeting point of four major roads connecting to the most distant zones of the city and the neighbouring municipality of Ananindeua.
- The Icoarací district is located at the north of the expansion area. It is a small urban core with medium values of population density, having strong commercial ties with the central area of belém and the nearby islands, so, there is the port with the greater movement of the city and the Icoarací hot spot, where different classes of public and cargo transport can be found.

From such distribution of attractors it is possible to expect the configuration of a cycling network covering evenly the city according to the demand for infrastructure. A further work should include the municipality of Ananindeua, the dense zone at the northeast of Belém, looking for a network integrating the whole metropolitan region.

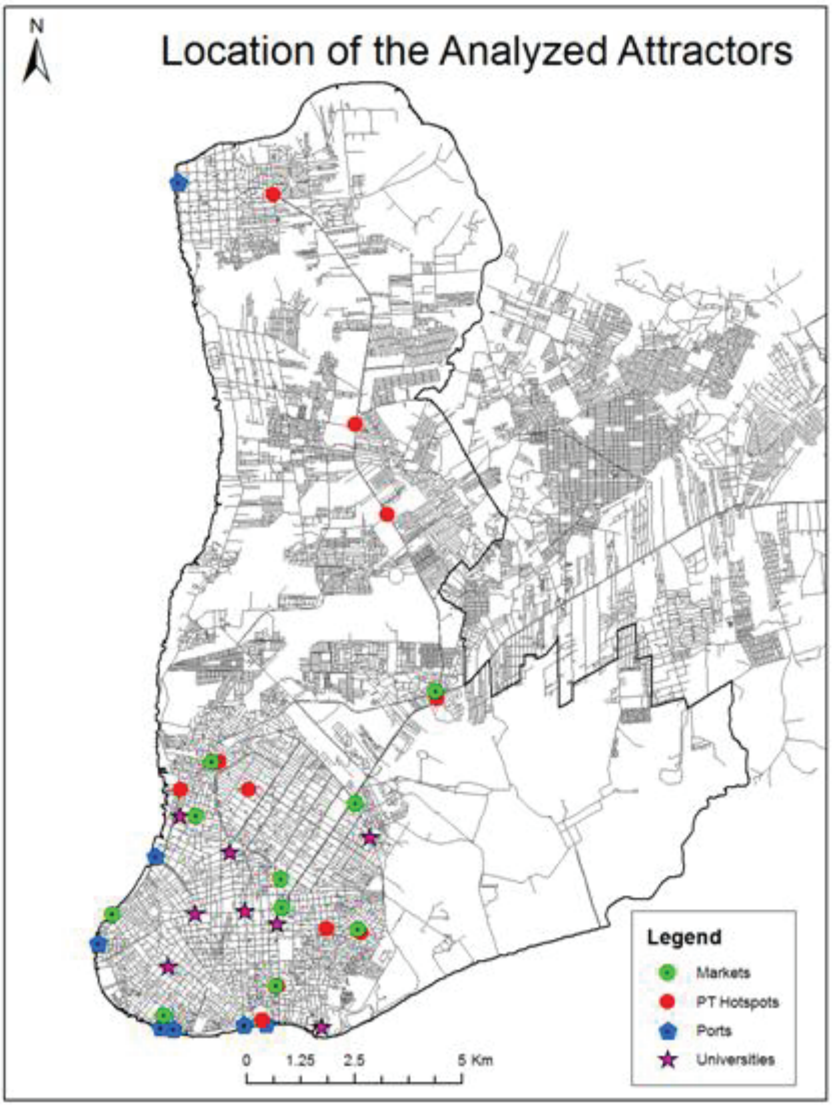


Figure 15 Location of the analyzed attractors in Belém

5.6. Factors

5.6.1. Safety

5.6.1.1. Accidents

From the statistics office of DETRAN, the Brazilian transport administration institution was possible to obtain records on accidents involving cyclists (fatal and non-fatal) within the metropolitan region of Belém for the years 2007 to 2010. The data is sorted by road allowing the identification of the corridors with the worst safety conditions for cyclists. Even can be different causes, it is clear that the absence of cycling infrastructure on such roads is a determinant factor in the occurrence of accidents.

In a general view, in any city where available, this information can be used to identify where a cycle path is really needed or have to be upgraded to better safety standards. The number of registered bike accidents must be proportional to the current amount of bicycle users in a given road, so it can also give us an idea of the demand for cycling infrastructure.

In the case of Belém, the data shows that the amount of fatal and non-fatal incidents is higher in highways where although exist cycling infrastructure it is not clearly separated from the motorized traffic zone, so an upgrading of it would be the recommended action in such cases. In the other hand, collectors and other lower category roads where incidents are also common and there is no cycling infrastructure at all should be considered very suitable based on the user´s safety.

In the map of the figure 16, available in the DETRAN web page, the neighbourhoods with higher number of accidents involving cyclists can be identified. However, the amount of accidents may be an indicator of high demand (many cyclists) and at the same time shows how unsafe for cycling a zone can be. To include this information as spatial factor in the SMCE methodology may be confusing: the same area can be considered not suitable due to safety concerns while if there is high demand of bicycle use should be considered suitable. So, an analysis of the causes of such accidents and their exact locations is needed, which is out of the reach of this study.

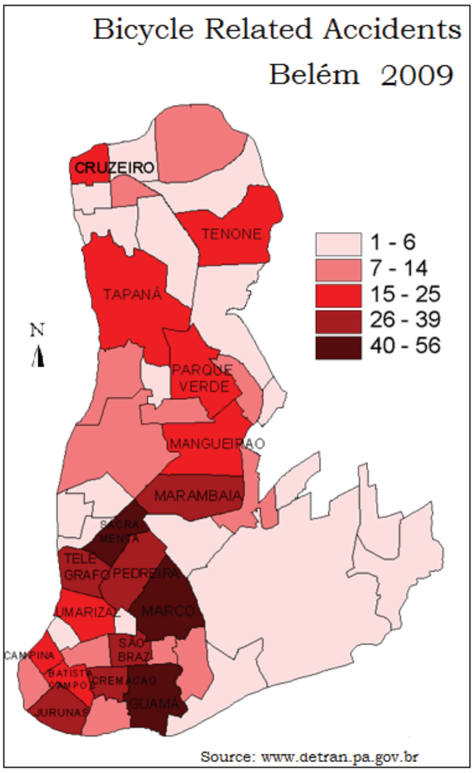


Figure 16 Number of accidents involving cyclists in Belém by neighbourhood.

Since more detailed information on this topic is not available, the practical use of it in this methodology will be to check critical points once a preliminary network has been defined and to identify where bicycle network is missing or needs to be upgraded.

After the suitability definition process, the roads inside such critical areas can be reviewed to verify if they were found appropriate to cycling infrastructure developing, and if not, the routing must be checked to ensure that such zones are properly attended.

5.6.1.2. Street lighting

In many cities, particularly in developing countries, the absence of street lighting is linked to safety in terms of exposition to robbery and with accidents due the low visibility.

Therefore, streets with street lighting can be considered more suitable to build new bicycle lanes considering the aforementioned safety issues and the additional cost of installing this service tailored to new cycling infrastructure.

Consequently, a municipality of Belém's map, where the neighbourhoods where the roads have street lighting are shown will be used as another criterion to prioritize suitable roads for cycling infrastructure development.

5.6.1.3. Road surface

When defining the suitable roads to build cycling paths, the information on the road surface material serve as a decision factor between possible alternatives. Economic factors and user's comfort related issues will influence the decision on the level of suitability of a given road. An unpaved road, for instance will not be appropriated, while if it is paved, the possible surface types will lead to different costs of implementation as well as to diverse levels of comfort offered by the new infrastructure.

For the present analysis, the available information on road surface was included on the road network layer by means of a new field where the attribute of each road is set as 'y' for paved and 'n' for not paved.

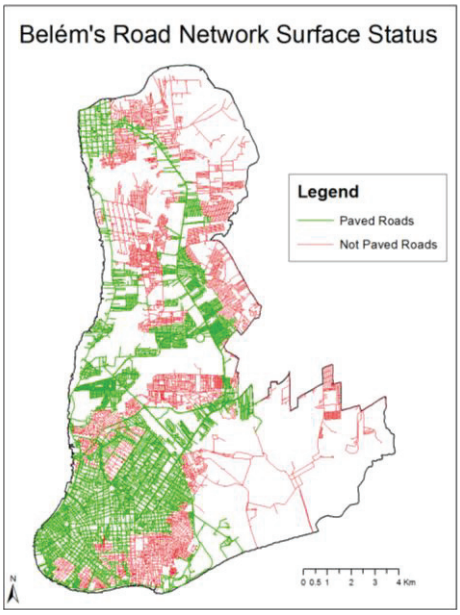


Figure 17 Belém's road network surface status

During the network definition this attribute will be used as a "soft constraint": if inside the identified suitable area there is a not paved road in which the development of a cycling path ensures accessibility or connectivity to the network, the possibility of to pave it should be considered by the city administration.

As can be seen in the figure 17, in Belém there are many no paved roads, so it is very likely to find the situation described above after the analysis. In such cases some recommendations can be suggested to be evaluated by the decision makers.

In a more detailed approach this methodology could be adjusted to include as an attribute of each element the estimated cost of upgrading (if applicable) and use it as an additional weighted criteria when calculating the suitability values.

