A GIS methodology for cycling investment prioritization using cadastre and urban form information.

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Key words: bicycle network, GIS, urban infrastructure development, urban form assessment, cadastre, spatial decision support system

SUMMARY

Around the world, cities appear to be increasing their desire for cycling as a real solution for their transportation problems. Most western cities have invested in cycling networks with facilities integrated to the core transport network.

As the development of cycling network has rarely followed strict planning guidelines, network gaps are common. This produces that cities are constantly searching technical methodologies for decision support around bicycle network infrastructure improvement.

This paper presents a methodology, using GIS. The aims of the methodology are to characterizing zones around bikeways understanding the variables that affect its use. A case study was conducted in Bogotá, the capital of Colombia.

It appears that the GIS methodology used was able to identify deficiencies of the Bogotá network in terms of accessibility, personal safety and road safety. Priority zones where bikeways are most needed were compared with existing network gaps and ranked based on priority needs.

Results from the case study in Bogotá suggest that this methodology facilitates the identification of infrastructure investments. However, prioritization of the intervention zones is highly dependent on expert knowledge and, therefore, limitations exist for using the methodology widely in other countries.

Further research is proposed in enhancing the methodology to not only evaluating current bicycle networks but also in identifying possible priority corridors for new infrastructure in areas where cycling could be a feasible transport option.

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1. INTRODUCTION

Today, authorities pay particular attention to the behavior of cities in terms of pollution and sustainable development. Transportation projects in cities are key for the sustainable development of those places. Such projects have to respond to challenges such as social inequality that is also likely to generate personal safety issues. The urbanism plans built around the new transportation projects contribute to this evolution as they tend to improve the quality of life in towns (Yigitcanlar, O'Connor, & Westerman, 2008). Additionally, today it is expected that transport systems contribute to air quality and provide comfort and efficiency. As more citizens leave the countryside for cities, the urban population grows, creating a need to tackle new transport necessities. Transporting people in a safe, efficient and comfortable way is a great challenge that every town worldwide is facing.

These issues concern Bogotá, the capital of Colombia. Bogotá is a city of social inequalities with more than 8 million inhabitants. Today, Bogotá is developing rapidly (Dawsey & Arora) (The World Bank, 2012), and the need for new transportation systems to tackle the pollution and the traffic congestion is emerging.

One of the green transport modes constituting a viable option is the bike, considered by its users as cheap and healthy (Heinen, Maat, & van Wee, 2010). Many bicycle networks have been implemented in Western countries (Martens, 2004). However, in some cities the use of the bicycle is declining significantly due to many factors including road safety, lack of continuous network and unsuitable infrastructure (Tolley, 1990).In Bogotá, limitations have been identified in the system (GDS, 2010).

This paper presents a methodology, using geographic information systems (GIS) to prioritize investment in transport infrastructure. A case study in the city of Bogotá was conducted where identified gaps in the cycling network were spotted. This paper is divided in four parts. The first part presents a review of current research in the area of cycling network development and prioritization. In this section the case study of Bogotá is introduced. The second part describes de methodology used. Then results from applying the methodology in the case study are discussed. Finally conclusions for the research and opportunities for further work are presented.

2. BACKGROUND

In order to prioritize interventions on a bicycle network, two main methods could be identified in the literature: users' survey and multi-criteria approach with expert knowledge. Significant popularity exists for the multi-criteria method (Rybarczyk & Changshan, 2009) (Neutens, Delafontaine, Scott, & De Maeyer, 2012). The paper: "Bicycle facility planning using GIS and multi-criteria decision analysis" (Rybarczyk & Changshan, 2009) is an example in which the method demonstrated advantages to produce a positive result.

The multi-criteria method requires finding relevant criteria. In general, those criteria are supply-based or demand-based. In the Multi-Criteria process, significant criteria indirectly related to supply and demand have been used (Rybarczyk & Changshan, 2009)

With the multi-criteria method, analysis results for each criterion are obtained. To superpose those results and build a complete answer, it is necessary to standardize them and then weight them (Hsu & Lin, 2012). GIS allows a display of the complete results with a map and tables.

GIS appears as a viable option for applying the multi-criteria analysis (Shaw, 2010). A GIS integrates hardware, software, and data for capturing, managing, analyzing, and displaying all forms of geographically referenced information. GIS allows us to view, understand, question, interpret and visualize data in many ways that reveal relationships, patterns and trends in the form of maps, globes, reports and charts (ESRI, 2012).

