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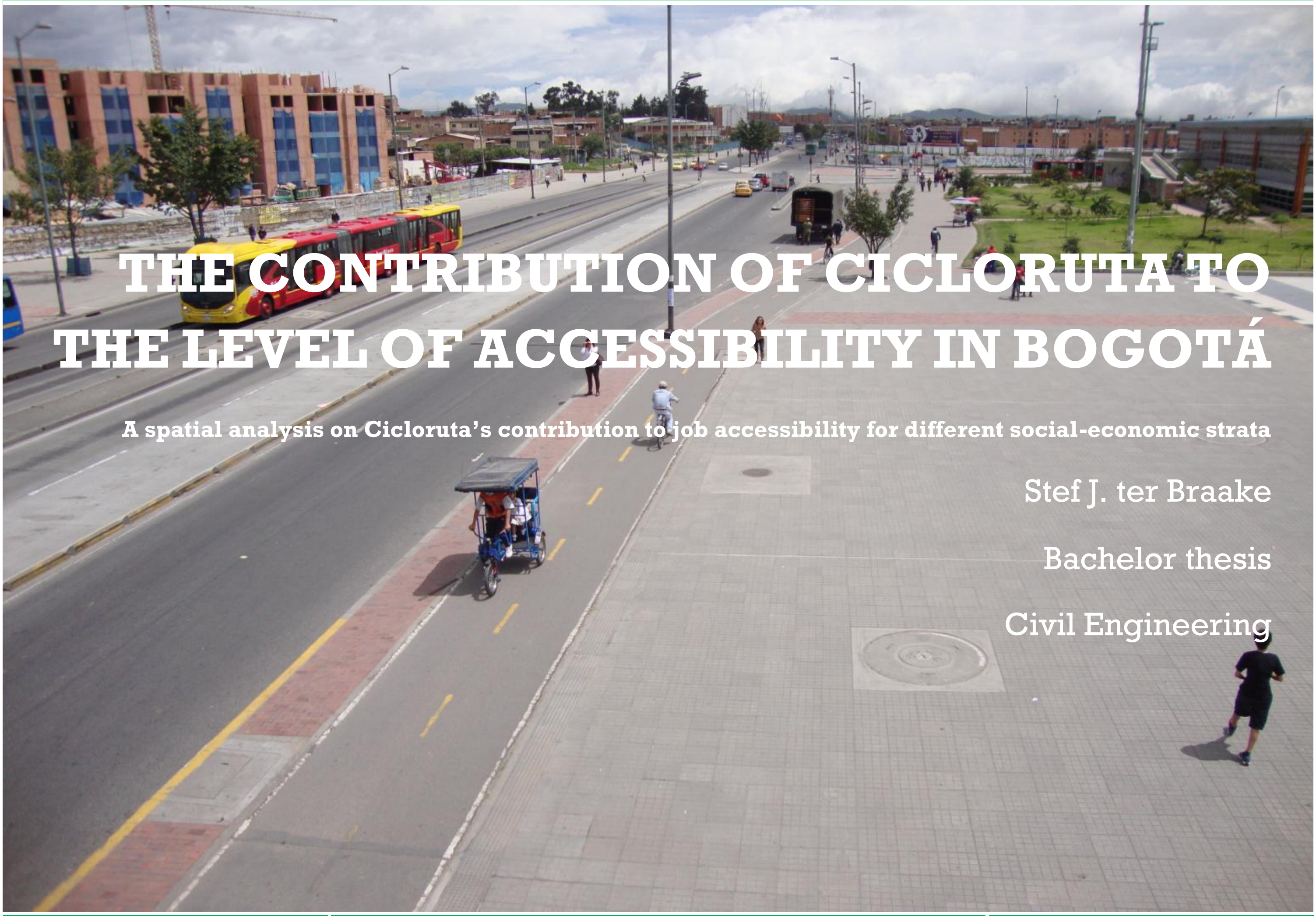

# THE CONTRIBUTION OF CICLORUTA TO THE LEVEL OF ACCESSIBILITY IN BOGOTÁ

**A spatial analysis on Cicloruta's contribution to job accessibility for different social-economic strata**

Stef J. ter Braake

Bachelor thesis

Civil Engineering

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# THE CONTRIBUTION OF CICLORUTA ON ACCESSIBILITY IN BOGOTÁ

## A spatial analysis on Cicloruta's contribution to job accessibility for different social-economic strata

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| Author: | S.J. (Stef) ter Braake |
| Student number: | s0203505 |
| Contact: | s.j.terbraake@student.utwente.nl |
| Institution: | University of Twente |
| Department: | Faculty of Engineering Technology (CTW) and Faculty of Geo-Information Science and Earth Observation (ITC) |
| Organization: | Universidad de los Andes |
| Location: | Bogotá, DC, Colombia |
| Supervisor University of Twente: | ir. M.J.G. (Mark) Brussel (ITC) |
| Second assessor University of Twente: | J.R. (Julia) Wijnmaalen MSc and MA |
| Supervisor Universidad de los Andes: | dr. O.L. (Olga Lucia) Sarmiento Duenas |
| Advisor: | dr. ir. M.H.P. (Mark) Zuidgeest (ITC) |

# SUMMARY

In Bogotá, the largest city and capital of Colombia, one of the most extensive bike paths in the developing world, called Cicloruta, has been built during the last decade. Likewise, a Bus Rapid Transit system (BRT) called TransMilenio (TM) has been built to improve urban transport within the city. Cicloruta may function as a lever for sustainable utilitarian transport, which makes it interesting to know the performance of the network as a way of commuting, whether or not in combination with TM. It is hypothesized that this is different for different social-economic strata (SES), which makes it necessary to be investigated for each of these SES.

Accessibility is a measure for the extent to which destinations can be reached from a given location. It is hypothesized that Cicloruta enables more people to reach more destinations, which equals a higher level of accessibility.

The purpose of this research is to model, map and assess the level of accessibility. This will answer the following questions:

***Main research question:*** *What potential level of accessibility is provided by the Cicloruta network for the different social-economic classes?*

1. What are the residential locations of the different SES levels and the corresponding job locations?
2. What are the properties of the Cicloruta and TM networks that are relevant to commuting?
3. How accessible are the suitable jobs for different SES levels using the Cicloruta network?
4. How can the information about accessibility improve liveability in Bogotá?

The residential locations of different SES are not equally distributed. Lower SES tend to live in the southern part and the edges of the city, while higher SES live north of the city centre. Jobs are mostly concentrated in the central eastern part of the city, with minor concentrations near corresponding SES residential locations.

Cycling on Cicloruta is quite slow, because the cycle paths are often interrupted at street crossings and they are often integrated into pedestrian zones which results in many pedestrians on Cicloruta. TM is the preferred transport system for longer trips; it is relatively fast and the costs of a ticket make it less likely to use TM for shorter trips, especially low SES. TM stations often do not have bicycle parking facilities, but that does not decrease potential accessibility.

The distance decay functions are estimated for each transport mode using data from the 2011 mobility inquiry for Bogotá. As the effect of Cicloruta is regarded in this research, only the decay function for cycling is used; for other modes a threshold is used. The input of this function, travel time, is calculated by modelling the network for two scenarios: with Cicloruta and without. Multiplying the distance decay function by the number of jobs within a location results in the accessibility of a location. Comparing the accessibility with Cicloruta with the situation without Cicloruta results in the effect of Cicloruta to the accessibility at each area for each SES.

The results are an increase in accessibility, but this increase is very unequal. Locations near Ciclorutas show a large increase, while parts of the city remote from Cicloruta only show a slight increase. This indicates that Cicloruta still needs to be improved and expanded to provide a higher level of accessibility through the whole city.

# PREFACE

I have done this research for my Bachelor thesis for the education of civil engineering at the University of Twente. As it is usual to do the Bachelor thesis of civil engineering at an external organization, I decided to try doing it abroad, which resulted in an interesting internship at Universidad de los Andes in Bogotá. At the moment of writing I can look back at ten nice weeks living the Colombian way of life, in which I have learnt a lot about both transportation in Bogotá as well as the culture in the city.

However, I would not be able to go on this adventure without the support of several people.

First of all, I thank Mark Brussel for the great supervision of my research from The Netherlands (and India and Brazil). He was willing to take some time almost every week to talk about my progress and give me feedback. I would also like to thank Mark Zuidgeest for establishing and maintaining the good contacts between the ITC, representing University of Twente, and Universidad de los Andes. This has resulted in my opportunity to travel to Colombia to do my research in Bogotá. Despite the fact that he was not able to supervise my research, Mark supported my research by giving me advice and feedback about my progress like a supervisor would do. Without the ArcGIS software it would be impossible to do the research. Hence, many thanks go to Frans van den Bosch of the ITC for providing me the required licences for ArcGIS and the knowledge to use the software.

Many thanks go to the nice people at UniAndes as well. I want to thank Pablo David Lemoine Arboleda for the collaboration at the research, as well as arranging my access to UniAndes. Many thanks go as well to Olga Lucia Sarmiento Duenas for providing me workspace at her department and for her great supervision on my research.

At last I would like to thank my family for supporting my journey to Colombia.

Stef

# INDEX

# INTRODUCTION

Bogotá is the capital city of Colombia. With almost 7 million inhabitants (DANE, 2005), it is also the largest city of Colombia. During the last decade a couple of sustainable transport networks have been constructed in Bogotá, like Cicloruta and TransMilenio.

Ciclorutas de Bogotá is one of the most extensive bike path networks in the developing world. Built between 1999 and 2006, the network consists of 376 kilometers of cycle paths throughout the city of Bogotá (Secretaría de Movilidad de Bogotá, 2013). The use of Cicloruta may function as a lever for sustainable utilitarian transport, such as commuting. Therefore it is interesting to know the performance of this network as a link between residential locations and job locations within the city.

Another sustainable transport network that has been constructed recently in Bogotá is TransMilenio (TM). This 87 km bus rapid transit (BRT) system consists of 11 trunk lines and 115 stations and accounts for 24% of the total number of travels, or 69% of the number of public transport travels in Bogotá (TransMilenio S.A., 2012). With an average velocity of 26 km/h (Teunissen, Sarmiento, Zuidgeest, & Brussel, 2013), TM is the primary sustainable transport mode for longer trips within Bogotá.

However, there are many people who live at more than ten minutes walking distance from a TM station, while the actual average walking time to a TM station is six minutes (Teunissen, 2012). This indicates that there is still a great potential for sustainable transportation from places located remote from TM stations. An example of such sustainable transportation is the increase of the TM stations' service areas provided by Cicloruta. The potential job accessibility by means of such combination of TM and bicycle needs to be determined for the purpose of possible sustainable transport increasing interventions.

As Cicloruta access is different for different Social-Economic Strata (SES) (Teunissen, 2012), it is hypothesized that job accessibility by means of Cicloruta is different for different SES who reside at different locations and travel for different trip purposes to different trip destinations. For this purpose, it is needed that job accessibility is determined for each SES in order to clarify social inequity. This is useful information for possible interventions, as it shows the areas and the SES that lead to the largest increase in both sustainable transport and increase in social equity.

In chapter 1, the problem is analyzed as well as the definition of accessibility. Chapter 2 shows how SES are distributed through the city. The distribution of jobs per SES is also shown in this chapter. The network is analyzed in chapter 3. In chapter 4 the accessibility of each location is calculated using the distance decay function and an estimation of the number of jobs. Chapter 5 contains conclusions, limitations and recommendations.

# 1 PROBLEM ANALYSIS

## 1.1 ABOUT ACCESSIBILITY

This research is about job accessibility in Bogotá by means of cycling and TM. Accessibility is a measure for the extent to which destinations of a certain type can be reached from a given location. Geurs & Ritzema van Eck (2001, p19) define accessibility as follows:

*'The extent to which the land-use transport system enables (groups of) individuals or goods to reach activities or destinations by means of a (combination of) transport mode(s)."*

For this research, this definition can be narrowed and thus become more concrete:

*The extent to which Bogotá's transport network including Cicloruta and TM enables people of different SES to reach their jobs by means of cycling and TM.*

However, accessibility is not a clear concept and there are several perspectives on accessibility measures (Geurs & Ritzema van Eck, 2001):

- Infrastructure-based: analyzing the performance of the network;
- Activity-based: analyzing the number of opportunities within a range, taking distance into account;
- Utility-based: analyzing the individual's benefits derived from the land-use transport system.