5.7. Constraints

5.7.1. Ecological

There are some parks inside the city that can attract many people through the year, even bicycle trips. However, the status of native flora and fauna protected area, makes it impossible to build any sort of infrastructure implying a negative impact to this environment.

There are also special protected areas, one at the east side of the city and another at the north (Lago Bolonha and Lago Agua Preta), working as nature and water reservoirs. There of course, any intervention is not allowed. Some parks in the centre and green zones in the transition area are also considered as constraints.

5.7.2. Physical

In the Belém's transition area (Figure 12), there are some institutional land use plots that constitute a barrier for the transport between the north and the south sectors of the city. Indeed, such connection is made only by two major roads: one at the east side, the Av. Almirante Barroso highway and one a little less important road at the west side, the Av. Arthur Bernardes.
Among the institutions in this zone are the International Val-de-Cães Airport, the military airport Julio Cesar, and some military bases, housing towns, and schools.

For the present study such areas are considered hard constraints, i.e. in the short and medium term it is not probable that the construction of cycling infrastructure will be allowed there. Therefore, a map layer containing all these areas was set up to be included in the analysis.

Small rivers and canals inside the city constitute a natural barrier to the development of any linear facility that could force detours in the routes to use the existing road bridges ensuring connectivity to the network. Since the cycling facilities will be built over the existing roads which generally pass through rivers and canals easily, only if the assessment of the developed system shows a specific problematic area the decision on the need of new bridges to improve the connectivity should be considered.

5.8. Processing and Formatting of SMCE Input Data

The software ArcMap 10.0 from the developer ESRI was used for the initial formatting and the road network based analysis, as well as the geoprocessing operations required during the implementation of the methodology.

A new Geodatabase was created and the main files of the study area (road network, neighbourhoods, ports, hotspots, etc.) were imported there, which allow keeping all the information organized to easily run the analysis operations.

Because the available files came from different sources and formats it was necessary to carry out some processes to ensure the proper performance of the tools during the ArcGIS analysis.

Original AutoCAD files were simplified deleting all unnecessary features and then were opened in ArcMap. There the files were converted to shapefiles and stored in geodatabases.

Relevant image files were opened and georeferenced also in ArcMap. For all the maps the projected coordinate system was defined as WGS_1984_World_Mercator and the working area was set to the extension of the Belém municipality.

Validate Topology

To define the attractors influence areas based on the network distance it was necessary to review the available road network dataset adequacy. To do so, the *validate topology* tool was used under the following parameters: Rules: must not overlap, must not self-overlap, and must not self intersect. The existence of dangles was not considered as an error because this would imply that the houses connected by these sections would not be considered part of the studied catchment areas.

5.9. Influence Areas

The *New Service Area* tool from the *Network Analysis* extension of ArcMap was used to generate the polygons representing the influence areas of each analyzed attractor. In table 6 the distances used to set up the *New Service Area* tool and the reason to select it are shown. Mainly, they were established based on the information gathered during fieldwork and in the results derived from the research on cyclists behaviour in the city.(Viana, 2003)

Table 6 Selected distances to define influence areas of the attractors

Attractor	Network Distance Break (m)	Description
Markets	1000	Distance identified as the maximum travelled by cyclists working around popular markets and fairs
Hotspots	3000	Estimated distance people are willing to ride to hot spots, as explained below.
Ports	4000	Mean distance travelled by cyclists for work purposes in Belém. (Viana, 2003)
Universities	3000	Mean distance travelled by cyclists for educational purposes in Belém. (Viana, 2003)

5.10. Attractors Analysis

In data scarce environments (assumption of this methodology) it is not likely to find origin-destination information on cycling. However it is possible to deduce the main possible directions and extends of the cycling trips based on the characteristics of the different attractors, the surrounding land use (Appendix A) and the users expected behaviour. Thus, in this section it is attempted to identify the practical cycling infrastructure configuration inside of the influence area of each attractor type being the Markets, Universities, Ports and Hotspots.

Markets

Coverage

Service areas around markets as mentioned before were delimited based on a network distance of 1 Km; it can be seen in green in the figure 18a.

Users

Typical cyclists around markets are informal workers in a very wide age range that make errands related to formal and informal business at the market. They move through the nearby streets towards commercial areas or to deliver customers' orders at home.

Possible routes design

A cycling road infrastructure distribution that could fit for this kind of users would be radial routes from the market location, evenly distributed, so that any user in the surroundings can reach a facility, and the other way around, any user leaving the market can reach any place in the catchment area easily, which means, taken into account the size of the zone, after a maximum ride of 400 meters. In most of the cases the grid pattern of the streets allows four clear defined radial routes from the market that can be considered in this first stage. Later these routes have to be checked to see that they fit in a larger scale design. In Figure 18**c** an example can be seen where selected roads for cycling are highlighted in purple for some markets' influence areas.

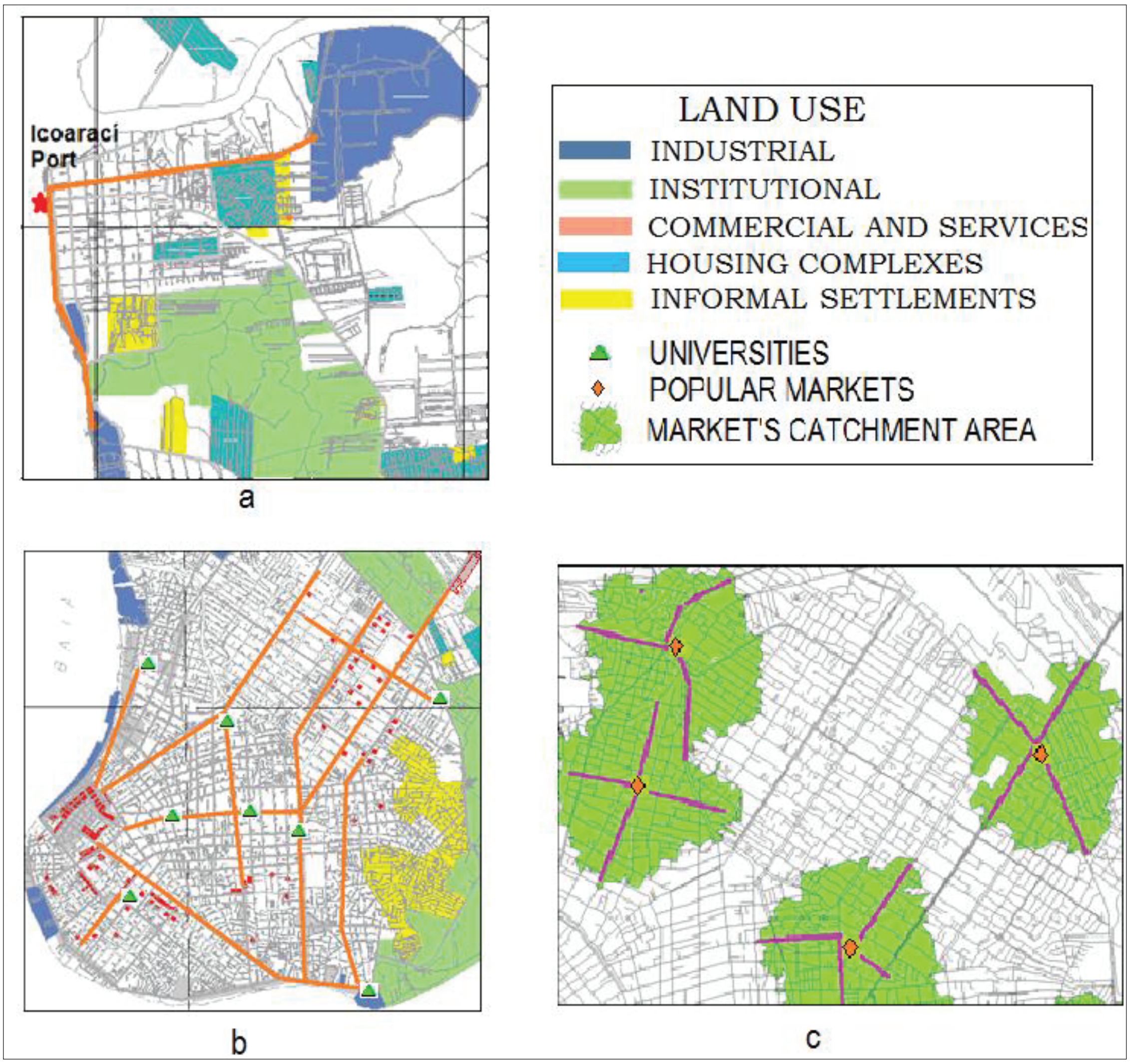


Figure 18 a) Potential routes from ports. b) Potential routes to universities. c) Potential routes to markets.

Universities

Coverage

A network distance of 3 Km was used to define universities catchment areas. Due to the distribution of such attractors inside Belém, their influence area covers entirely the central zone of the city. ("central" refers to the homogeneous zone in Figure 12).

Users

Most of the users aiming to reach these educational centres are spread in the residential zones located in the central area. There are sectors inside these areas where many high buildings have been developed concentrating middle to high income families, which more likely university students come from. Such buildings can be seen as red dots in the maps of figure 19. Most of them are located in regions where middle to high income prevails.