2.1 Case study

For an administrative and political purpose, Bogotá is divided in 20 districts. The bicycle network in Bogotá was designed to connect the main activity zones for each district in order to present an alternative to compete with the other transport systems (Pucher, 1996).Nevertheless, today the bicycle network has two important problems: on one hand, the network presents gaps along its length, and on the other, the coverage does not offer a good transportation option for the population (GDS, 2010).
The next map presents the bicycle network in Bogotá. The disconnections along the network, most of them in the periphery of the city, should be noted.

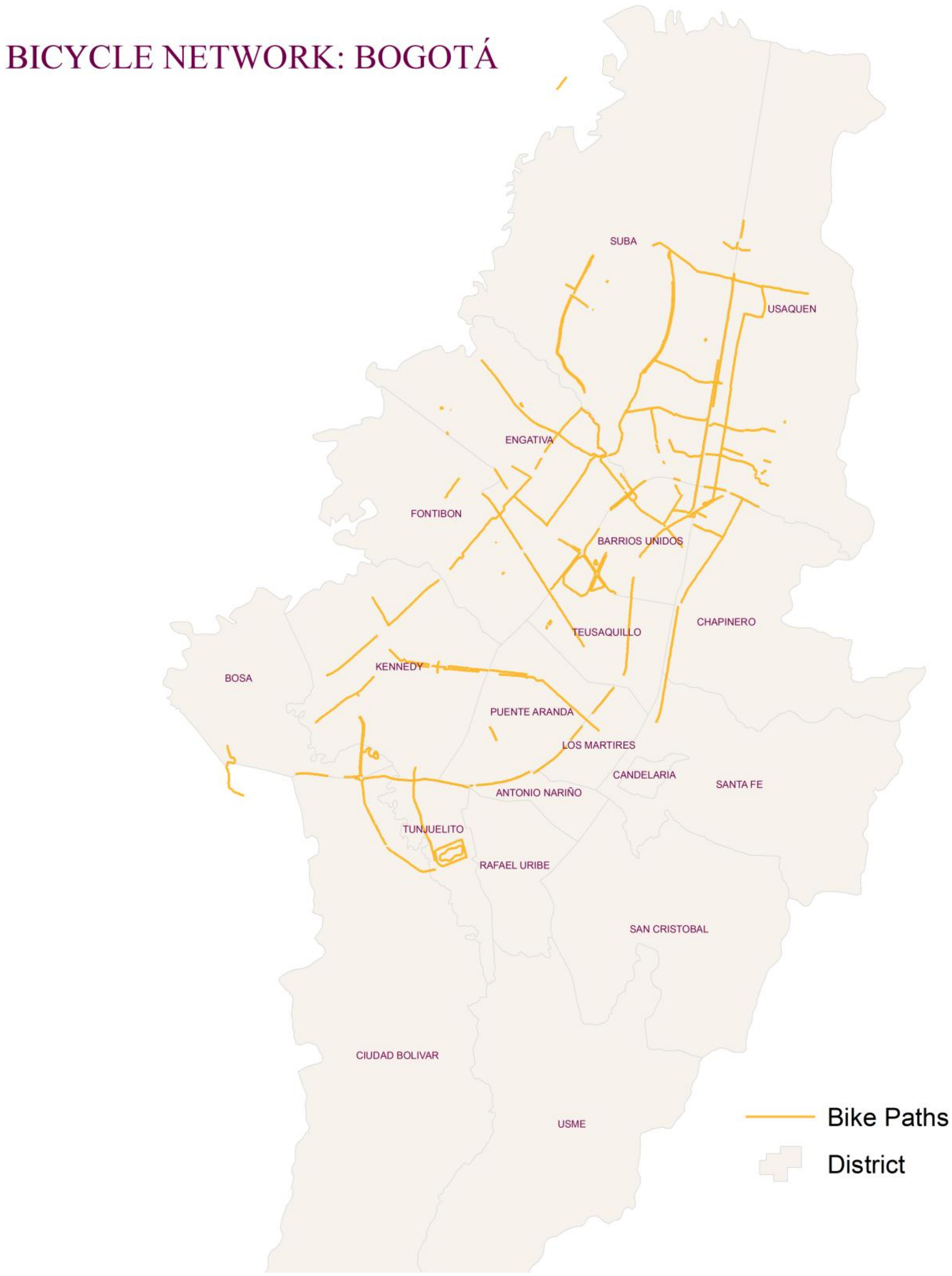

Figure 1. Bicycle network

The other problem is the coverage. Most of the districts in Bogotá have a significant poor bicycle network presence. The bicycle networks in districts such as Suba, Usaquén, Chapinero, Fontibón, Puente Aranda, Santa Fe, Tunjuelito and Ciudad Bolivar are not sufficient to offer a transport option in the totality of the area. People in districts such as San Cristóbal, Rafael Uribe, Usme, Candelaria and Sumapaz suffer from an even worse situation.