This research will contain activity-based accessibility measures as the approach of this research is about the ease of reaching jobs. Furthermore, there are several components of accessibility (Geurs & Ritzema van Eck, 2001): a transport component, a land-use component, a temporal component and an individual component.

In this research, the transport component consists of the properties of roads, Cicloruta, TM and the connection between these. Each network has its own properties which influences the route choice. Which network is used depends on various factors such as the network's properties (and SES, see individual component).

The land-use component is the spatial distribution of both jobs and residential locations per SES. This is important, because it is a major determinant of travel time as it represents the distances from residential locations to job locations. It probably varies with the SES because residential locations and job locations for each SES may be situated at different places in the city.

The individual component regards the properties of SES itself. People from lower SES tend to spend less money on transport than high SES, which result in on average shorter TM trips for higher SES. The type of job for an SES and the corresponding distribution in the city is also important, see land-use component.

The temporal component consists of the times on which an opportunity is available, which are the working hours in this research.

This research will cover all components except the temporal component, because most jobs have the same working hours and activity-based job accessibility does not depend on time of the day (except few midnight jobs with long travel distance, as there is no TM service during the night (TransMilenio S.A., 2012)).

## 1.2 PURPOSE

The purpose of this research is to model, map and assess the level of accessibility to opportunities by means of the Cicloruta system for the different SES in the city of Bogota. This will be done by operationalizing a potential accessibility indicator for these different SES. The results of this research will be used to recommend bicycle network changes for Cicloruta. The model will be implemented in the existing GIS network models of TransMilenio and Cicloruta.

### 1.2.1 SCOPE

Determining the accessibility of the Cicloruta and TM networks demands examination of several aspects:

1. SES and their corresponding locations
2. The networks themselves and its impedances
3. Job destinations and attractions

First of all, this research consists of mapping the accessibility to Cicloruta for different locations and corresponding SES. For this purpose, the extent of a 'location' needs to be defined and the SES will be determined for every location. The reason why SES are regarded is that it is hypothesized that both accessibility in general and the contribution of Cicloruta to job accessibility is different for every SES.

Secondly, the networks will be analyzed, since the properties of the network is one of the factors that affect the accessibility of activities. When the network has poor quality, the impedance will be larger.

Third, it is necessary to examine the commuting patterns, such as the locations and attraction level of the job locations that attract the corresponding SES. Subsequently, these patterns need to be fitted on the Cicloruta and TM networks.

### 1.2.2 RESEARCH QUESTIONS

***Main research question:*** *What potential level of accessibility is provided by the Cicloruta network for the different social-economic classes?*

1. What are the residential locations of the different SES levels and the corresponding job locations?
   1. What is a suitable definition of a 'spatial unit'?
   2. How can SES be assigned to spatial units?
   3. What are the job locations for people of the different SES?
2. What are the properties of the Cicloruta and TM networks that are relevant to commuting?
   1. What is the cycling travel time from residential locations to the Cicloruta network?
   2. What are the cycling travel times of commuting trips by means of Cicloruta?
   3. What are the travel times of commuting trips by means of the combination of Cicloruta and TM?

3. How accessible are the suitable jobs for different SES levels using the Cicloruta network?
    1. How can the distance decay on the Cicloruta and TM networks be determined?
    2. What is the level of accessibility of jobs by means of Cicloruta, whether or not in combination with TM, for different SES levels?
4. How can the information about accessibility improve liveability in Bogotá?
    1. How can the received information be used to improve the accessibility for every SES level?
    2. To which extent is the Cicloruta network able to improve the job accessibility of different SES, whether or not in combination with TM?

# 2 SES LOCATIONS AND SUITABLE JOB LOCATIONS

## 2.1 SES

The inhabitants in Bogotá can be divided into six social-economic strata (SES). The SES are indicators for the level of wealth, 1 being the poorest and 6 the richest. The SES is determined for every property (Catastro Distral de Bogotá, 2013). However, as many properties have a function other than residential, these properties do not have an SES (figure 2-1).

To make clear the level of accessibility for each SES, both the residential and job locations are regarded for each one of them.

## 2.2 ORIGINS AND DESTINATIONS

Bogotá can be divided into several types of spatial units. The most important ones are localities, zonal planning units (ZPU) and traffic analysis zones (TAZ). For each of these types of locations, there is an indication of the inhabitants and jobs and the corresponding SES.

There are 19 localities within Bogotá (Secretaría distrital de movilidad de Bogotá, 2011). These localities all have a name and a number, and are the most common way to divide the city. As localities are quite large, most of them include several SES which make them not applicable for research on accessibility.

The localities contain several ZPU (Spanish: Unidades Planeamiento Zonal (UPZ)). These UPZ consist of one or more urban or suburban districts (Secretaría distrital de movilidad de Bogotá, 2011). There are 115 of them in Bogotá, and they are used for urban planning. Despite the ZPU are smaller than localities, often they still contain more than one SES.

Transport analysis zones (Spanish: Zonas análysis de transporte (ZAT)) are de results of a division made for the purpose of transport analysis (United States census bureau, 2001). Each TAZ contains more or less the same level of inhabitants, while the area may vary largely. In Bogotá, there are around 950 TAZ (Secretaría distrital de movilidad de Bogotá, 2011). In this research the center points of the TAZ represent the origins and destinations of job trips.

## 2.3 RESIDENTIAL LOCATIONS

The map on the next page shows the residential locations within Bogotá for different SES. The map shows that the lowest SES (1-2) are in the southern and western parts and on the edges of the city.  The middle SES (3-4) are south and west of the city center, as well as in northern Bogotá. The highest SES (5-6) are north of the city center.

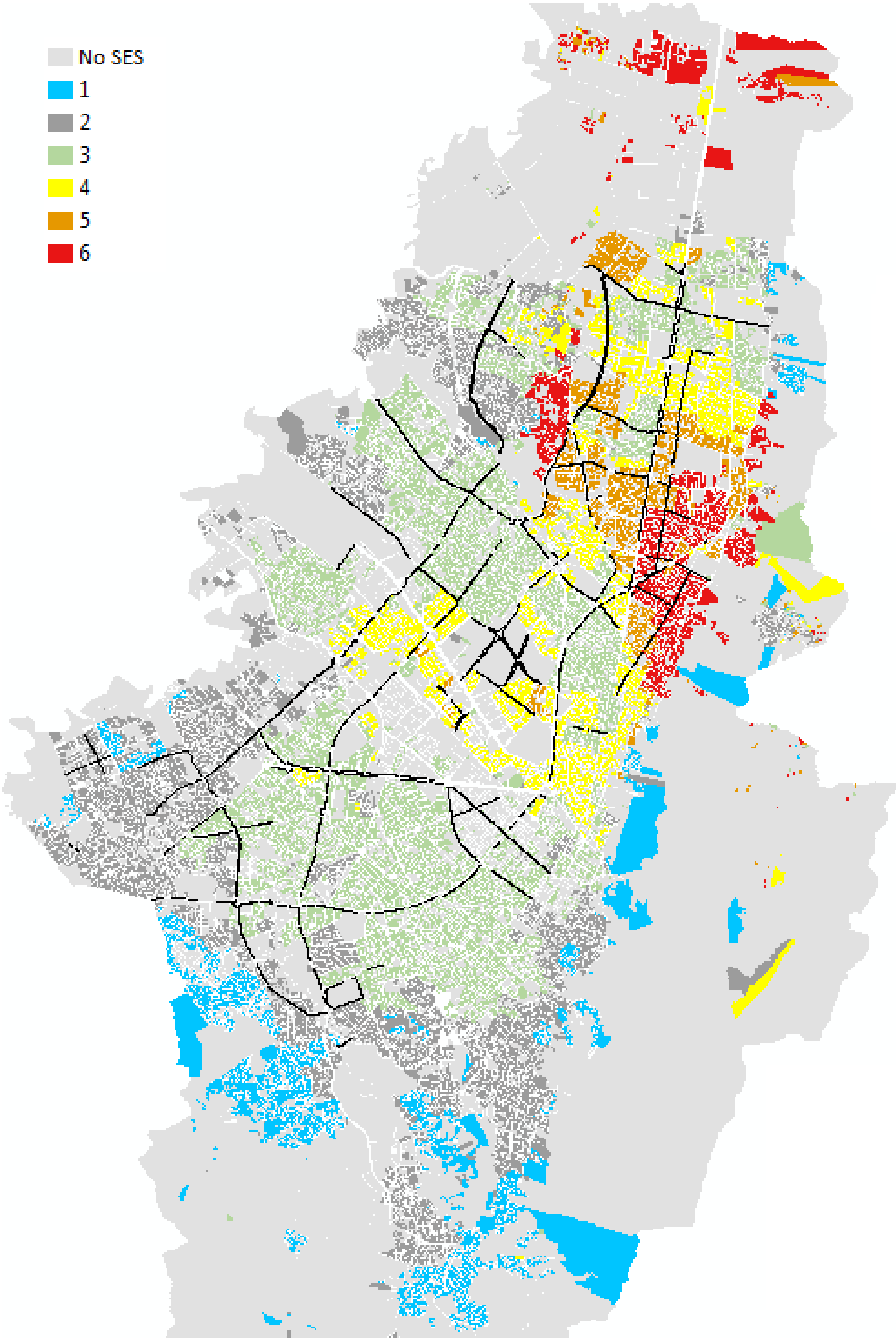


FIGURE 2-1: SES' RESIDENTIAL LOCATIONS (CATASTRO DISTRAL DE BOGOTÁ, 2013)

## 2.4 JOB LOCATIONS

The job locations are not equally spread within Bogotá. Most of the jobs are located in the central eastern part of the city (Figure 2-2). To a lesser extent, jobs are located in or near the residential locations of the associated SES. This is visible in figures X-Y. The used data is calculated from the number of jobs (3,1 million) within Bogotá (Camara de comercio Bogotá, 2006) and the number of job trips per SES (Secretaría distrital de movilidad de Bogotá, 2011). In this research, the number of jobs within certain TAZ is a measure for the attraction of that location (see also section 5.1.2).