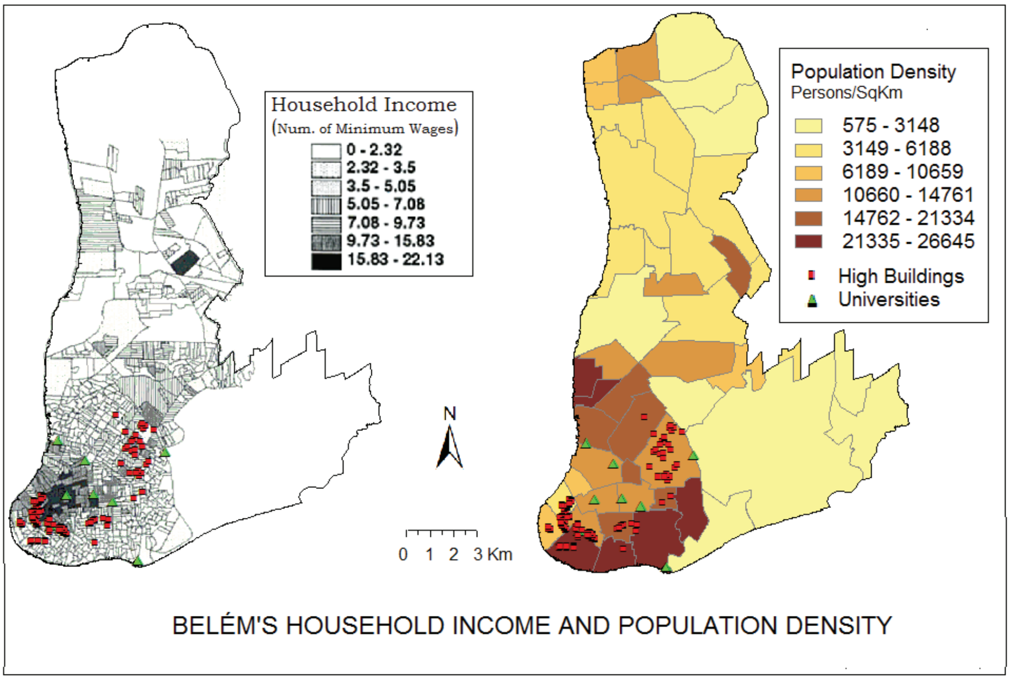


Figure 19 Location of universities and high buildings with respect to household income and population

From these maps is also clear that neighbourhoods with the highest population density have the lowest household income and neither universities nor high buildings are located there.

5.10.1. Design of potential routes

Thus, the potential routes serving these attractors would benefit – and encourage - the highest amount of users if they come from such clusters of buildings and go as direct as possible to the universities, as indicated by orange lines the figure 18 **b**, which is a section of the land use map of Belém included in the Appendix A.

Ports

Coverage
As explained previously, a network distance of 4 Km was used to define the catchment areas of the ports.

Users
Current and potential bicycle users coming through the ports are mainly workers from nearby islands that daily go to the zones where the industrial and manufacturing type of jobs are concentrated.

Possible routes design
Thus, it can be assumed that most of the users arriving at the Icoarací port located at the north west of the municipality will travel to the Icoarací industrial district at the northern end of the city, and some others will lead to the Av. Arthur Bernardes' industrial district, located at around 3 Km. southwards from the Icoarací port. (Industrial districts are dark blue coloured zones in the Figure 18 **a**)

So, for this port, it can be expected that the allocation of infrastructure following the streets highlighted in orange in the map in Figure 18 **a,** will benefit the largest amount of users.
Following the same reasoning, workers arriving through the ports located south of the city centre will probably lead to the small industrial areas at the neighbourhoods Condor, Guamá and Umarizal, near the downtown area. Those arriving through ports on the west side could also lead to the Av. Arthur Bernardes' industrial district aforementioned. From this assumption it is possible to focus in some corridors within the influence area which more likely will be used.

Hot Spots

Coverage
The influence area was defined by a 3 Km network distance from the hot spots, as shown in figure 20.
Users
Potential users interested on bicycle-Bus integration for their daily transport are those making long trips to work and who will look for the hot spots where their bicycles can be safely parked. Their homes are far from the main public transport routes so cycling would be more attractive than walking for them.

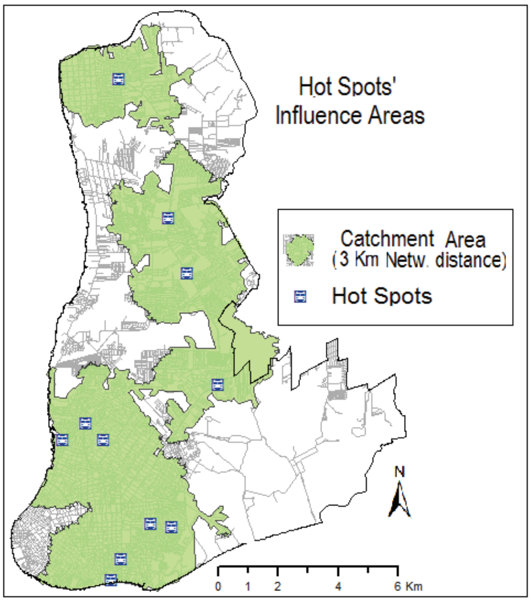


Figure 20 hot spots' influence areas

Possible routes design
So, an approach to roughly identify most likely travel corridors can be consider the densest populated regions as origins and a combination of secondary streets as routes to these attractors.
As can be seen in the map of figure 21, in the central area of the city and in the north district of Icoarací, the hot spots are inside the densest populated areas, so a radial pattern evenly distributed could fit there.
In the middle zone of the city there are three hot spots near to high density neighbourhoods where bicycle infrastructure originating from these areas and leading as direct as possible to the attractors will serve the

most users. Analyzing the current public transport routes, the red lines on the map, the zones with more population density are less served. As has been noticed before the poorest households are located there, and the roads width and condition must influence the decision of the transport companies not to plan routes there. Therefore, the potential bicycle routes as sketched in orange in the figure 21 will also benefit those in needs.

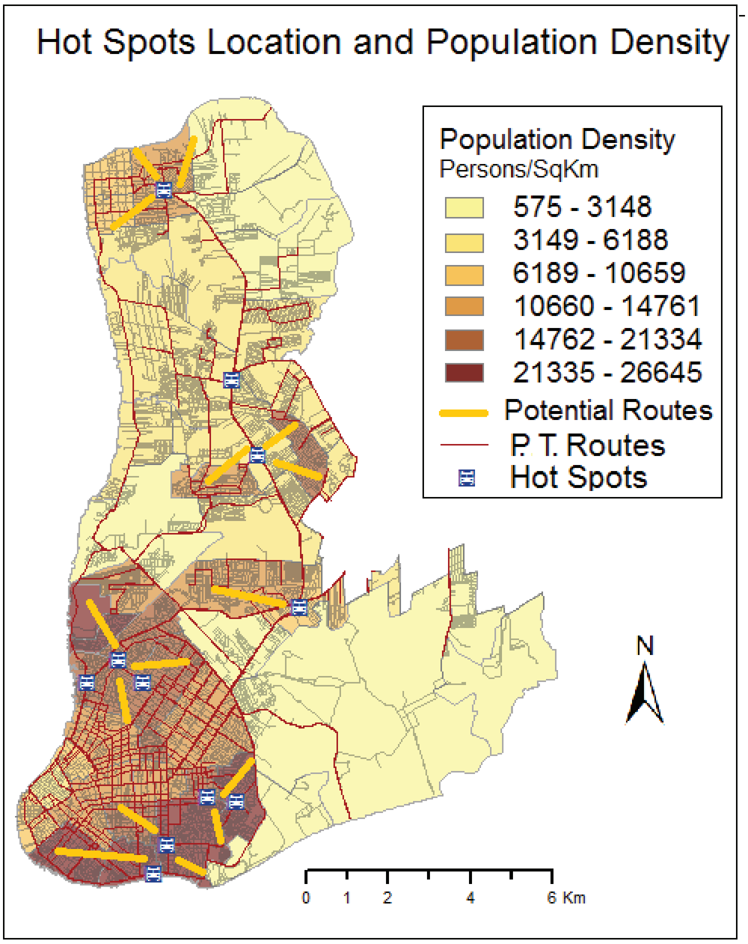


Figure 21 Hot spots location regarding to Population Density

This first exercise inside the catchment areas of each attractor gives a basis to consider some routes as potentially more useful for cyclists according to their origins, always looking for those locations that will benefit the highest amount of people.

Furthermore, from this exercise it was possible to get an idea of the origins of the trips where the most users likely will come from according to their destinations. For instance, fluvial ports can be seen as the origin of bicycle trips to working places like specific industrial districts in the city. The centroids of medium-high income neighbourhoods where high buildings predominate can be considered the origin of most of the bicycle trips to universities, and in general, a rough assumption can be made, aiming to benefit the greatest amount of people, in which the centroids of the most densely populated residential neighbourhoods inside the catchment areas of the attractors would be considered the origin of most of bicycle trips to the hot spots.

These assumptions will be used in the further analysis phase when origin and destination points have to be defined to solve the least impedance routes.
In a second stage the analysis is conducted on a larger scale, taking into account the combined influence areas of all the attractors. The overlapping of such areas will indicate the regions where the presence of cycling infrastructure can be tapped by users with different trip purposes.
The steps followed to perform this analysis and the results are described in the next section.