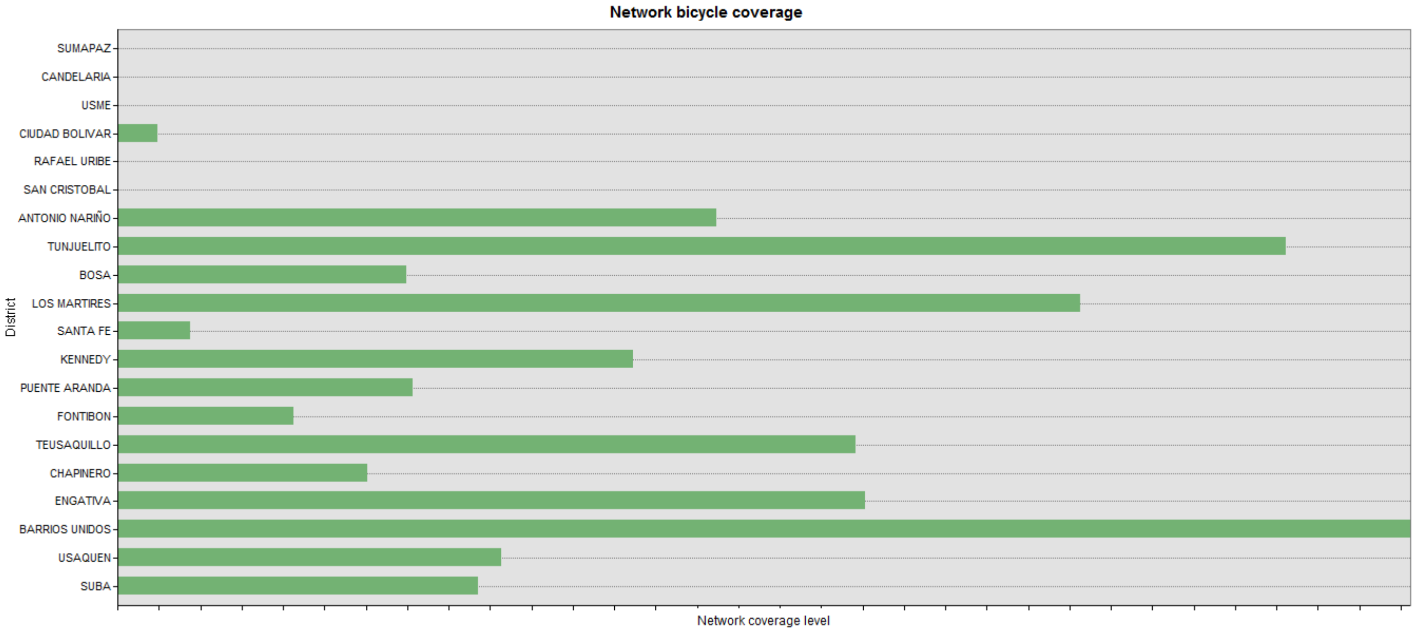

Figure 2. Network bicycle coverage

The gaps and the coverage make the bicycle use an impractical alternative for the mobility in the city.

The next section presents a methodology to identify the priority zones in Bogotá to develop improvements in the bicycle network using GIS.

3. METHODOLOGY

In this paper we formulate a GIS based methodology with a multi criteria analysis for the identification of the main cycling network gaps in Bogotá. The methodology is divided in four phases (see next figure).