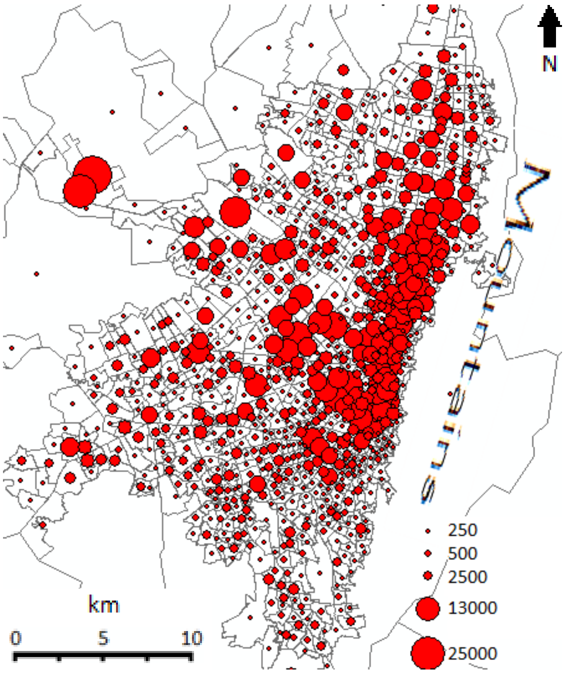


**FIGURE 2-2: NUMBER OF JOBS PER TAZ**

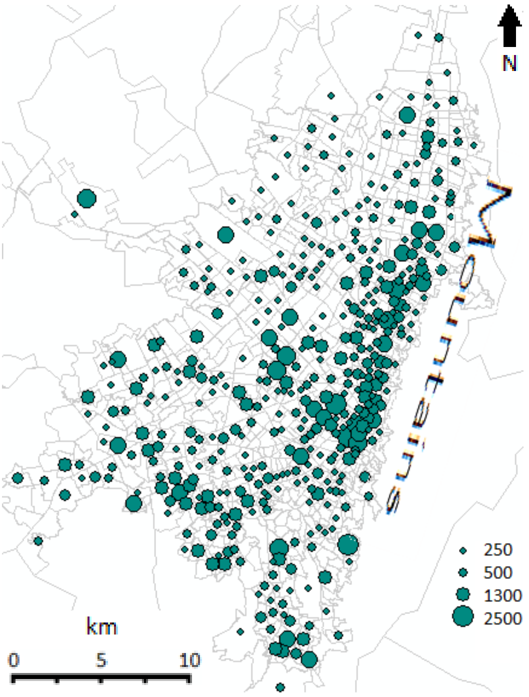


FIGURE 2-3: NUMBER OF SES1 JOBS PER TAZ

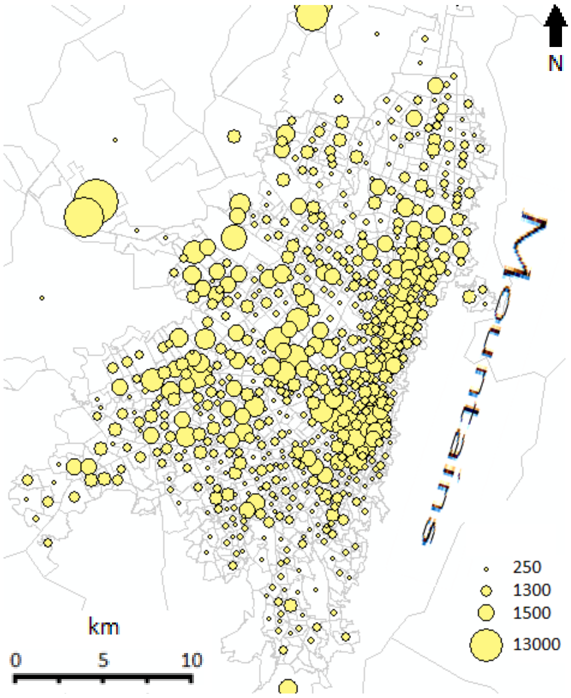


FIGURE 2-4: NUMBER OF SES2 JOBS PER TAZ

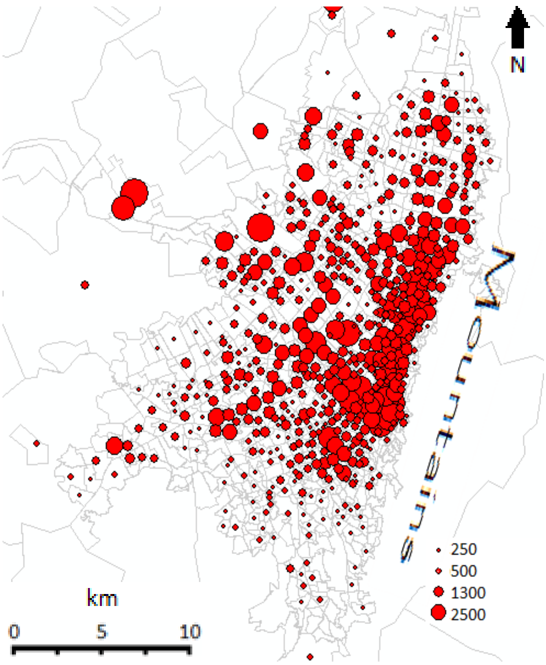


FIGURE 2-5: NUMBER OF SES3 JOBS PER TAZ

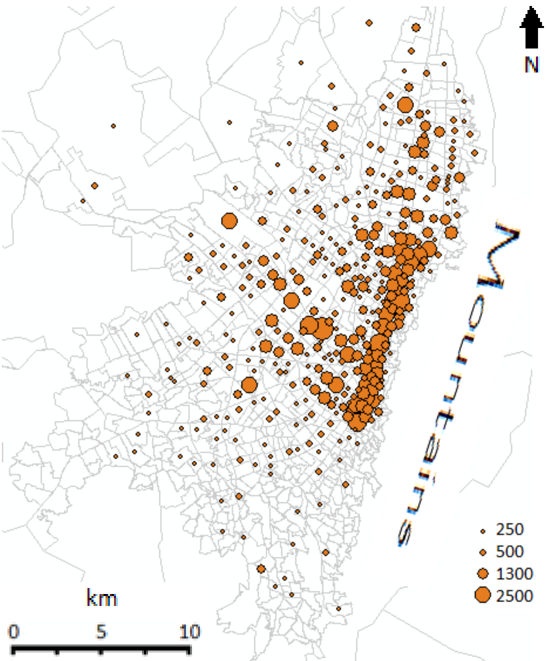


FIGURE 2-6: NUMBER OF SES4 JOBS PER TAZ

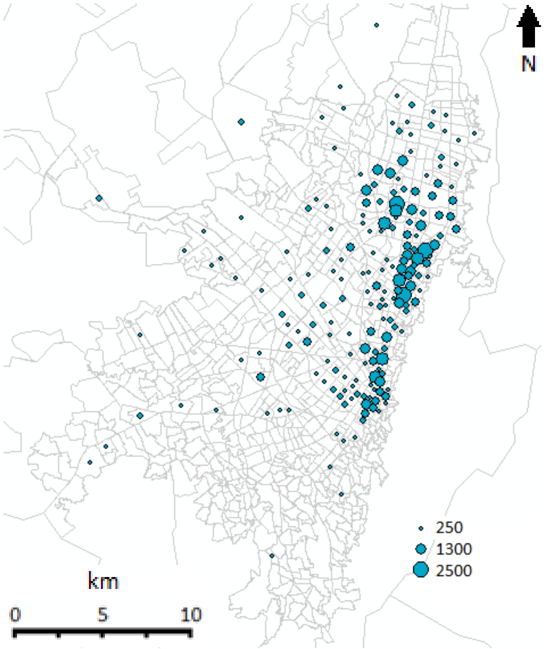


FIGURE 2-7: NUMBER OF SES5 JOBS PER TAZ

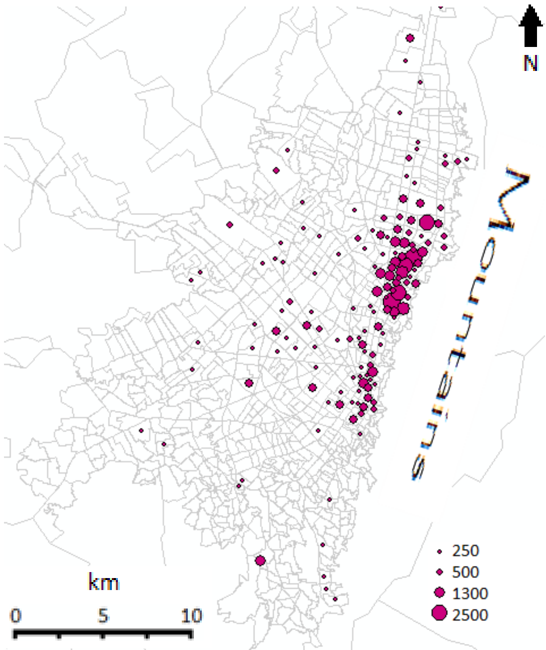


FIGURE 2-8: NUMBER OF SES6 JOBS PER TAZ

# 3 BOGOTA'S TRANSPORT NETWORKS

The backbone of sustainable transport in Bogotá consists of several networks. The basis is the street network. In recent years, the network has been expanded by the TM network and Ciclorutas. Ciclorutas have most potential to function as a network for shorter trips and as a feeder for longer TM trips.

## 3.1 STREET NETWORK

Bogota's largest network is the street network, which is the basis of the transport system within the city. The street is meant for two different ways of transport: walking and motorized transport. Cycling on the street is possible as well, but this is not regarded in this research. Cycling speed on the street is roughly the same as cycling speed on Cycloruta network (see also 3.2.2) which would result in very little use of Cicloruta when modelled this way. Although cycling speed is only one of the impedance factors, this is the only quantifiable one given the current data available, which makes it the only one able to put into the model. Cicloruta probably offers better levels of road safety (it is divided from the road which makes accidents less likely) and comfort (quieter traffic because of the absence of motorized traffic). As these factors are considerable but not quantifyable, in this research only walking is considered possible at streets, as this probably offers similar levels of comfort and safety.

This way, the street network can be used as a feeder network for cyclorutas. The Cicloruta service area is shown in Figure 3-2. On average, the walking speed is 4,392 km/h (Teunissen, 2012).

## 3.2 CICLORUTA NETWORK

The Cicloruta network aims to provide a safe and sustainable alternative for utilitarian trips for the entire city of Bogotá (Secretaría de Movilidad de Bogotá, 2013). It consists of 376 kilometers of cycling paths, that are situated outside of the road. However, there are still many places that are remote from Cicloruta and the cycling circumstances are suboptimal. Nonetheless, it still has potential to increase the job accessibility in Bogotá.

### 3.2.1 EXTENT OF THE CICLORUTA NETWORK

The aim of Cicloruta is to provide the whole city safe cycling, which is likely to result in a very dense network that covers the whole city. However, there are still large areas without a near cycle path, especially in the southern part of the city. This may be caused by the mountainous terrain of these neighbourhoods (Figure 3-1).

Furthermore, there are many areas within the network that are more than 1000m away from Cicloruta (Figure 3-2). This makes it less attractive for those areas to make use of Cicloruta.

**FIGURE 3-1: VIEW ON NORTH WESTERN CIUDAD BOLIVAR, AN SES1 NEIGBOURHOOD IN SOUTHERN BOGOTÁ**

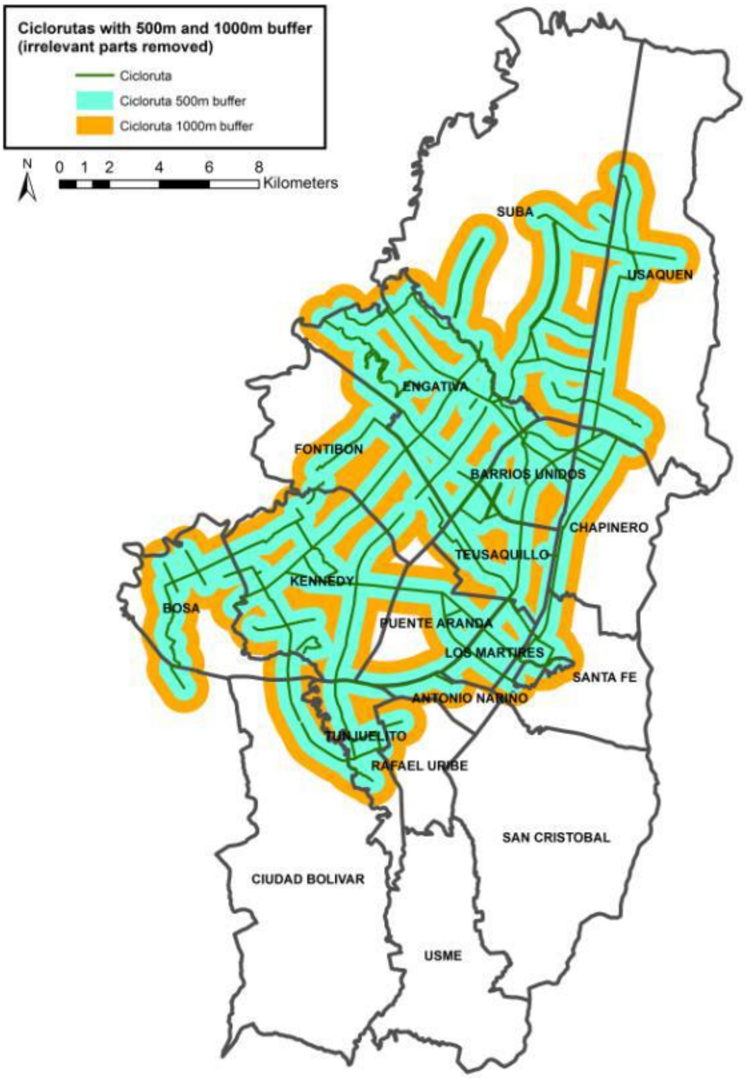


**FIGURE 3-2: CICLORUTA 500M AND 1000M BUFFERS, IRRELEVANT PARTS REMOVED (TEUNISSEN, 2012)**

### 3.2.2 CYCLING SPEED ON CICLORUTA

Field work has shown that the average cycling speed on Cicloruta is 13 km/h, which is quite slow (C40 Large Cities, 2011). A possible reason for the slow cycling speed is the widespread integration of Ciclorutas within the pavement, which causes pedestrians and other non-cyclists  to use the cycling path as well. This effect occurs on all Ciclorutas that are integrated with the pavement, and especially when the pavement is narrow (Figure 3-3). Another problem is the awareness of pedestrians with Cicloruta. The mentioned field work has shown that pedestrians are likely to walk on the cycle path without looking whether a cyclist is coming.