5.11. Spatial Multi-criteria Evaluation SMCE

5.11.1. Introduction

To perform this phase of the analysis it was decided to use the SMCE module of the ILWIS 3.3 software, for which the outputs of the previous ArcGIS process had to be prepared to be ready for use.
Firstly, after the *new service area* tool operation the polygon layers representing the influence area of each attractor were converted to raster format and exported to ILWIS. A cell size of 50 m was defined to work with due to the presence on the city of wide highways where possibly cycle lanes in both directions could have a separation of more than 30 m. Thus, it is assumed that the identification of a road as suitable after applying this methodology implies cycling infrastructure implementation in both directions.

Once all the maps were opened in ILWIS, by the Spatial Multi-Criteria Evaluation tool under the Raster Operations menu, a new criteria tree (Figure 22) was created and the raster maps of each attractor were aggregated and standardized.

A first attempt was made just with the attractor's catchment areas, assigning to each one the same weight, as can be seen in the figure 23.

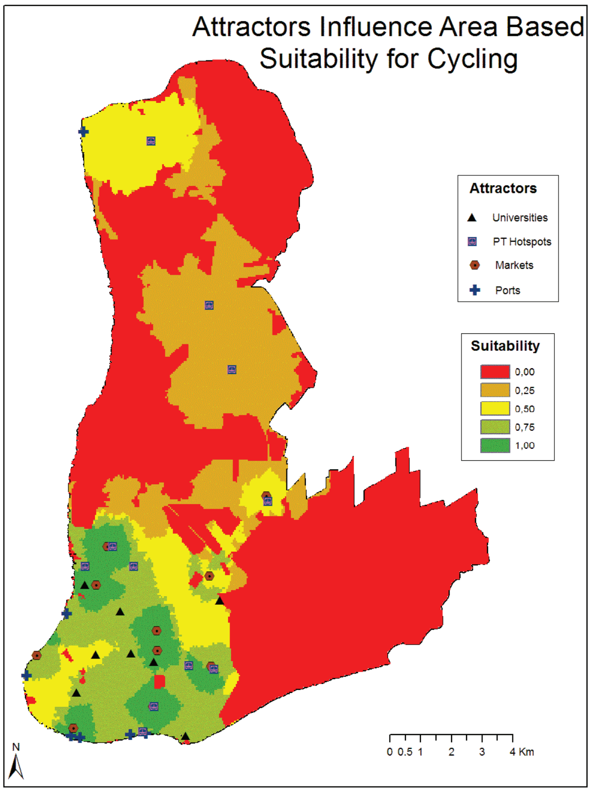


Figure 23 Suitability for cycling map based on the selected attractors.

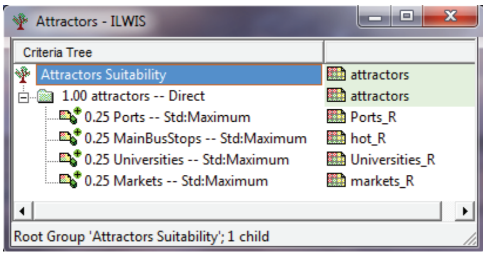


Figure 22 Ilwis Criteria Tree for

The map on figure 23 gives us a first general picture of the demand for bicycle infrastructure based on the selected attractors' influence areas. As the green and dark green colours highlights, in the central area of Belém this demand is higher. As mentioned before, there are very few cycling infrastructures in this zone, so the analysis must be carried out carefully to determine the routes that more efficiently will serve the users here.

Since in the northern half of the city there is not many overlapping of the catchment areas of the attractors the inclusion of other factors will give more insight on the appropriate distribution of the demand.

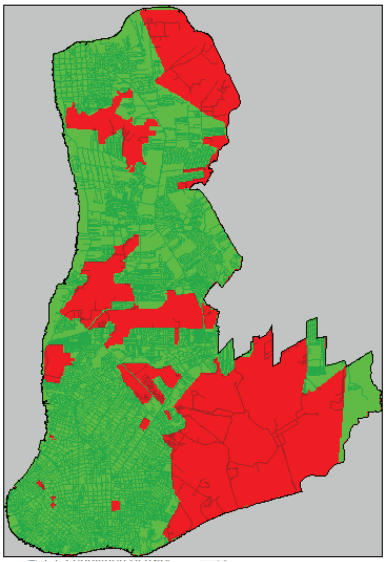


Figure 24 Combined constraints preliminary map

5.11.2. Constraints

The map on Figure 24 shows in red all the places that are considered strong constraints to the development of cycling infrastructure. As mentioned before, parks, ecological protected areas, and institutional land use zones like airports and some others belonging to the military forces are not likely to be intervened; therefore all were excluded of this analysis.
As the superimposed road network layer shows there are very few, if any, roads inside the red polygons in the figure. Mostly they are small not paved roads developed many years ago, before the enactment of environmental protection laws.
As strong constraints, in this analysis red areas value will be zero (0) while green ones will be one (1).

5.11.3. Existing cycling infrastructure

To include Belém's existing cycling infrastructure in the analysis in such a way that the connectivity with the new network can be somehow "promoted", a distance map was produced in ArcMAP from the existing cycle paths shapefile. In such map the pixel values decrease proportionally to the distance to the cycling lanes. After exporting it to ILWIS, as part of the Spatial Multi-Criteria Evaluation process, the standardization was defined as shown in figure 25.

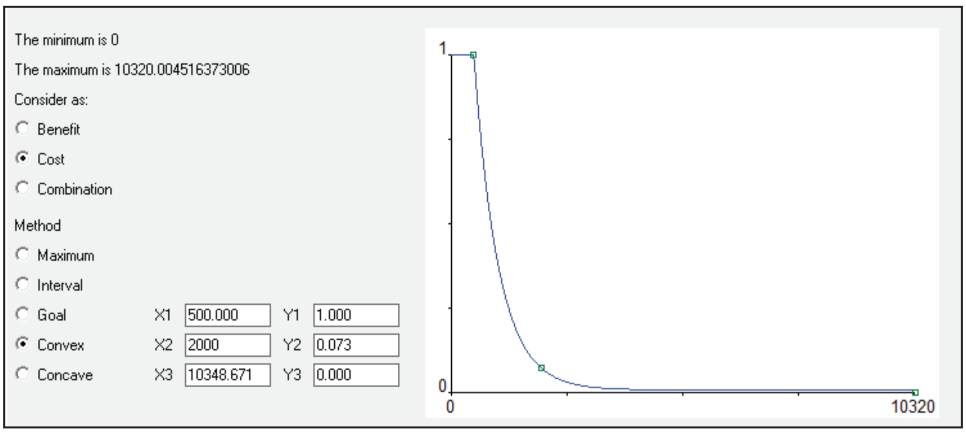


Figure 25 Standardization used for the existing infrastructure map

So, areas within a distance of 500 m from existing facilities will score the highest value while the score will decrease significantly from 500 m onwards, as the convex shape of the graphic indicates.

Figure 26 shows the resulting map after the standardization described above, the existing infrastructure and the values that each pixel will score during the analysis. The boundary of the municipality was included as reference.

By including such map in the analysis, the closest areas to existing lanes (and therefore the roads) will have an extra suitability score. However, a final review of each existing cycle lane must be performed to ensure integration with the new network.

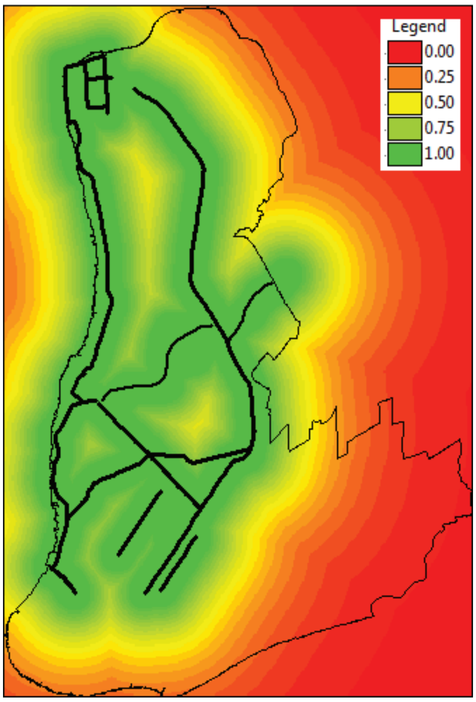


Figure 26 Distance to existing cycling infrastructure suitability map

5.11.4. Population Density

Except for the ports, the residential areas are expected to be the origin of the bicycle trips in the city, so, it is possible to assume that the design that will benefit the highest amount of people is that connecting the neighbourhoods with the top population density.