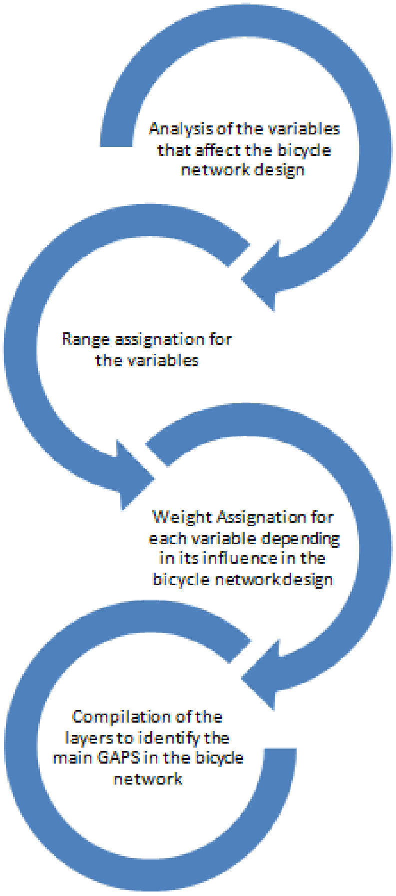

Figure 3: Research methodology

There are many variables that affect the bicycle network use. This research focuses on the factors that affect the current situation in Bogotá and the ones identified in the studies realized in Europe (Martens, 2004), (Vandenbulcke, et al., 2009).

The following variables are the pillars to identify the priority zones for the bicycle network improvement for this research:

- Population density
- Income repartition
- Personal safety
- Employ density
- Land uses
- Crime concentration
- Presence of illegal districts near the bikeways

After the individual analysis of each variable, the methodology proposes the compilation of the information found to determine where the priority zones for the bicycle network improvement are. A multi criteria methodology analysis was developed for this goal. ArcMap allows the development of one surface summarizing the important information of each criterion. The problem is that the criteria are represented in a raster surface that contains the main information in a specific range, making it impossible to compare in an adequate way with other criteria. For this reason, each criterion surface was normalized to obtain a comparable range. The range determined is between 0 and 1.

Criterion	Range	Note	
Population density	0-1	0 represents the zones with the lower level of population density	
Income	0-1	0 represents the zones with the higher level of income per home	
Employment	0-1	0 represents the zones with the lower level of employment	
Accident	0-1	0 represents the zones with the higher number of bicycle accidents	
Land use	0-1	Commercial	1
		Residential	1
		Official	0.8
		Historical Zones	0.6
		Green zones	0.2
		Industrial	0.1
		Non built	0
		Floor extraction	0
Crime	0-1	0 represents the zones with the higher number of homicides	
Illegal neighborhoods	0-1	0 represents the illegal neighborhoods with the higher network coverage	

Table 1. Criteria range

The next step of the proposed method is to assign a weight to each of the variables given that they don't have the same influence and importance to the priority zones (Handy, Xing, & Buehler, 2010). The assignation of each weight is based on the (AHP) Analytic Hierarchy Process. , which allows to make important decisions based on mathematics and psychology. The system computes hierarchically the answers of a group of people asking for the importance of different options to make a specific decision (Olson, Fliedner, & Currie, 1995). A questionnaire with 21 questions about the variables mentioned above was designed to apply the AHP. Each of these questions was designed to compare a pair of variables; the respondent has to answer each question taking into account his preference between two options in a defined context (bicycle network improvement). The respondents were selected based on their experience and knowledge in the transportation, infrastructure, urban planning and logistic fields.

The matrix presented below displays the variable pair comparisons. Each pair of variables was compared on a scale 1 to 9, where 1 represents an equal importance between the variables, 5 represents a strong preference of one variable over another, and 9 represents the highest preference of one variable over another.

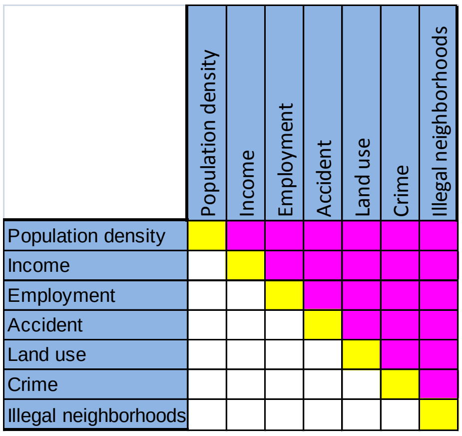

Figure 4. Criteria matrix.

The responses were grouped in one matrix to start the weight assignation (Olson, Fliedner, & Currie, 1995). The results found in the process are shown in the following table.

Criterion	Weight
Population density	21%
Income repartition	26%
Personal safety	7%
Emplloy density	25%
Land uses	8%
Crime concentration	5%
Presence of illegal neighborhoods near the bikeways	8%

Table 2. Criteria weight assignation.