**FIGURE 3-3: NOT ONLY CYCLISTS USE CICLORUTA**

**FIGURE 3-4: NARROW SIDEWALKS ENFORCE NON-CYCLISTS TO USE CICLORUTAS AS WELL**

Another cause of the slow cycling speed on Cicloruta is that the cycle path ends at every road crossing, leading into the pedestrians' zone. In some cases, the path already ends at several dozens of meters before the crossing (Figure 3-5). The cyclists need to cross the roads along with the pedestrians, which brings the average speed down. There are no separate bicycle traffic lights (Figure 3-6), while at several places there are no traffic lights at all as in Bogotá not at every pedestrians' crossing traffic lights are present.

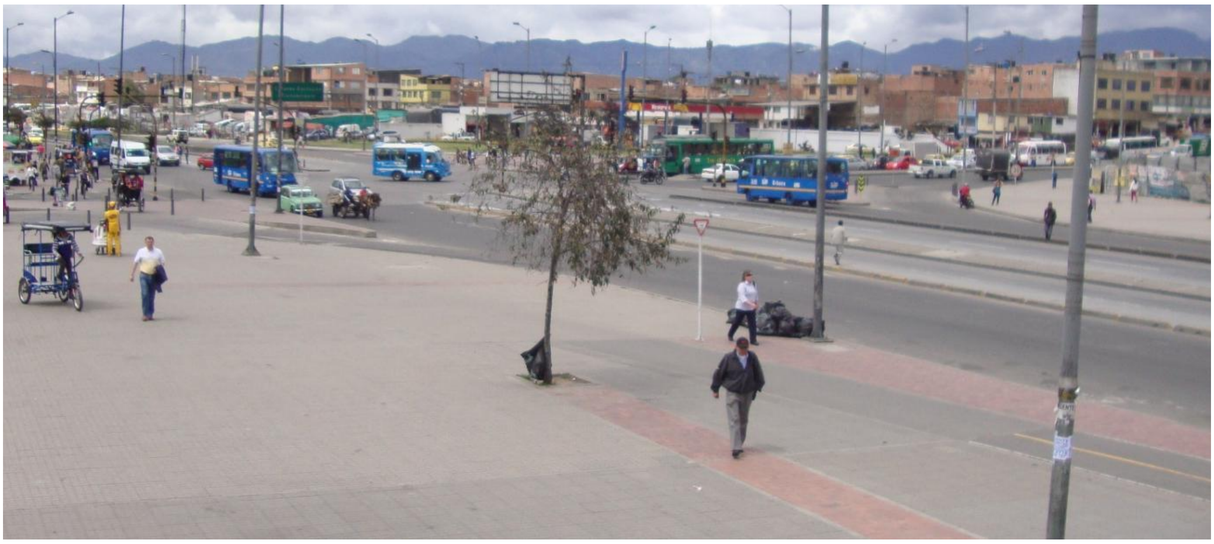

**FIGURE 3-5: WHEN APPROACHING A ROAD CROSSING (LEFT ON PHOTO), CICLORUTA ENDS AND LEADS TO THE PEDESTRIAN'S AREA**


**FIGURE 3-6: EXAMPLE OF A 'CICLORUTA CROSSING'**

## 3.3 TM AND MULTIMODAL TRIPS

The BRT system TM consists of 87 km of separate bus lanes (TransMilenio S.A., 2012). This network enables to cross larger distances within Bogotá at an average speed of 26 km/h (Teunissen et al, 2013). As there are many people living relatively far away from TransMilenio stations, there is still a large group of potential TM users. A way to enforce those people to use TM, and thus improve their job accessibility, is to enlarge the service area of TM stations. Cicloruta may be able to provide a connection to TM stations. For this purpose there are bicycle parking facilities needed at the TM stations. Although there are very few TM stations with parking facilities at the moment, this has no effect on potential accessibility. The effect of travel costs express themselves as a minimum trip length for TM trips that descends with the SES.

### 3.3.1 BICYCLE PARKING FACILITIES

When people cycle to a TM station and continue their trip by TM, they need to park their bicycle at or near the station. However, very few TM stations currently contain free and safe bike parking facilities (Appendix 1), which makes it in most cases impossible to make such a multimodal trip.

Most bicycle parkings are located at the so-called portales, large stations at the entrances of the city at which most TM lines start and end (TransMilenio S.A., 2012). Those are integrated within the building of the station (Figure 3-7). Bicycle parking facilities located at smaller TM stops consist of a separate compact building with a similar design as the stations itself. These buildings are very compact and easily fitted in the surrounding area (Figure 3-8), making it possible to provide bicycle parking facilities at virtually any TM station in the future. For this reason, it is assumed that the absence of bicycle parking facilities at TM stations are no restriction on potential job accessibility.


FIGURE 3-7: BICYCLE PARKING WITHIN THE 'PORTAL AMÉRICAS' TM STATION

FIGURE 3-8: BICYCLE PARKING BUILDING AT THE 'ALCALA' TM STATION (ECONOMÍA EN LA PANADERÍA, 2009)

### 3.3.2 Costs

The fare for a TM trip is $1.400 (Colombian pesos) off-peak hours and $1.700 during peak hours. This applies for TM trips of any length, including interchanges (TransMilenio S.A., 2012), which means that the cost impedance drops as trip length increases. This effect is the largest for low SES, since they are able to spend less on transport. Higher SES are more likely to make shorter trips with TM. In table 3-1, the minimum TM trip lengths are shown for every SES. These lengths are the $10^{th}$ percentiles of TM trip lengths provided by the mobility inquiry of Bogotá (Secretaría distrital de movilidad de Bogotá, 2011), which means that 90% of the inquired TM trips are longer for the regarded SES.

| SES | Minimum TM travel time (mins) |
|---|---|
| 1 | 60 |
| 2 | 52 |
| 3 | 45 |
| 4 | 40 |
| 5 | 30 |
| 6 | 25 |

**TABLE 3-1 MINIMUM TM TRAVEL TIMES**

### 3.3.3 Waiting time

TM buses appear at the high frequency; on average every six minutes a bus of a particular trunk line appears (TransMilenio S.A., 2012). Because of this high frequency and as there is no schedule provided, people appear at TM stations at random times. The times at which people appear at the station are uniformly distributed, which means that the average waiting time equals three minutes.

# 4 THE GIS MODEL

To calculate the distance between each origin and destination, Bogotá's transport networks need to be modelled in ArcGIS. The cadastre provides these GIS models (Catastro Distral de Bogotá, 2013). However, these models are separate for each transport network, so the models need to be merged within one GIS model in order to calculate the shortest route between each origin and destination. This has been done by doing a few adjustments and creating a network dataset.

## 4.1 MODELLED TRANSPORT NETWORKS AND THEIR IMPEDANCE

The following transport networks are provided by the cadastre:

- Street network. Travel speed: 4,392 km/h (walking)
- Cicloruta network. Travel speed: 13 km/h (cycling)

Furthermore, the TransMilenio network is provided (Universidad de los Andes, 2013):

- TransMilenio network. Travel speed: 26 km/h (bus)

## 4.2 CONNECTIONS BETWEEN THE NETWORKS

In ArcGIS, it is possible to combine these networks into a network dataset. However, without modelling the connections between the network dataset will not contain connections between the original transport networks.

Transport network models in ArcGIS consist of many separate lines that are connected. These lines consist of a single straight line or a line with one or more bends within. When creating a network dataset there are two options for connectivity: any vertex and endpoint. Endpoint means that connections are only possible at the end points of a line, while at the any vertex option connections are possible at bends as well. Connections are never possible at a straight part of a line outside of bends. Therefore, connections between the networks need to be modelled before creating the network dataset.

### 4.2.1 CONNECTIONS BETWEEN STREETS AND CICLORUTAS

To model connections between streets and Cicloruta, at the relevant places (when a Cicloruta close enough to a road) the modelled Cicloruta part is slightly moved and connected to a connectable street part (line end or vertex). If necessary, these parts are created by splitting a line element and connecting both end points to the connection point.

### 4.2.2 CONNECTIONS BETWEEN TM AND STREETS/CICLORUTAS

Modelling connections between TransMilenio and streets is a bit more complicated, as waiting time needs to be modelled as well. A number of two new GIS layers have been created to provide these connections. The first layer connects the road and Cicloruta with the TransMilenio station, which is another layer on itself. The second layer connects the station with the TransMilenio bus lanes, containing an impedance of three minutes waiting time. This is shown in Figure 4-1, that represents a section of a single transport corridor containing streets, Cicloruta, a TM line and a TM station.

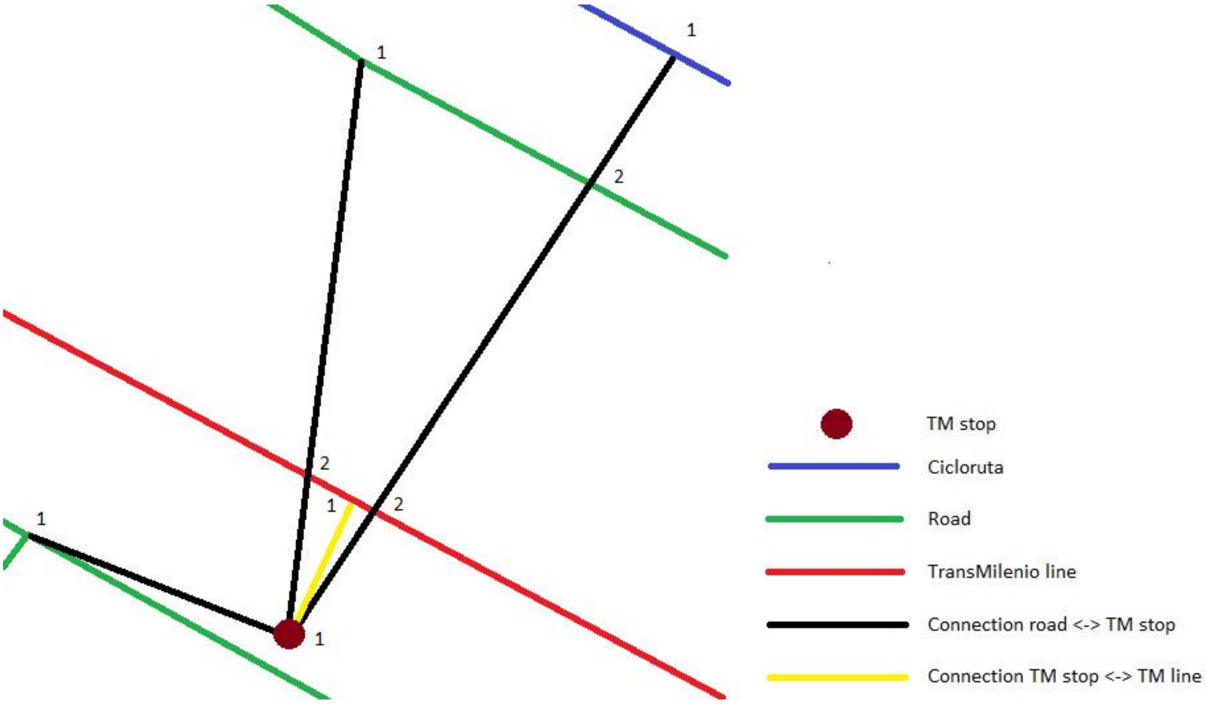


**FIGURE 4-1: EXAMPLE OF CONNECTION BETWEEN TM AND ROAD**

This is an accurate way to model the connections. As the TM line runs between two roads, both of these roads need to be connected with the TM station. In this example the Cicloruta has a separate connection as well, because there is no connection modelled between this part of Cicloruta and the road. This example models the connection between Cicloruta and the road as well, as the connection lines do not have any impedance.