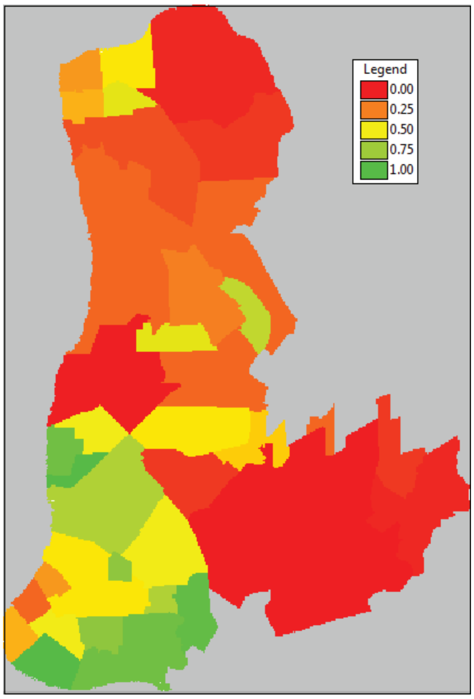


Figure 27 Population density based preliminary suitability map

As noted before the poorest neighbourhoods are among them, so, to consider this factor in the methodology, it has to be taken into account the equity concerning the infrastructure provision.
To do so, a population density map by neighbourhood was developed in ArcMap, rasterized and exported to ILWIS. After the respective standardization, the map of figure 27 was obtained.

As it can be seen, the residential neighbourhoods where the population is concentrated are located in the south and northwest parts of the central area of Belém.

5.11.5. Weighting

Through weighting process, the priorities of the different stakeholders can be emphasized. Even the basic principles of bicycle network design can be taken into consideration.

For instance, from an equity point of view, to provide infrastructure that benefits people from the poorest neighbourhoods can be more important than ensuring accessibility to universities, for which medium and high income people are expected to be the main beneficiaries. Or the integration of bicycle and public transport in the city can be considered a not very realistic goal in the short term due the new investments, policies and educative campaigns that such initiative implies, so a cycling network connecting the ports of the city may be more practical given the current amount of people that make use of them. On the other hand, economic factors like the costs of upgrading unpaved roads or providing street lighting may be important when deciding on allocating a budget for infrastructure provision.

With this in mind, and with the aim of showing the flexibility of the methodology to evaluate different alternatives that could support decision making processes, three 'visions' were assumed as the possible concerns of different groups of people interested in the project, namely Social, Promotion of Cycling and Multimodal Integration. Thus, three suitability maps were produced by assigning different weights to the factors and attractors considered in the SMCE process to each vision.

In the first one, **Social**, the existing facilities got a high weight due to the importance of integrating it with the new network, followed by the social factor score representing the inclusion of the densest and poorest neighbourhoods.

The next highest value was for the attractors, where a slightly higher weight was assigned to the markets and hot spots taking into account that the their expected number of cyclists will be higher than those going to universities and ports.

The soft constraints group including pavement and street lighting got the lowest score which means that the absence of such items is not so critical, i.e. only if many people will benefit, this will be worth the upgrading investment.

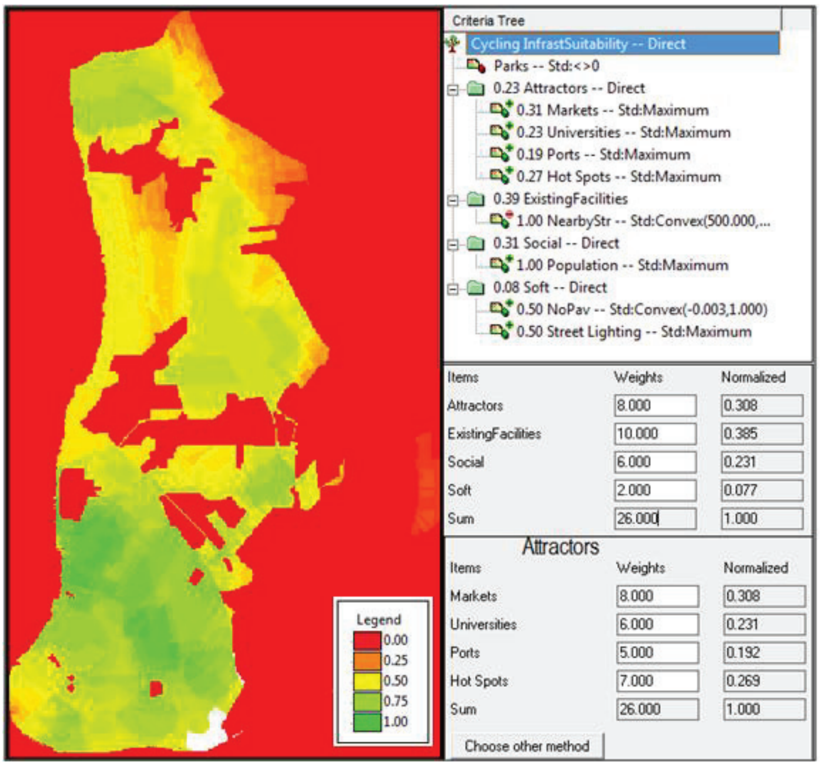


Figure 28 Suitability map for Social vision and assigned weights

The suitability map, the criteria tree and the assigned scores for the Social vision are shown in figure 28.

The integration of existing cycling infrastructure is a main objective of this methodology, therefore, the second vision, **Promotion of Cycling**, has also gotten the highest weight. Among attractors, universities and hot spots are prioritized aiming to promote the bicycle use among groups of people that, although they are seen as having a great potential, currently cycling is not very popular.

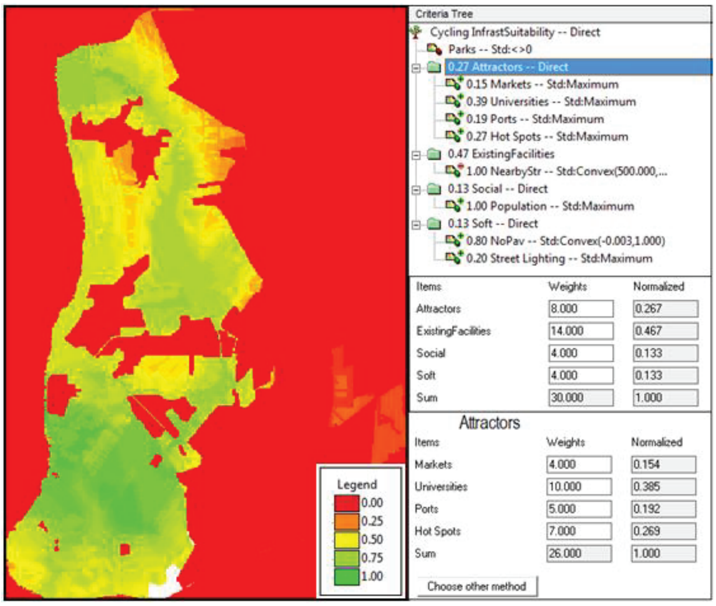


Figure 29 Suitability map for Promotion of Cycling vision

Among the soft constraints, more importance is given to the existence of pavement due the high costs that the upgrading of such roads can imply.. The suitability map and the assigned weights for this vision are shown in Figure 29.

In a third vision, the **Multimodal Integration** of the public transport is the main concern, so the ports and hot spots got the highest scores and the group 'attractors' and 'existing facilities' are prioritized in the general weighting, as can be seen in figure 30 below.

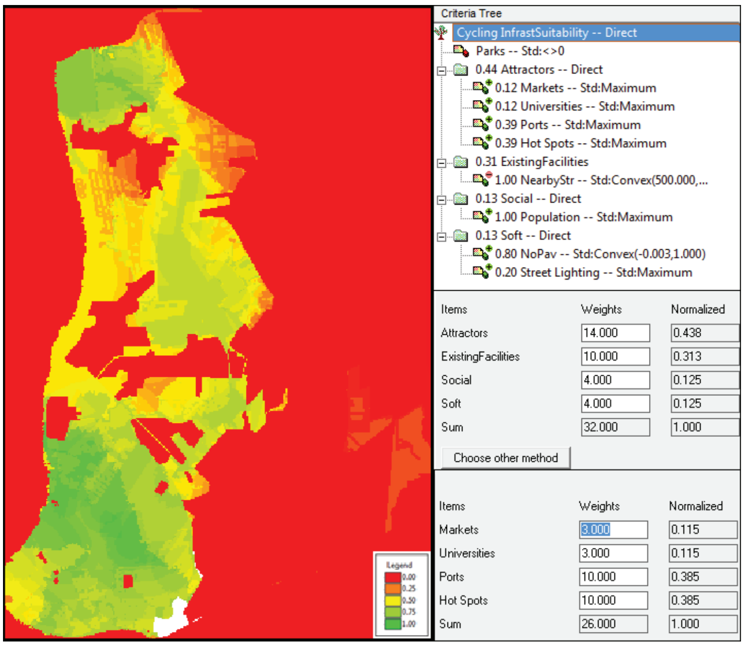


Fig. 30 Suitability map for Multimodal Integration vision

As can be seen in the previous maps the differences between them cannot be easily appreciated. It is likely that by including additional localized factors or stronger stakeholders' visions in the analysis the suitability values distribution can show identifiable different trends. However, by the use of a tool that is described in the next chapter, the road segments can be prioritized based on their respective suitability, inherited proportionally from the corresponding raster maps' pixels.

5.12. Network Analysis

Once the road network is overlapped with the suitability maps obtained in the previous stage, it is possible to visualize the streets where the provision of cycling infrastructure will produce better results. An ArcGIS tool that allows assigning proportionally to each road segment the suitability value of its underlying raster cell will be very useful in this part of the analysis. Such tool is called the Line Weighted Mean (LWM) that is under the Line Raster Intersection Statistics menu in the "Hawth's tools" extension. This is an open source extension designed, according to its author, "to perform spatial analysis and functions that cannot be conveniently accomplished with out-of-the-box ArcGIS" (Beyer, 2004). A version that is available for ArcGIS 9.3 was used here.