The last step of the methodology proposed is to summarize (with ArcMap) the information from each criterion in one continuous surface with the weight assignation.

4. RESULTS

In this section, results for each of the variables studied are presented for the case study of Bogotá. At the end, a final priority map with a rank for each of the gaps is shown.

4.1 Population density

The following tables present the current situation that characterizes the populations that have access to the bike facilities and the ones that don't benefit from it. The percentages are the number of men/women that live within a certain distance of the bike paths and belonging to a certain range of age over the total population of Bogotá. It can be noticed that the ones who have an easier access to the bikeways are the younger than 15 years old and the one that are between 25 y 45 years old. The percentages of men and women are slightly different, but the tendencies with age are the same.

Male age rank / Distance (m)	<15	15-25	25-45	45-55	>45
<15	0.1%	0.04%	0.07%	0.02%	0.02%
15-50	0.3%	0.1%	0.3%	0.06%	0.07%
<50	0.4%	0.2%	0.3%	0.08%	0.09%
50-100	0.3%	0.2%	0.4%	0.2%	0.2%
<100	0.7%	0.4%	0.8%	0.2%	0.3%
<200	3%	2.3%	4%	1%	1%
200-500	5%	3.6%	6.3%	1.5%	1.8%
500-1000	5.5%	3.7%	6.6%	1.5%	1.7%

Table 3.Male age Bicycle accessibility rank

Female age rank / Distance (m)	<15	15-25	25-45	45-55	>45
<15	0.06%	0.05%	0.09%	0.02%	0.02%
15-50	0.2%	0.2%	0.3%	0.07%	0.1%
<50	0.3%	0.2%	0.4%	0.1%	0.1%
50-100	0.4%	0.3%	0.5%	0.2%	0.2%
<100	0.6%	0.5%	0.9%	0.3%	0.4%
<200	3%	2.3%	4%	1%	1%
200-500	5%	3.6%	6.3%	1.5%	1.8%
500-1000	5.5%	3.7%	6.6%	1.5%	1.7%

Table 4. Female age Bicycle accessibility rank

Following the current situation analysis, the 2011 Mobility Survey made by the city council of Bogotá (Alcaldía Mayor de Bogotá, 2011) indicates strong differences in the spatial population density repartition (population densities of each district).

The methodology studied the importance and the existing relationship between the population density and the bicycle network. This is particularly significant to prioritize the accessibility for those zones with an important number of people per square kilometer.

Multiple factors contained in the population density information (Alcaldía Mayor de Bogotá, 2011) such as geographic location, personal information (gender, age, and income) and persons per household were analyzed to present the population density range distribution in each district of Bogotá.

4.2 Income

Studies suggest that the motorized level of a household is linked to its income (Alcaldía Mayor de Bogotá, 2011). A Belgian article noted that those that used bicycles more regularly are the households with the lowest income levels (De Backer, 2010). In Bogotá the income levels are known as strata. There are six strata for Bogotá for which the first stratum corresponds to the lowest income range (Alcaldía Mayor de Bogotá, 2011). The 2011 mobility survey shows that almost 40% of low-income households' daily trips are made on foot or by bicycle (Alcaldía Mayor de Bogotá, 2011). The ones that use bicycles the most are the second and third strata (Alcaldía Mayor de Bogotá, 2011).
The following table presents the current percentages of population density (divided in the income level) that have access to the bicycle network.

Stratum / Distance	Stratum 1	Stratum 2	Stratum 3	Stratum 4	Stratum 5	Stratum 6
< 200 m	2%	4.7%	2.5%	1.7%	1.5%	5.7%
200-500 m	3%	6.9%	2.7%	1.5%	1%	7%
500-1000 m	4.5%	7.6%	1.5%	0.7%	0.56%	7.6%

Table 5. Strata

It should be stressed that the first and third strata (representing the poorest) have low access level to bikeways compared to the results obtained for the other strata. The second and sixth strata are the ones that benefit from the "best bike paths cover" .As a general observation for Bogotá; those percentages are quite low for any of the income levels. For instance, less than 2% of the people in the fourth stratum have a bike path less than 200m from their home. However, the largest percentage is found for the sixth stratum: almost 6% benefit from bicycle facilities within a distance of 200m.

4.3 Personal Safety

A study (Mosquera, Parra, Gomez, Sarmiento, Schmid, & Jacoby, 2012) about the demography in Bogotá argues that the following elements play an important role in the cyclist's perception of the bike network:

- Built environment conditions were linked with bicycle use
- People perceived conflicts over public space related to the use of bike-paths

Furthermore, a Belgian study (Vandenbulcke, y otros, 2009) showed that fewer people commuted where more bicycle accidents were noticed.