The crossing of the connection lines and the TM line (2) do not provide connections between these two layers, even after the network dataset has been created. This is because at (2), there is no end point or vertex, so a connection will not be modelled. At (1), there are end points and/or vertices at both layers, so a connection is modelled here.

# 5 DISTANCE DECAY AND ACCESSIBILITY

## 5.1 METHODOLOGY

The level of job accessibility can be calculated by the accessibility function (Skov-Petersen, 2001):

$$A_i = \sum_{j=1}^{n} S_j * f(d_{ij})$$

**FUNCTION 1: ACCESSIBILITY FUNCTION**

- $A_i$ is the level of job accessibility at location $i$;
- $S_j$ is the number of suitable jobs at location $j$ ('attraction');
- $f(d_{ij})$ is the distance decay function.

The accessibility function consists of two factors. The distance decay factor is calculated by calculating the distance in minutes between every ZAT's $i$ and $j$, and calculating the distance decay from this. The result is a list of origins (O) and destinations (D), as well as the distance in minutes between every O and D. The distance decay function turns this distance into a number between 0 and 1. The other factor is attraction, which is an approach of the number of jobs within TAZ j. The result is a measure for the number of jobs within the reach of TAZ i.

### 5.1.1 DISTANCE DECAY

Distance decay is the phenomenon that a short travel distance between origin and destination result in more trips than a long travel time. The distance decay can be estimated using a distance decay function. This results in a discount factor, between 0 and 1, by which the attraction of the destination is multiplied to determine the level of accessibility. For a given location (in this research being Bogotá), the distance decay function varies with the transport mode. An estimation of the distance decay functions in Bogotá can be found using transport inquiry data (Secretaría distrital de movilidad de Bogotá, 2011). For every 5 minute travel time interval, the frequency is put in a graph along with the graphs of some possible distance decay functions. The following functions are regarded (Skov-Petersen, 2001):

$$f(d_{ij}) = \begin{cases} 1, & d_{ij} \leq treshold \\ 0, & d_{ij} > treshold \end{cases}$$

**FUNCTION 2: TRESHOLD FUNCTION**

$$f(d_{ij}) = \frac{1}{{d_{ij}}^{\lambda}}$$

**FUNCTION 3: POWER FUNCTION**

$$f(d_{ij}) = e^{-\lambda * d_{ij}}$$

**FUNCTION 4: EXPONENTIAL FUNCTION**

$$f(d_{ij}) = a * \frac{1}{\sigma\sqrt{2\pi}} * e^{-\frac{1}{2}\left(\frac{d_{ij-\mu}}{\sigma}\right)^2}$$

**FUNCTION 5: GAUSSIAN FUNCTION**

These functions are put in a graph along with the measurements, after which the parameters are calibrated. Doing this for several transport mode results in different distance decay functions per transport mode.

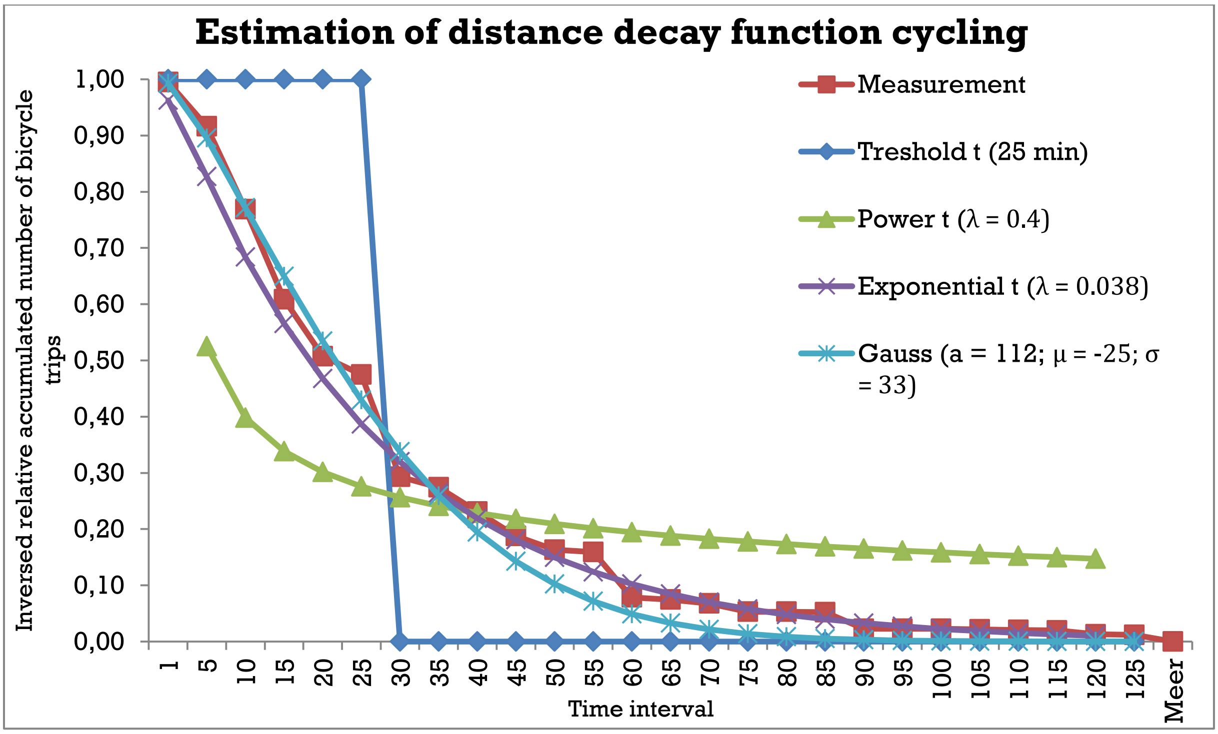


**FIGURE 5-1: ESTIMATION OF DISTANCE DECAY FUNCTION FOR CYCLING**

The graph shows that for trips shorter than 35 minuts, a Gaussian function with parameters a = 112, μ = -25 and σ = 33 is the most accurate. For trips of 35 minutes or longer, the exponential function with parameter λ = 0.038 is most accurate. This is summarized as Function 6. Estimations of distance decay functions for other transport modes can be found in appendix 2.

$$f(d_{ij}) = \begin{cases} 112 * \frac{1}{33\sqrt{2\pi}} * e^{-\frac{1}{2}\left(\frac{d_{ij+25}}{33}\right)^2}, & d_{ij} < 35\, minutes \\ e^{-0.038 * d_{ij}}, & d_{ij} \geq 35\, minutes \end{cases}$$

**FUNCTION 6: DISTANCE DECAY FUNCTION FOR CYCLING**

When considering multimodal trips (i.e. cycling and TM), there needs to be a distance decay function for multimodal trips. An option is to calculate one distance decay function for multimodal trips using data, but this is not accurate because, for example, a trip consisting of 15 minutes cycling to a TM stop combined with a 30 minutes TM trip will have a different distance decay than a trip consisting of 5 minutes cycling to a TM stop combined with a 40 minutes TM trip. More accurate is combining the distance decay functions for cycling to TM and TM itself. However, there is no information available about combining distance decay functions to account for this. For this reason, distance decay will only be estimated for cycling and cycling to TM using the decay function. To simplify the calculation, a 80 minute threshold function will be used to calculate the distance decay of the TM-part of the multimodal trip. This means:

$$f(d_{ij}) = \begin{cases} 1, & d_{ij} \leq 80\,minutes \\ 0, & d_{ij} > 80\,minutes \end{cases}$$

**FUNCTION 7: DISTANCE DECAY FUNCTION FOR TM (TRESHOLD)**

This will just slightly reduce the accuracy of this research, because only the effect of Ciclruta is considered. Because the distance unit is time and not distance, the cycling-to-TM-stop part of the trip can be calculated using the same distance decay function as walking-to-TM-stop, because the travel time is used as a distance unit. This function is as follows:

$$f(d_{ij}) = e^{-0.16*d_{ij}}$$

**FUNCTION 8: DISTANCE DECAY FUNCTION FOR CYCLING TO A TM STATION**

The independent variable of each distance decay function is the travel time. The travel time from every O and D is calculated using a model of Bogotá's transport network. To calculate the difference of accessibility caused by Cicloruta, it is necessary to make two models of the network: one with Cicloruta and one without. The network is modeled in a way that every TM station is connected with Cicloruta and/or the street network, and is only accessible at TM stations.

The distance calculations are done for every SES, only calculating the travel times from each corresponding origin TAZ and each destination TAZ.

This has been done for four different scenarios for each SES: with and without Cicloruta and for both of these with and without TransMilenio. The scenarios with TM trips are used when this travel time is longer than than the cost treshold (Table 3-1). Otherwise, the travel time without TM is used.

The result is a table of travel times for every O-D relation, Table 5-1 contains a small part of this.

| ZAT_O | ZAT_D | Minutes |
|---|---|---|
| 83 | 3 | 91,21764 |
| 83 | 4 | 87,98515 |
| 83 | 7 | 81,10601 |
| 83 | 27 | 73,57877 |
| 83 | 51 | 46,97686 |
| 83 | 53 | 56,40082 |
| 83 | 58 | 43,24407 |
| 83 | 59 | 31,5784 |
| 83 | 60 | 25,42635 |
| 83 | 63 | 46,41517 |

**TABLE 5-1: INCOMPLETE TABLE OF TRAVEL TIMES (SES6, WITH CICLORUTA)**

Afterwards, the distance decay factor is calculated in Excel, with three possible functions:

- If the trip is a cycling/walking only trip, the distance decay function for cycling/walking is used (Function 6);
- If the trip is a multimodal trip, the distance decay function for walking to TransMilenio is used for the walking/cycling to TransMilenio part of the trip (Function 8).
- If the trip takes more than 80 minutes, the distance decay factor equals zero (Function 7).

### 5.1.2 Attraction

The other factor of the accessibility function, attraction, depends on the number of suitable jobs per TAZ, which means the number of jobs for the SES for which the accessibility is calculated. The more jobs a certain TAZ contains, the more trips there are to that location. Secretaría distrital de movilidad de Bogotá (2011) provides a part of this information, namely a number of job trips to a certain TAZ. This needs to be multiplied by the total number of jobs in Bogotá and divided by the total number of job trips from the inquiry to estimate the number of jobs within a TAZ. This can be done per SES.

$$S_j = Number\ of\ job\ trips\ to\ j * \frac{Total\ number\ of\ jobs\ in\ Bogotá}{Total\ number\ of\ job\ trips\ from\ inquiry}$$

**FUNCTION 9: ESTIMATION THE ATTRACTION OF TAZ J**

The total number of jobs in Bogotá was 3.100.000 in 2005 (Camara de comercio Bogotá, 2006) and the number of job trips is 11.811, which makes the factor 262,5. The number of job trips to j is sorted by SES, so $S_j$ is different for every SES.