In brief, the Line Raster Intersection Statistics operation is as follows:
The input is a line layer (the road network in this case) and any number of raster layers representing continuous data (the different suitability maps).
The output is a statistical summary of the raster data along each line written to the new fields created purposely in the line attribute table. In this case only the LWM was calculated which is based on the next formula:

$$\text{Line Weighted Mean } (LWM) = \frac{\sum_{i=1}^{n} (l_i \; v_i)}{L}$$

Where, l_i is the length of a segment i,
v_i is the suitability value of the raster cell underlying that segment, and
L is the total length of the polyline of which this segment forms part.

5.12.1. LWM calculation

The three suitability raster maps and the road network file were stored in a new geodatabase to run the described LWM application. And excerpt of the resulting attribute table containing the calculated LWM values for the three visions is shown in the table 7 below.

Table 7 LWM values for the three visions

OBJECTID *	Shape *	Shape_Leng	Shape_Length	social_LWM	Promot_LWM	multim_LWM
1	Polyline	170.453601	170.453588	55.57598	56.093966	56.57598
2	Polyline	143.733001	143.732936	46.033218	54	53
3	Polyline	97.898406	97.898418	46.03789	53.674914	53
4	Polyline	64.297674	64.297621	44	51.406226	51
5	Polyline	61.428343	61.428309	45	52	52
6	Polyline	57.618803	57.618724	47	55	54
7	Polyline	119.325989	119.326025	47	55	54
8	Polyline	52.442555	52.442578	45	53	52
9	Polyline	60.358248	60.358161	47.079775	55.924019	54
10	Polyline	72.116634	72.116608	58	61.007508	60
11	Polyline	141.065329	141.065328	56.634838	61.25034	59.639089
12	Polyline	103.667058	103.666996	58.661575	61.661575	60.661575
13	Polyline	115.824325	115.824285	57.540542	63.531405	60.540542

1 (0 out of *2000 Selected)

A road map like the one shown in figure 31 was then obtained for each vision and the layer with the existing infrastructure was superimposed, so, their relation with the suitability values of the roads can be appreciated. In general, the current cycling network's coverage in the north of the city is better than that on the transition zone, where east-west links are missing as well as some branches in the direction of other suitable zones. At the central area, on the contrary, there are many demand and suitable roads but very few infrastructure. So, this zone requires a more detailed analysis, which is carried out below.

5.12.2. Routes Analysis

Since a proper network must follow the least cost path to connect origins and destinations it is necessary to invert the obtained LWM values for the three visions by subtracting them from 100 (suitability values rank from 1 to 100), in this way road segments showing the highest suitability values will have the lowest cost or impedance scores during the analysis as can be logically expected.

Thus, the values of each segment of the road layer, for the three visions, were calculated and used to define the impedance attribute during the set up of the ArcGIS' build network command.
In order to find the least cost routes by the ArcGIS' network analyst tool it is necessary to define the origins of the trips. As mentioned before, the identified most likely origins of the bicycle trips were located as follows:

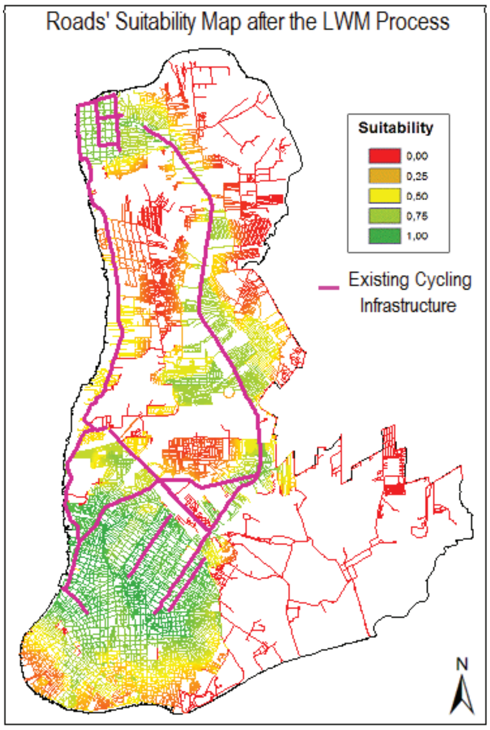


Figure 31 Roads suitability map after the LWM process

- Centroids of medium-high income level zones where modern high buildings prevail, as origins of trips to universities.
- Centroids of the more dense populated neighbourhoods, as origins of trips to hot spots.
- Ports and Industrial districts can be considered either origins or destinations of bike trips if we consider the morning or afternoon travel flow of workers. Here, the industrial districts were considered the origins although there is no difference in the results.
- The small catchment areas of the popular markets and the continuous bicycle trips inside them makes it difficult to identify specific origins to analyze. Also it is clear that it is not likely to build infrastructure inside the influence areas of all the markets but rather to consider to prioritize those which routes are shared with users leading to different attractors. This fact was actually considered during the SMCE process when the proper weight assigned to market areas strongly influenced the calculated suitability values, so they will not be considered here as origin destination couples like in the other cases. At the end, the resulting routes will be checked against the markets' catchment areas and, if necessary, the distribution of the new infrastructure can be adjusted.

Once the origins were selected based on the criterion to serve the highest amount of people, they were added to the roads suitability map together with the attractors and the existing facilities to identify the big picture and draw the first conclusions. As mentioned before the analysis will be focused in the central area of the city.

As can be seen in figure 32, there is a transversal strip with high suitability values connecting or passing close to different attractors. At the middle of such strip is the avenue Canal do Galo (highlighted in red) that goes along the canal of the same name, first southwards an then to the southeast where, in addition, two existing lanes come to end, and a little beyond, following other streets, there are two hot spots and one of the selected origins. So, there are good reasons to consider it as an element of the new network.
Another finding of this first review is that by prolonging some existing bike lanes over suitable roads (the blue segments in figure 32) it is possible to reach other attractors while the overall connectivity, directness and coherence is improved.

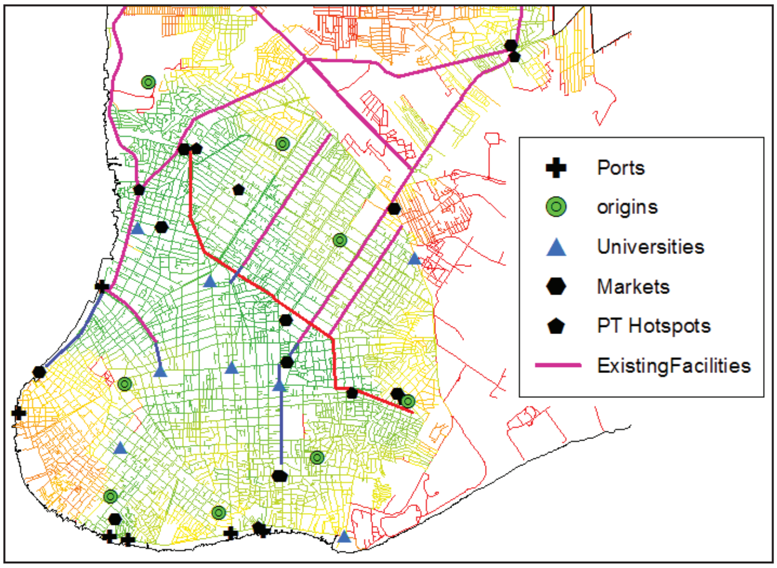


Figure 32 Potential routes identified after the first review of origins and attractors over the road´s suitability map.

5.12.3. Optimal Routes

Since it is necessary to deal with many origins and destinations in this situation, a tool showing the true shape of the optimal calculated routes drawn over the road network is needed to easily visualize and define the cycling network. For that reason, it was decided to use the *New Route* tool and to select some of the origins and destinations to run it for the different visions after the setting of the respective impedance and accumulation parameters.

Regarding to the universities location, the routes connecting the two origins with the outer universities creates a central network that can be used to connect with the four inner universities (circled in red in figure 33) easily, therefore, the figure 33 shows the optimal routes to this attractors.

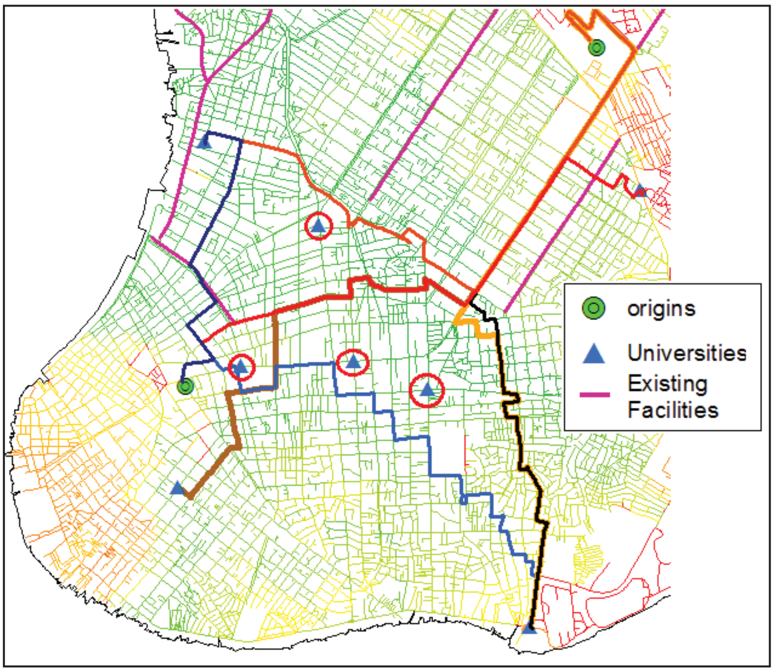


Figure 33 Optimal routes to universities under the different visions

As can be seen, many routes overlaps along some sections wich indicate the more appropriate roads to form the network. The routes coming from the northern origing follow the route of an existing lane showing that is well located to the kind of attractors studied. The potential road identified in the previous first review along the Canal do Galo avenue is also confirmed here as optimal.