Based on these factors, it is vital to analyze the accident causation (Vandenbulcke, y otros, 2009) (Myungseob, Eungcheol, Jutaek, & Junwook, 2010) and their relationship to the gaps of the network (Krizek & Roland, 2005) and to the bicycle infrastructure in Bogotá.

The police department data concerning the 2011 accidents on the main and secondary roads of Bogotá were used to develop a surface for accident density in the city. These data include the information about the geographical location, the time and the types of vehicle involved in the accident. Furthermore, the data divide the accidents in three groups:

- Group 1: contains the accidents with a minor severity (crash without injuries)
- Group 2 :contains the accidents with a significant severity (crash with injuries, but without any fatalities)
- Group 3: contains the accidents with the highest level of severity (crash with fatalities).

In Bogotá, most of the accidents that involve bicycles are contained in the second group because a major percentage of the accidents occur in the secondary roads; the cyclists don't have another option besides sharing the roads with the vehicles. Since the vehicle speed is lower compared to the vehicle speed in the highway, most accidents don't involve deaths.

Accident percentage	
Group 1	2%
Group 2	84.5%
Group 3	13.5%

Table 6. Group accident percentage

	Percentage
Accidents in Highways	6.2%
Accidents in secondary roads	93.8%

Table 7. Accident percentage in highways and secondary roads.

Furthermore, the number of accidents increases proportionally with the distance between its location and the bicycle network.

Distance	Accident percentage
< 10m	8.4%
10 - 200 m	19%
200 - 500 m	30%

Table 8. Accident percentage near to the bicycle network

4.4 Employment

The reasons for using a transportation system are the destination and the activities the user expects to realize once he has arrived; these reasons include education, work (Alcaldía Mayor de Bogotá, 2011) and leisure. Studying the employment density and the spatial repartition of universities is key to understanding the availability of bikeways to certain destinations.

The following table shows the employment repartition in Bogotá. Each column corresponds to the percentage of jobs localized within a certain distance of the bike paths considering the total number of jobs in the city. Only one quarter of workers can go at work by bicycle.

	Jobs into 200m / Total Jobs	Jobs between 200 and 500m / Total Jobs	Jobs between 500 and 1000m / Total Jobs
%	26	27.6	23.5

Table 9. Jobs

As education is one of the main reasons for using transport systems, the research looks at the universities' accessibility to the bike paths. Once again, the percentages are very low, signifying the poor network coverage regarding universities.

Distance	Number of universities
< 15 m	0
15-50 m	3
50-100 m	2

Distance	Percentage of universities within this distance (%)
< 15 m	0
15-50 m	2.7
50-100 m	1.8

Table 10.Universities

For the control and the organization of Bogotá, the government has a political sub division called UPZ (planning zones). Bogotá has 112 planning zones, which are an important tool that permits the design of improvements and the development of the urban planning in a detailed level. The research identifies and develops a continuous surface with the employment density distribution for each planning zone.

4.5 Land use

Following the same idea that the objective of the user is to arrive at a specific location; therefore, land uses are useful when considering them as an origin or a destination. Bogotá presents the following land uses: commercial, residential, industrial, non-built, floor extraction, official, Green zone and Historical. The hypothesis is that some uses are considered as attractive zones (commercial, residential, official), others as disturbing zones (floor extraction, industrial), and a last group as dangerous zones for cyclists (non-built).
Currently, only 14.7% of the land that is within 200m of the bike paths is of commercial use, whereas 54% is residential and almost 10% is Non-Built land. The last group is dangerous

and not very attractive as it is not a destination or origin itself for the bicyclists.

Figure 5. Land use within 200 m of the bike paths

4.6 Crime

Another interesting point is the criminality. In Bogotá, some bicycle ways pass through dangerous districts in terms of personal safety, which can affect the use of the bicycle. To avoid those zones, one has to go out of the bikeway and take another route passing by streets that don't offer bicycle facilities, which means less security and comfort for the users.
The information for homicides between the years 2000 and 2003 was obtained from the forensic science department (Instituto nacional de medicina legal y ciencias forenses de Colombia) to determine where the dangerous zones in the city are. The geographic location of the homicides on a surface indicates the crime concentration. (Páez & Bocarejo, 2012)

4.7 Illegal neighborhoods

The illegal neighborhoods refer to the neighborhoods located in zones that are not allowed for residential construction. These neighborhoods are composed of populations with low incomes and low accessibility to the public transport systems.
The following map presents the bicycle network cover in illegal neighborhoods. These zones in Bogotá represent an area of almost 70,000,000 square meters, but only 35% is covered by the network within a 500-meter service distance. The people who live there are the households with the lowest incomes. This fact isn't reflected in the accesibility to the transport facilities.