### 5.1.3 Accessibility

For each SES, the accessibility has been calculated. This is done by multiplying the distance decay by the attraction according to Function 10, which results in the accessibility of j from i.

$$A_{ij} = S_j * f(d_{ij})$$

**FUNCTION 10: ACCESSIBILITY OF TAZ I TO TAZ J**

To determine the total job accessibility of each TAZ i, the accessibility to the TAZ j's are summarized (Function 11)

$$A_i = \sum_{j=1}^{n} A_{ij}$$

**FUNCTION 11: SUMMARIZING THE ACCESSIBILITIES OF O-D RELATIONSHIPS**

To determine the effect of Cicloruta on job accessibility, for both scenarios (with and without Cicloruta) the accessibility is calculated, after which the difference is determined.

## 5.2 Results

### 5.2.1 Level of accessibility with Cicloruta

The level of accessibility is calculated for each SES and for each TAZ at which the regarded SES has residential locations. The total level of accessibility, with Cicloruta, for each SES is shown in Table 5-2. The distribution of accessibility through the city is shown in the figures 5-1 to 5-6.

| SES | Average job accessibility | Standard deviation |
|---|---|---|
| **1** | 5787 | 2309 |
| **2** | 18126 | 14145 |
| **3** | 25441 | 21343 |
| **4** | 15815 | 11809 |
| **5** | 6303 | 7554 |
| **6** | 15045 | 9000 |

**TABLE 5-2: AVERAGE LEVEL OF JOB ACCESSIBILITY AND STANDARD DEVIATION PER SES**

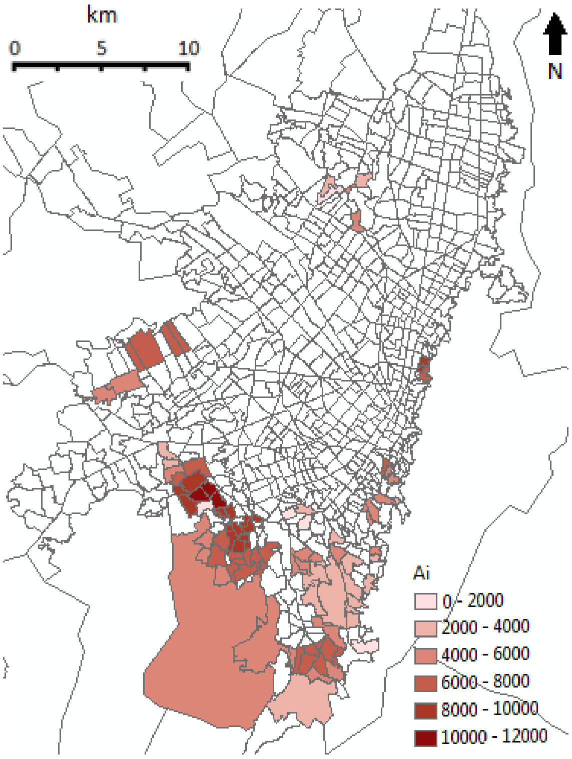


**FIGURE 5-2: JOB ACCESSIBILITY PER TAZ SES1**

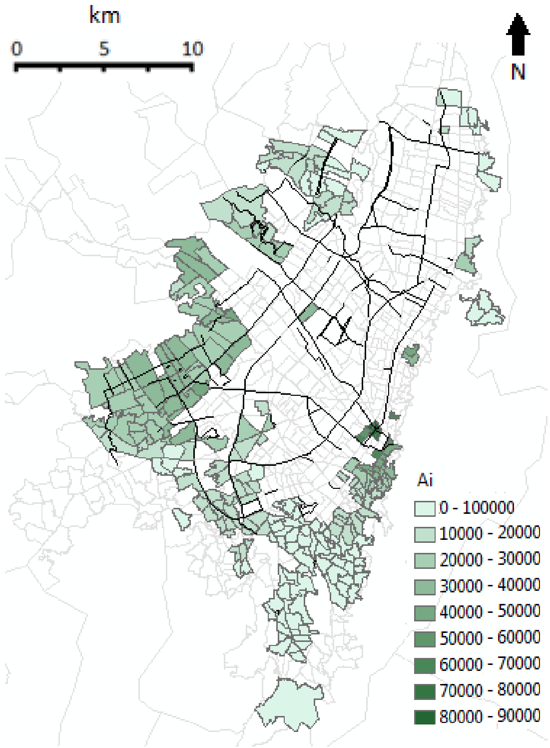


**FIGURE 5-3: JOB ACCESSIBILITY PER TAZ SES2**

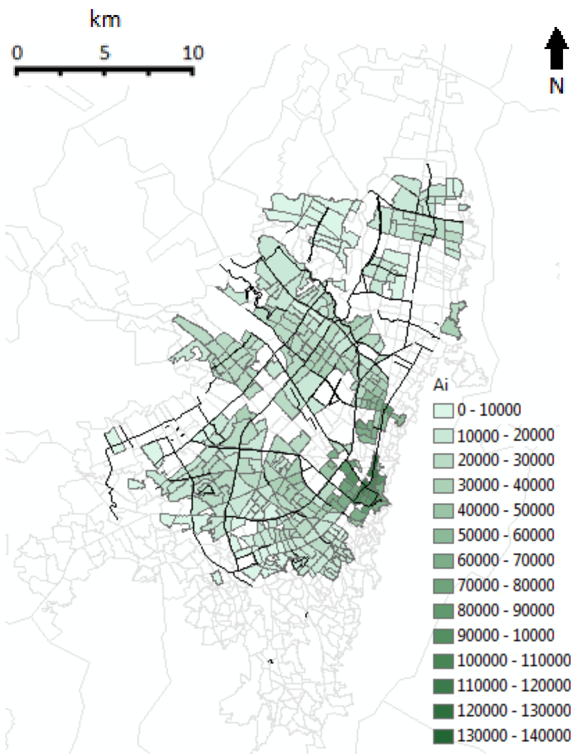


**FIGURE 5-4: JOB ACCESSIBILITY PER TAZ SES3**

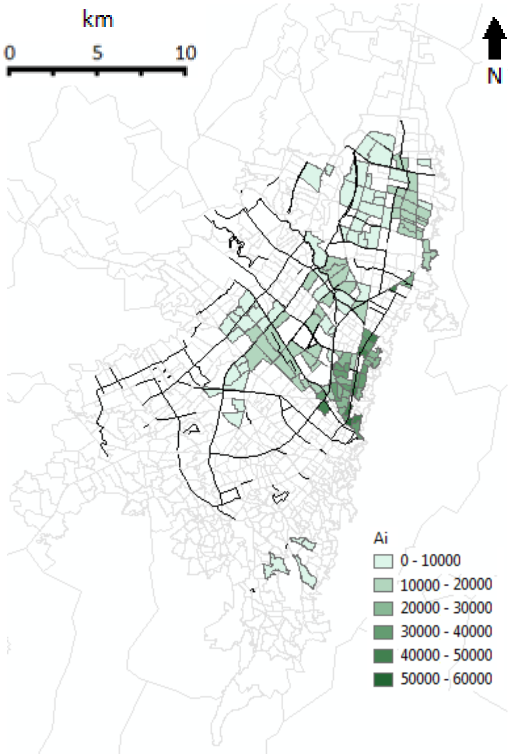


**FIGURE 5-5: JOB ACCESSIBILITY PER TAZ SES4**

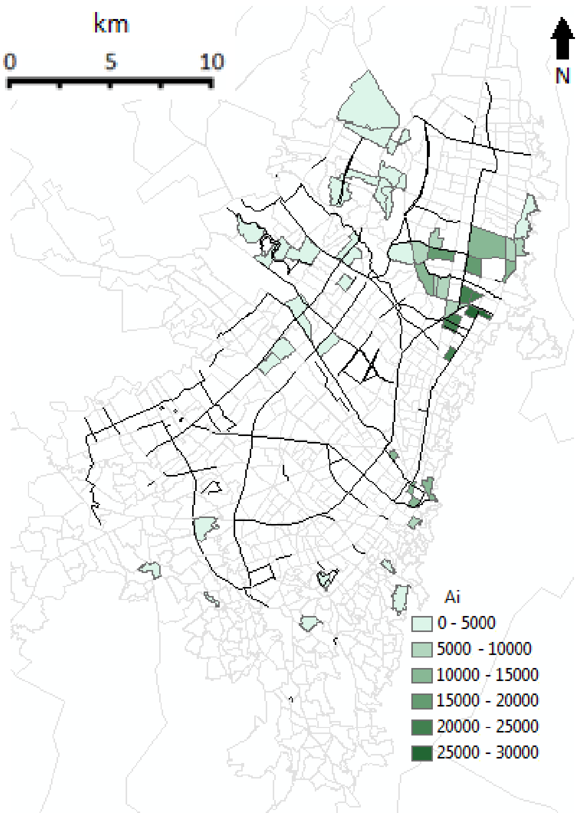


**FIGURE 5-6: JOB ACCESSIBILITY PER TAZ SES5**

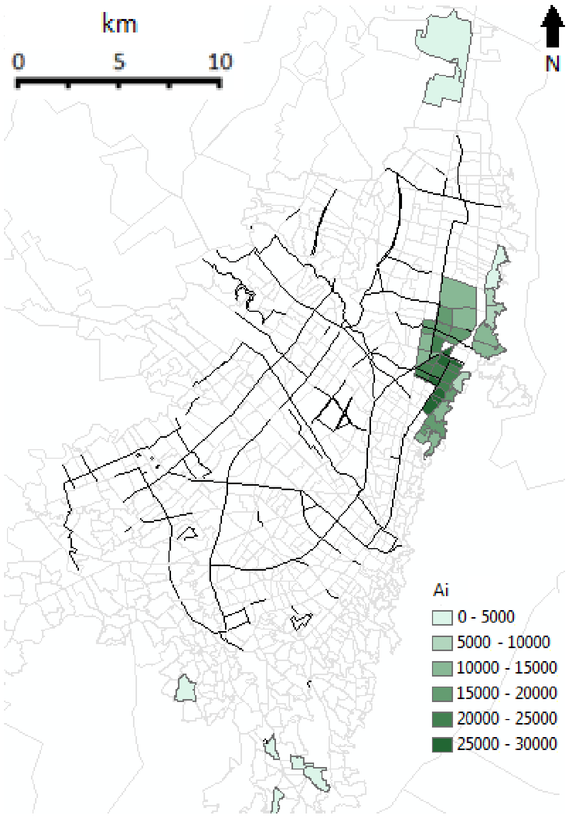


**FIGURE 5-7: JOB ACCESSIBILITY PER TAZ SES6**

### 5.2.2 CHANGE OF ACCESSIBILITY BY CICLORUTA

The chance of average job accessibility caused by Cicloruta is shown in Table 5-3. The change of the standard deviation of the accessibility is shown in Table 5-4.

| SES | Ai with Cicloruta | Ai without Cicloruta | Increase of Ai | Increase % |
|---|---|---|---|---|
| 1 | 5787 | 5047 | 740 | 15% |
| 2 | 18126 | 12843 | 5283 | 41% |
| 3 | 25441 | 15114 | 10327 | 68% |
| 4 | 15815 | 8447 | 7368 | 87% |
| 5 | 6303 | 3417 | 2886 | 84% |
| 6 | 15045 | 10381 | 4664 | 45% |

**TABLE 5-3: INCREASE OF ACCESSIBILITY CAUSED BY CICLORUTA**

| SES | Std with cicloruta | Std without cicloruta | Difference Std | Percentual difference Std |
|---|---|---|---|---|
| 1 | 2309 | 2079 | +230 | +11% |
| 2 | 14145 | 8905 | +5240 | +59% |
| 3 | 21343 | 11746 | +9597 | +82% |
| 4 | 11809 | 6173 | +5636 | +91% |
| 5 | 7554 | 3954 | +3600 | +91% |
| 6 | 9000 | 6489 | +2511 | +39% |

**TABLE 5-4: EFFECT OF CICLORUTA ON STANDARD DEVIATION OF ACCESSIBILITY**

The situation without Cicloruta is a situation in which there is no cycling traffic at all, as cycling on the street is considered both not safe and comfortable. The results show that the accessibility increases. SES1 has the least increase of accessibility, while SES4 and 5 show the largest increase. The standard deviation increases as well, which indicates that the growth of accessibility is not equally distributed across the TAZ. This is shown by the maps of the spatial distribution of accessibility change (Figure 5-8 to Figure 5-13). The change of the Z-score indicates the degree of growth compared to the average. A low Z-score means little or no growth, while a high Z-score indicates large growth. At every SES, the growth is the largest at Cicloruta connected TAZ near job concentrations and the fewest in areas remote from Cicloruta.