Hot spots and Ports

At this point, three of the assumed more likely origins of trips to ports were selected consisting of centroids of industrial land use zones. It was assumed also that workers will arrive to the ports that are closer to their workplaces, so, there will not be very long routes. Thus, the routes analyzed were those from the origins to their nearest ports.

It is assumed also that routes to hot spots may be longer, since people will look for the hot spot where the offer of public transport routes are useful for them, which is not always the closest one. So, routes to different hot spots were calculated.

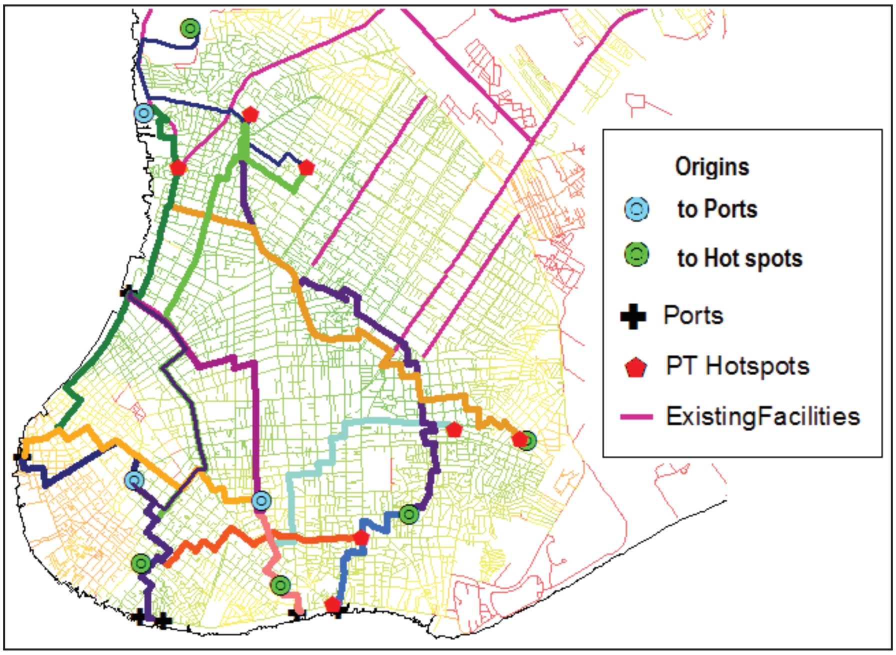


Figure 34 Overview of calculated optimal routes to Hot spots and Ports

As figure 34 shows, the overlapping of routes is clear in the same canal road of the previous figures, confirming the usefulness of such route. Also, the dark green route connecting two ports at the west side of the city is the prolongation of an existing cycle lane mentioned before, so it will be part of the network.
As a result of the grid pattern of the road network, sections of the routes between some origins and destinations shows a zigzag pattern which is not really appropriate for a bicycle lane since the users' comfort, among other issues, can be compromised.

Since the aim of this methodology is to identify potential routes, in such cases other alternatives may be considered without significantly reduce the overall adequacy of the routes. By replacing the zigzag portions with two or more straight sections, as the red line in figure 35 shows, can be more appropriate.

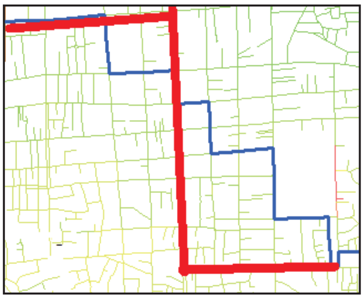


Figure 35 Alternative to improve zigzag sections on potential routes

Given that the objective of a desision making process is not the selection of a design derived from just one vision but a kind of consensus between stakeholders based on the results obtained from desision support tools like this methodology, by displaying all the routes calculated for the different visions in the same map the overal visualisation can help to come to an agreement.
Thus, in figure 36 all the routes, origins and destinations are shown. The catchment areas of the markets are drawn in light green, which allows to see that, as pointed before, many routes to different attractors pass through such areas, in fact very close to the markets and in diferent directions. So, by a proper selection of the routes the markets can also be served.

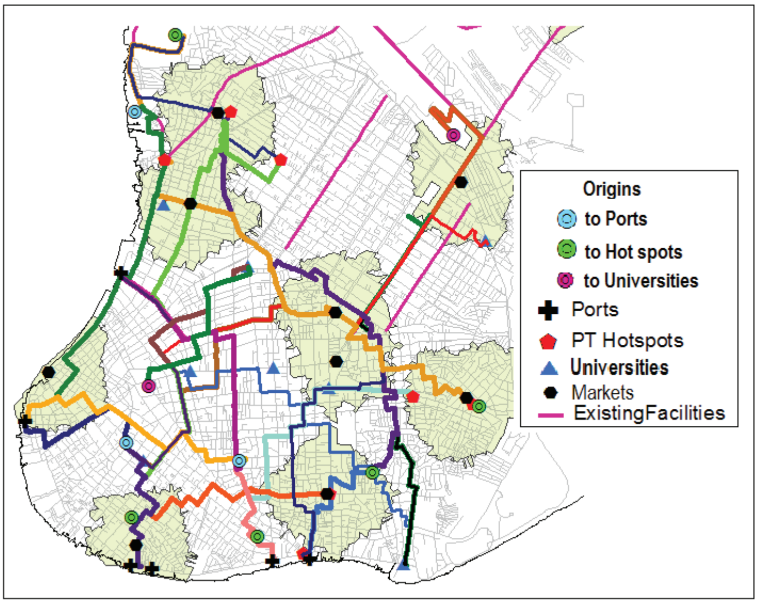


Figure 36 Potential routes for all visions.

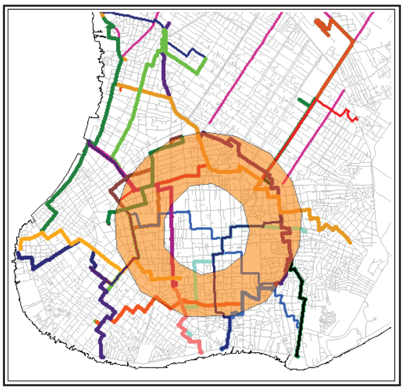


Figure 37 Abstraction of a simplified network shape of the calculated routes.

It can be observed that the distribution of the calculated routes shows a kind of ring shape, highlighted in orange in figure 37, with radial branches towards the ports and other external attractors. However, the mentioned grid pattern prevents the implementation of such shape efficiently so a squarer pattern should be selected.

Also, this is an area of the city that concentrates commercial, social, educational and institutional activities and, as mentioned before, the roads are narrow and in some cases congested. So, a good option that has been used in other cities can be to exclude in some of the identified potential roads the motorized traffic permanently.

Two routes in each of the branches towards the ports can be selected so a continuous and connected network can be drawn while such attractors are covered. Again, the zigzag pattern has to be reduced by the selection of direct routes where possible.

The potential routes obtained through this methodology can serve as a guide to identify the roads that will be part of the final network. After an initial sketch based on the visual analysis of the output and other relevant factors that decision makers could consider, it is necessary to confirm on field the viability of the design.

However, as a final result of the methodology applied in this study case, a proposed new bicycle network for the central zone of Belém was drawn taking into account the following elements:

- The potential routes identified before
- The location of the markets' catchment areas
- The directness of the routes
- The existing cycling routes
- The overall connectivity
- The neighbourhoods with higher accidentality (figure 16)

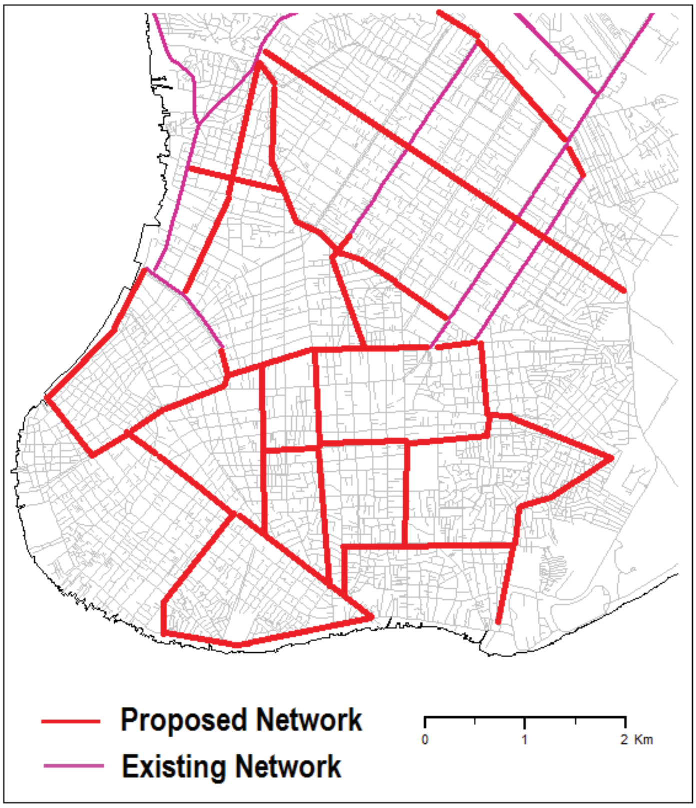


Figure 38 Proposed cycling network

As figure 38 shows, a network of around 40 Km is proposed to be implemented in this area of the city. Even a longer network is always desirable; this design provides a proper accessibility to the considered attractors. As logical, budget constraints have to be also taken into account when defining the extent of the network, so, beforehand, an average cost per kilometre of finished cycle path could be used to establish the possible length of the routes to be designed.