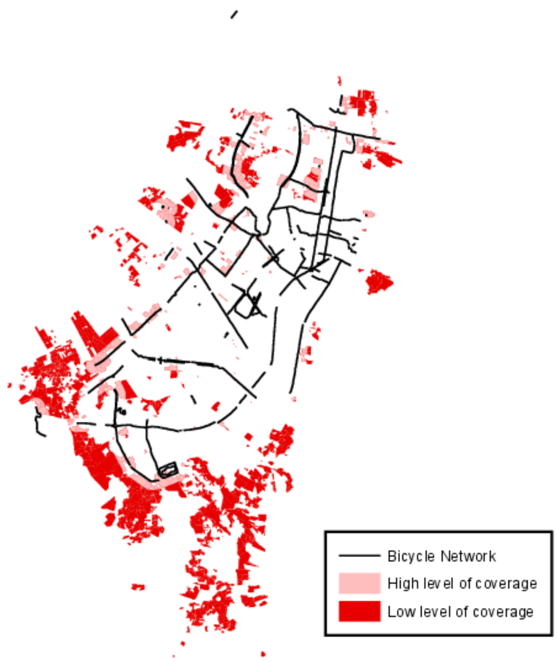

Figure 6. Illegal neighborhoods

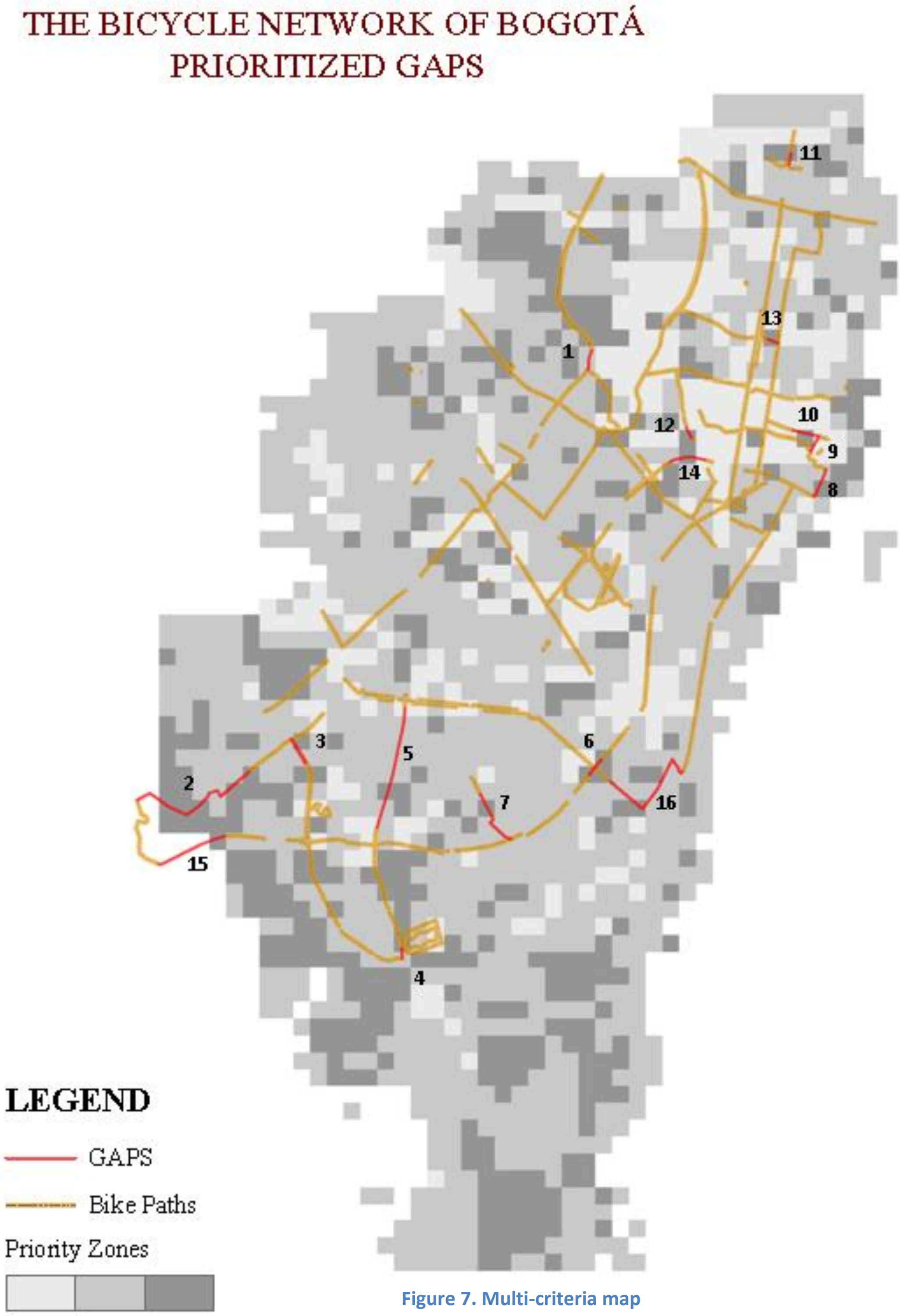

Figure 7. Multi-criteria map

The map presents the priority zones in Bogotá for the bicycle network improvement. The dark zones are those that have the highest score in the multi-criteria evaluation and need special attention. They are the main concern when designing the connections in the gaps.

The research proposal is to choose the gaps that are contained in the priority zones to connect the network in an efficient way. For this purpose, the problem is divided in two.
First, the gaps of the total network are connected following the principal and secondary highways because the bicycle facilities are only needed in places that affect the personal safety of the cyclists (Pettinga, y otros, 2009). Furthermore, the highways offer the best option to connect the trip distribution. 82 connections for the gaps were identified.

Second, the connections were ranked based on their location in the priority surface.
The ones within a significant dark area are the ones that have priority in their construction. These priority connections are summarized in the following table.

ID	Gap Lenght (m)
1	534.11
2	3874.97
3	754.51
4	304.20
5	3315.56
6	532.81
7	1613.91
8	832.74
9	460.81
10	712.06
11	316.84
12	291.12
13	296.25
14	976.17
15	1951.60
16	3252.81

Tabla 1. Gap connection priority

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5. CONCLUSIONS

In this paper a present assessment of the bike paths in Bogotá was developed. Various characteristics of the network were analyzed, determining where the bike paths pass. The gaps of the network were then identified and finally the results were reached using a GIS and a multi-criteria analysis.

For the case study in Bogotá, the methodology identified that the bike paths serve only a quarter of the places of work and two percent of the universities, indicating that the cover is not sufficient in regard to the education and work-based trips. Three-quarters of the workers in Bogotá don't have the choice to use bicycles to go to work and must use other more expensive modes of transport, which may be slower and less comfortable.