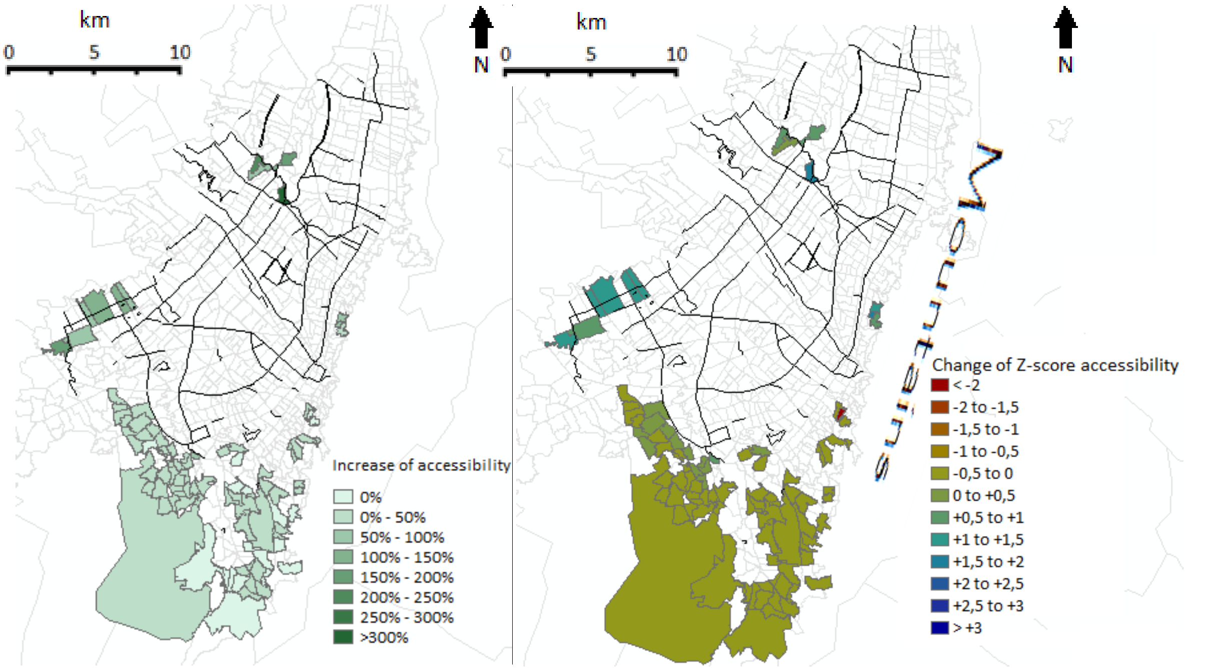


**FIGURE 5-8: SES1 – PERCENTUAL INCREASE OF JOB ACCESSIBILITY (LEFT) AND CHANGE OF Z-SCORES (RIGHT)**

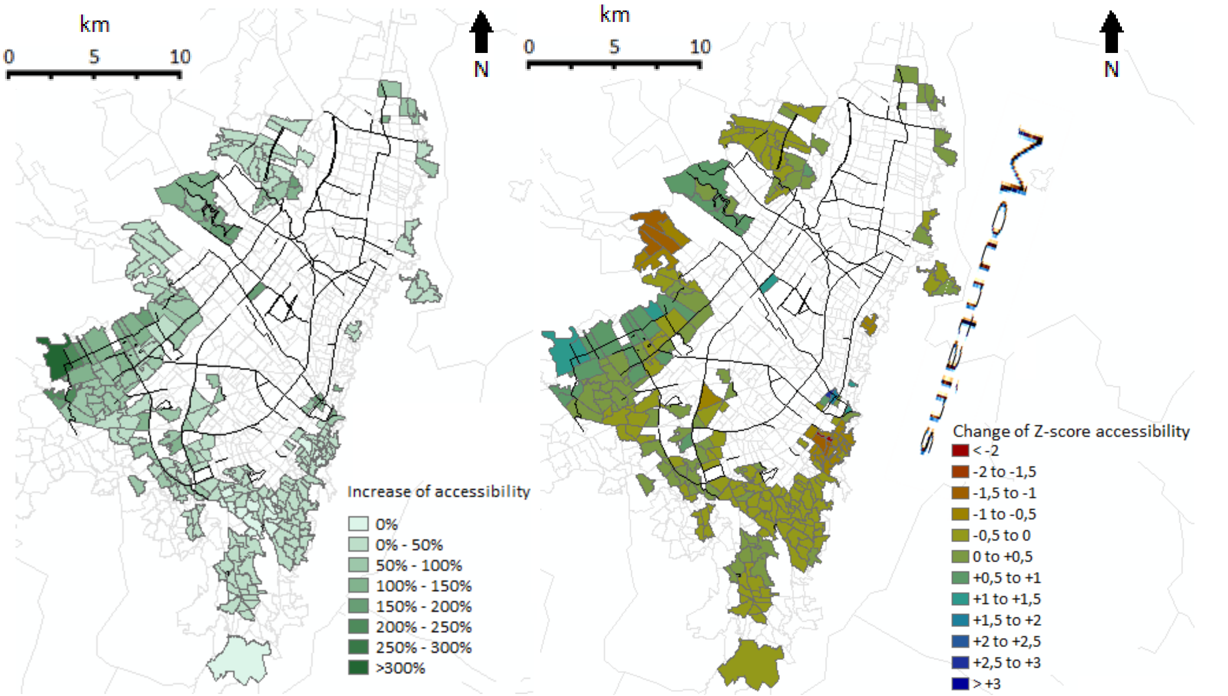


**FIGURE 5-9: SES2 – PERCENTUAL INCREASE OF JOB ACCESSIBILITY (LEFT) AND CHANGE OF Z-SCORES (RIGHT)**

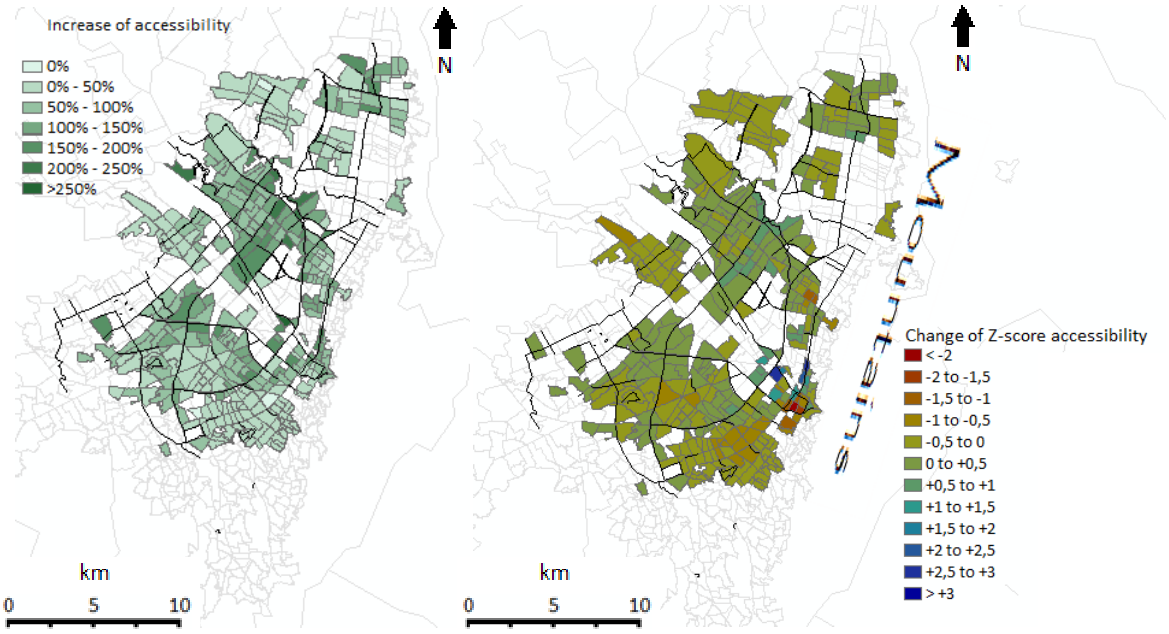


**FIGURE 5-10: SES3 – PERCENTUAL INCREASE OF JOB ACCESSIBILITY (LEFT) AND CHANGE OF Z-SCORES (RIGHT)**

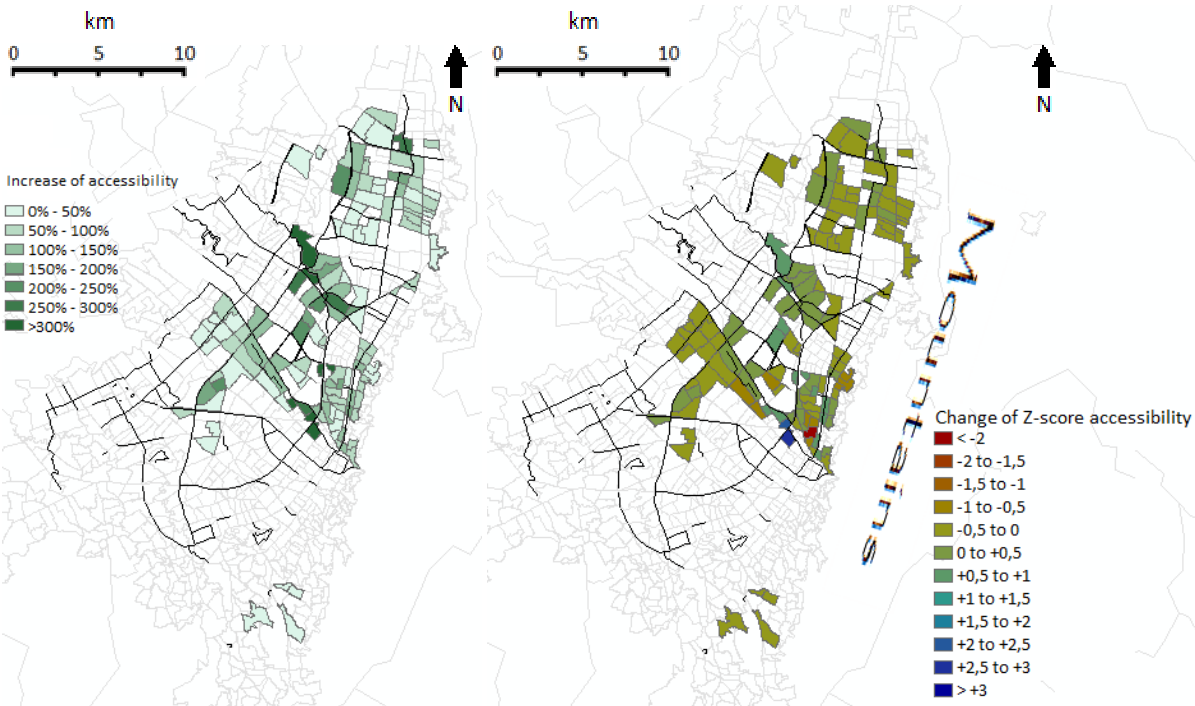


**FIGURE 5-11: SES4 – PERCENTUAL INCREASE OF JOB ACCESSIBILITY (LEFT) AND CHANGE OF Z-SCORES (RIGHT)**

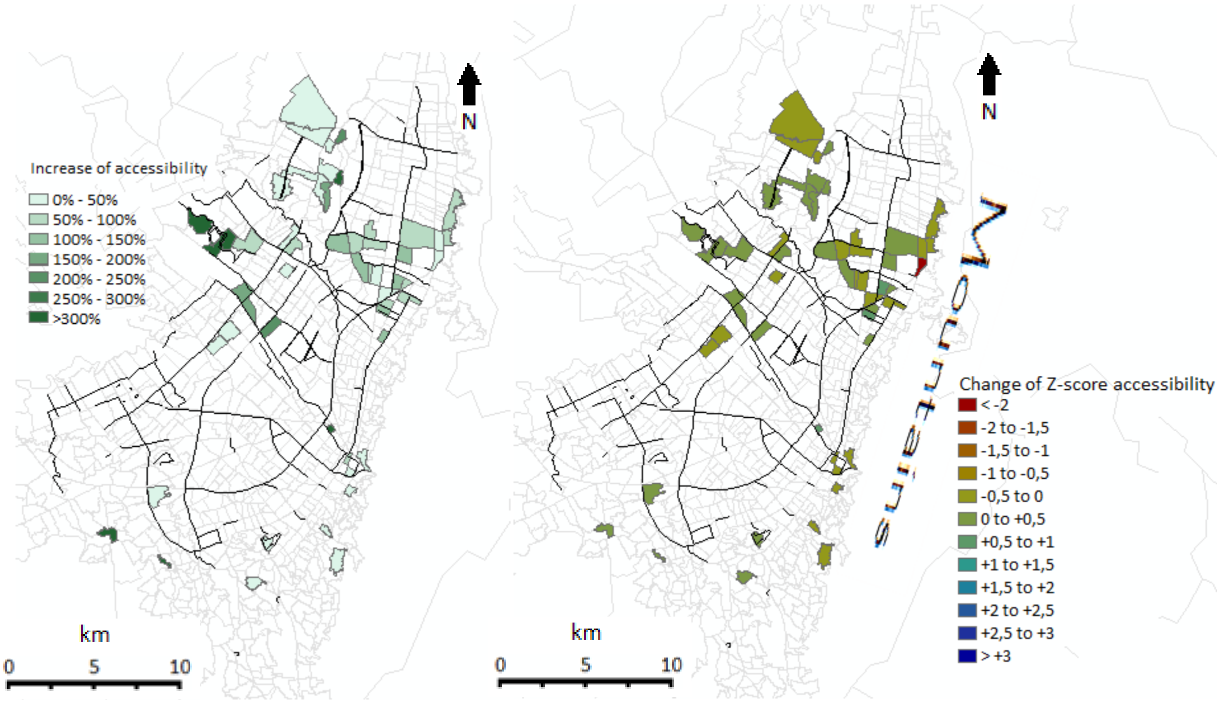


**FIGURE 5-12: SES5 - – PERCENTUAL INCREASE OF JOB ACCESSIBILITY (LEFT) AND CHANGE OF Z-SCORES (RIGHT)**

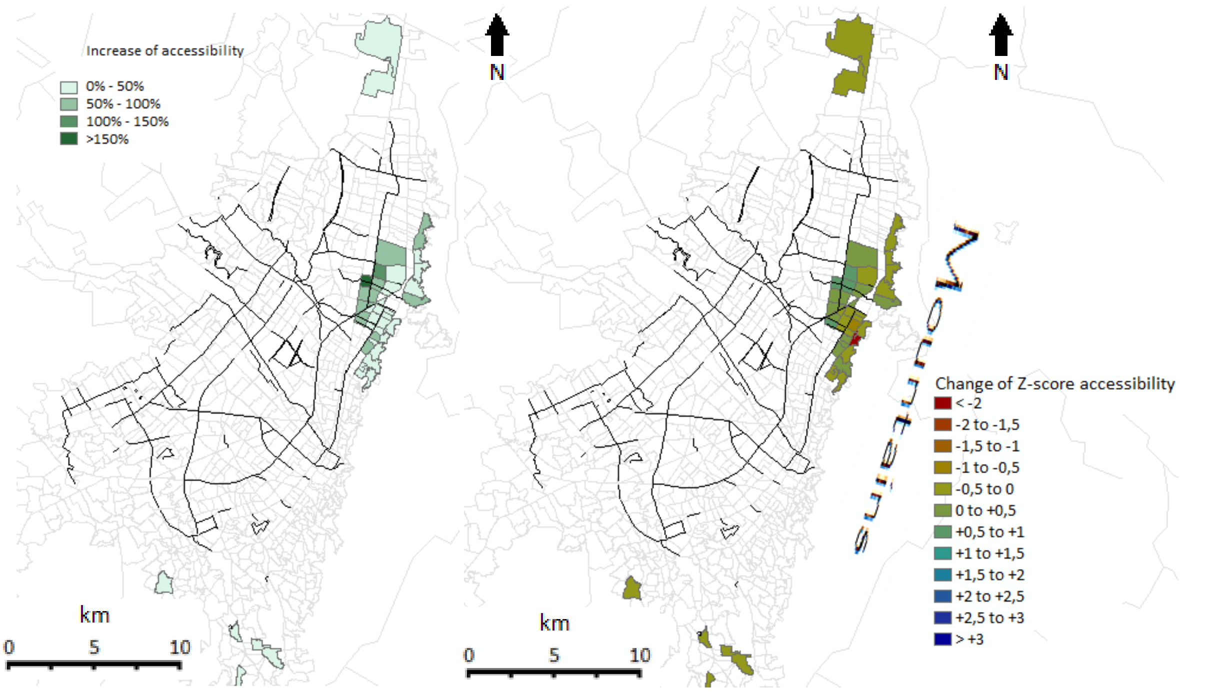


**FIGURE 5-13: SES6 – PERCENTUAL INCREASE OF JOB ACCESSIBILITY (LEFT) AND CHANGE OF Z-SCORES (RIGHT)**

# 6 CONCLUSIONS AND RECOMMENDATIONS

## 6.1 CONCLUSIONS

*What potential level of accessibility is provided by the Cicloruta network for the different social-economic classes?*

1. *What are the residential locations of the different SES levels and the corresponding job locations?*
    1. *What is a suitable definition of a 'spatial unit'?*
    2. *How can SES be assigned to spatial units?*
    3. *What are the job locations for people of the different SES?*

The potential accessibility can be determined for several spatial units: Localities, ZPU and TAZ. The 2011 mobility inquiry for Bogotá provides information about job trips for each of these spatial units. Because TAZ are most detailed and have the least overlap of SES, this is the most accurate distribution to focus accessibility research on (1.1). People from different SES tend to live at different locations within the city, the lowest strata at the edges and in the southern and southwestern parts of the city and the highest north of the city centre (1.2). There is a major job concentration for every SES in the central eastern part of the city, while minor job concentrations are coincided with the conforming residential SES location (1.3).

2. *What are the properties of the Cicloruta and TM networks that are relevant to commuting?*
    1. *What is the cycling travel time from residential locations to the Cicloruta network?*
    2. *What are the cycling travel times of commuting trips by means of Cicloruta?*
    3. *What are the travel times of commuting trips by means of the combination of Cicloruta and TM?*

Travelling to Cicloruta is possible by either cycling or walking. However, in this research only walking has been taken into account. Otherwise the would show no increase in accessibility because the cycling speed on both networks is probably the same. This would not be a desirable result as speed is not the only impedance factor; there are other, not yet quantified factors that are probably reduced by Cicloruta. For this reason, the travel speed at the street network equals walking speed (2.1). Ciclorutas provide cyclists to travel separately from motorized traffic, though at a fairly low average speed. The low average speed is a result of the integration with the pavements, so the cycle path is busy with pedestrians and other things for that Cicloruta is not designed and slow down the cycling speed. Ciclorutas are also commonly interrupted by pedestrian areas around road crossings, which enforces cyclists to share the space with pedestrians and cross the road along with them. When the average cycling speed on Cicloruta increases, the distance between origin and destination decreases, which results in a higher level of accessibility (2.2). For trips of a certain length depending on the SES, a multimodal trip by means of both Cicloruta and TransMilenio is preferred. One average speed of

TransMilenio trips has been taken into account, which is considerably higher than cycling (2.3)

3. *How accessible are the suitable jobs for different SES levels using the Cicloruta network?*
    1. *How can the distance decay on the Cicloruta and TM networks be determined?*
    2. *What is the level of accessibility of jobs by means of Cicloruta, whether or not in combination with TM, for different SES levels?*