When possible, the densification of the network should start dividing the largest polygons defined here while considering the suitability values found.

6. RESULTS

The objective of this research is to develop a methodology for the evaluation of potential bicycle routes within an urban area, aiming at the optimization of the cycling network design, with the limitation of a data scarce environment as it is the case of many cities in developing countries. In order to deal with this problem detailed objectives and research questions were developed.
On the basis of a literature review a conceptual diagram was developed (Figure 3) aiming at general approach and methodology. Through a case study implementation in the Brazilian city of Belém such methodology was evaluated, so the questions were answered accordingly as follows:

Q1. Which are the main attractors of bicycle trips by purpose (work, education, recreation, tourism)?

Based on the local knowledge and on the characteristics of Belém four main types of attractors were selected to perform this analysis:

1. Fluvial ports: aiming to serve many workers from the nearby islands which bring their bikes by boat every day.
2. Hot Spots: or highly demanded bus stops, where the integration bicycle- public transport has the potential to be developed in the long term.
3. Popular Markets: according to local research in these places and their surroundings a very high bicycle usage has been observed every day. Even there are many markets spread over the city, only the biggest were selected to be included in the analysis.
4. Universities: The biggest universities in the city were selected because they concentrate many potential bicycle users (students and staff) that could switch to this transport mean if the appropriate infrastructure is present.

Q2. Where are the attractors located?

All the selected attractors described above were georeferenced and stored in different layers to enable the subsequent analyzes. They are shown in the map on figure 12

Q3. How can the distances people are willing to ride to the different attractors be defined?

Even literature references can help to estimate these distances, local knowledge is the basis to define it properly because the conditions can vary.
For this particular case it was possible to find a study (Viana, 2003) on the Belém's cyclists characterization in which the mean distances travelled by them, sorted by purpose, are listed. The assumption made is that bicycle users are willing to travel the same distances to reach the selected attractors according to the purpose of the trips.

Q5. Which spatial and non-spatial factors influencing the suitability for cycling can be included in the model?

In a general approach, there is a variety of factors that can be included in this model depending on the data availability and the analysis of the local situation before hand.
In this case, the catchment area of the attractors was the main concern, and the additional factors included were the existing cycling infrastructure, the population density, the pavement condition and the street lighting presence.

Q6. How can these factors be properly formulated in order to be included as input for the analysis?

For each factor it is necessary to build a map in which the attributes indicates the spatial variability of the characteristics to be evaluated.

Q7. Which kind of constraints can be considered and modelled?

Due to the configuration of the city with several protected areas and plots of institutional land use that cannot be intervened, at least in the short and medium term, a layer of physical constraints was developed. So, parks, reservoir areas, airports and military batches were included there.

Canals and rivers inside the city, that in other circumstances could constitute obstacles, were not considered as constraints because the existing road network has overcome such obstacles by bridges and the cycling infrastructure will follow the same paths.

Q8. Where is the existing cycling infrastructure located?

In a given city, administration offices should have at least the as-built blueprints of the existing infrastructure. When this is not possible, other sources can be reviewed: contractors, universities, private institutions, and as a final option, given the time and resources consumption, a survey should be considered.

The map on figure 6 shows the location of the existing cycling infrastructure in Belém. The existence of insulated sections and areas without coverage is evident there.

Q9. What is its current condition?

Some cycle paths constructed recently are in good conditions. The main identified problem is the user's safety in cycle lanes along fast roads. Since one of the main elements defining the quality of a cycling network is safety, an upgrading of such infrastructure is badly needed.

Q10. How can the existing cycling infrastructure be ranked or weighted?

The objective of this research question is to look for a way to integrate the existing cycling infrastructure with the new network ensuring the overall connectivity. The approach used here was to assign a high score in the suitability analysis to those roads near and/or connected to the existing bicycle lanes, by the definition of an appropriate standardization function. As mentioned before, after an assessment of the suitable roads of each section the desired connectivity can be achieved.

Q11. How can the previous items be weighed to perform the analysis?

The weighs of the factors needed to produce the final suitability maps in ILWIS were defined based on assumed visions that prioritize different aspects according to particular interests.

Q12. How can the best possible roads within the suitable areas be prioritized?

The Line Weighted Mean tool used here allows the proportional assignment of the suitability values to each segment of the road network. So, in a first overview, the numerical values of each road indicate its suitability. A second stage is needed to ensure a proper network, i.e. well connected and serving all the attractors in the best way.

Q13. Which indicators can be used to evaluate the network?

7. DISCUSSION

The main aspect in which the methodology described here differs from that found in the literature is the absence of OD data. Most of the literature deals with cities in developed countries where this kind of data is available. Thus, in other environments a detailed analysis of the information is needed to fill this gap when applying this methodology.

Although a data scarce environment was assumed in developing this methodology, the use of additional data on cycling can improve the output by characterizing the users' behaviour, selecting the attractors based on measured demand and establishing more precisely the origins of the trips.

The flexibility offered by the GIS software to include and relate data in different formats and from diverse sources and the possibility to define and weight the evaluation criteria and to combine it in a spatial way through the SMCE process allows the use of this methodology in different cities. Local knowledge and basic information usually available from city's administration offices are the basic inputs.

8. CONCLUSIONS

This thesis describes a methodology for the evaluation of potential routes within an urban area aiming the optimization of a cycling network in a data scarce environment. This approach includes a GIS based Spatial Multi-Criteria Evaluation process in which key bicycle trip attractors and their catchment areas along with other relevant spatial factors affecting the suitability for cycling are taken into account to identify the most adequate roads for cycling infrastructure provision.

An aspect included here that hardly had been considered in bicycle network design methodologies is the existence of previous infrastructure, which promotes the overall connectivity of all the elements and the coherence principle

The methodology was tested through a case study in the Brazilian city of Belém, which allowed the verification of their flexibility by the inclusion of very specific and local characteristics in the analysis.

This methodology can serve as a decision support tool on upgrading or providing for cycling infrastructure in cities where there is not specific data on cycling available. However the method can also be adapted to include this kind of data improving the effectiveness of the result.

A basic principle for the implementation of this methodology is the local knowledge, i.e. people having the understanding of how the transport works in the city, which are the places the citizens want to go and, in a general way, how they behave.

8.1. Limitations of this research

- In a data scarce environment it is necessary to make assumptions regarding to the more likely origins for the selected destinations of the bicycle trips. Although an attempt was made to base such assumptions on the available data and the knowledge of the city, a more accurate result can be obtained if data on cycling behaviour is at hand.

- The different visions proposed in this work and their weighting criteria are based on assumptions and views based on the literature review and personal experience. It is more an exercise to demonstrate the flexibility of the process to analyze diverse view points and interests.

- The number of factors influencing the suitability for cycling infrastructure provision considered was constrained by the format of the available dataset, so, simplifications and generalizations to a neighbourhood level had to be made to use it.

- The available data on accidents was a counting of fatal and non incidents sorted by road, which can be used to identify the current most dangerous roads for cyclists. Since among them are avenues were cycling lanes are already present, accidentality can't be used as a demand factor but as indicator of the need of upgrading to safer levels the existing infrastructure.

- Even after a visual inspection of the network it can be checked that the attractors are served, the existing network is integrated and the routes appear to be direct, an objective assessment of the final network is missing.

9. RECOMMENDATIONS

- Further research identifying and involving stakeholders concerns will result in a more reliable output.

- Even if there is not specific information on cycling available, (counts, O-D surveys, cyclists' behaviour, etc.) in every city there are official and educational institutions that have data about many local phenomena that can be used to characterise the potential users of a cycling network and thereby achieve a better design. In a data scarce environment each source of information must be seized.

- Where available, Level of Service data can be used to prioritize roads. Either before the suitability analysis just defining which ones are appropriate and in which level or at the end of the analysis as a criterion to decide between many suitable roads in a specific corridor.

- To apply this methodology in a city where a proper network design obtained from a different approach is available, and to compare them could be a way to evaluate the validity of the results.

- As further improvement, an option to set the minimum length of a segment forming an 'optimal' route before make a turn could be programmed in the software and added to the analysis settings of the tool to reduce the zigzag outputs.

- A set of indicators can be used to assess the appropriateness of the designed network. They can be programmed to be evaluated after any change is made in the routes to check if really are improving it.

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10. APENDIXES

10.1. Apendix A Land Use Map of Belém Municipality