The majority of the access is attributed to the highest income level: almost 6% of the total area of this income range has real access to the bike paths (distance less than 200m), whereas for the same distance, approximately 2% of the first, third, fourth, and fifth strata boast access. In both cases, the percentage remains very low. Moreover, as seen before, the poorest should benefit first of those facilities, but we observed the contrary.

ArcGIS allowed us to obtain all the gaps of the network. With the method of weights exposed above and the survey made to define those weights, we presented a map including all the data we had analyzed. This map indicates where it is more useful for the user that the bike ways pass. Superposing this map with the gaps identified, we could prioritize the gaps that are more important to solve.

Regarding those weights, we only 4% was attributed to low criminality. Finally it appeared that passing through the zones where population needs most those facilities (low income, high population density, working places) was privileged against the problems that the bicyclists can face (criminality, accidents, land use).

Results from this investigation suggest that the bike ways in Bogotá were not designed taking into account the criteria studied in this paper. With a quick look at the literature, the importance of those criteria is evident. The data and information we obtained is striking as nothing is as expected and as it should be.

The methodology facilitates the identification of priority zones based on specific criteria. These zones are a significant tool to take decisions concerning investment in the network improvement and an option to encourage bicycle use. However, the prioritization is highly dependent on expert knowledge and, therefore, limitations exist for using the methodology widely in other countries.

Further research is proposed in enhancing the methodology to not only evaluating current bicycle networks but also in identifying possible priority corridors for new infrastructure in areas where cycling could be a feasible transport option.

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