The distance decay can be estimated by means of a distance decay function. The distance decay functions themselves are estimated for each mode by fitting possible functions and their parameters to data about trip lengths. Little is known about combining different distance decay functions for the purpose of multimodal trips, so in this research only the distance decay function for cycling is used, while the TransMilenio part of trips is not discounted when below a treshold level (3.1). The Cicloruta network provides people living in near TAZ's a faster way to travel to jobs whether or not using TM as well, providing a higher level of accessibility. However, regarding the current state of the network, the job accessibility is unequally distributed through the city. There is a large difference in potential accessibility increase between areas that are near Cicloruta and those remote from Cicloruta. Areas that are remote from Cicloruta are spread through the city; some places are in a remote part of the city where is currently no Cicloruta, while other places are remote from the network because it is not dense enough. This indicates that the current network is not extensive enough to provide an increase of accessibility for the benefit of the entire city (3.2). This becomes clearest when regarding the lowest SES.

1. *How can the information about accessibility improve liveability in Bogotá?*
    1. *How can the received information be used to improve the accessibility for every SES level?*
    2. *To which extent is the Cicloruta network able to improve the job accessibility of different SES, whether or not in combination with TM?*

Most SES1 neighbourhoods are located at remote places that Cicloruta has not reached yet, which results in relatively little increase of accessibility. To increase the level of accessibility of the poorest inhabitants of Bogotá, and thus increase their chances to participate in society, Cicloruta needs to be extended to these areas. However, as these neighbourhoods are quite mountainous, it is questionable whether this is possible (4.1).

Even when the average speed is improved, there will be still many places that are not sufficiently connected by Cicloruta. It is true that Cicloruta provides a higher level of accessibility, but as that is only for areas close to the network the spatial difference in accessibility is increased by the network. This enhances the need to both expand Cicloruta to remote parts of the city and dense the network throughout the whole city, so Cicloruta will provide a higher level of accessibility for every inhabitant of Bogotá (4.2).

## 6.2 Limitations

- Few is known about the cycling speed on the normal street. It is not likely that people travelling to Cicloruta will walk with their bicycle, but the streets in Bogotá are not designed for cyclists. Further research about cycling on the street in Bogotá is needed to do statements about this.
- Like cycling speed on the street, there is not much known about road safety on the street. The only data available are numbers of accidents, but there is no known relationship between this and the influence on people's route choices. When this information is known, it can provide a way to determine the impedance of certain streets, so the route choices can be modelled more adequately.
- TransMilenio is currently overcrowded (The Economist, 2011), which makes it less possible to exploit its potential of a part of multimodal transport. It is recommended to investigate the effect of multimodal transport on the occupation of TM, as well as its residual capacity. Furthermore, it is recommended to investigate whether the complete system is overcrowded or only a couple of trunk lines, so multimodal transport can be focused on less crowded lines.
- Criminality still occurs at several parts of Bogotá, including parts of Cicloruta. This may decrease the accessibility because people may avoid cycling through certain areas. This increases the travel distance and decreases the accessibility. Like on road safety, research needs to be done on criminal safety and the influence on people's decisions.

## 6.3 Recommendations

By doing further research on limitations of this research, conclusions of both this research and similar researches will become more valid.

- Investigate and quantify the impedance factors of cycling on both streets and Cicloruta other than speed. This will result in a more accurate and valid view of the change in accessibility caused by Cicloruta.
- Establish a way to combine distance decay functions for the purpose of multimodal trips. This will result in a more accurate way to estimate distance decay for these multimodal trips.

The current distribution of jobs in de city of Bogotá is also a limitation for the job accessibility for the neighbourhoods situated far from the city center.

- In this research, every job is considered as suitable for only 1 SES, without taking the type of job itself into account. Do research on this, and the job types for each SES will become clear making it easier to do interventions on increasing the number and/or accessibility of jobs for certain SES. There may also be jobs suitable for more than just one SES.
- When doing interventions on the number of jobs within Bogotá, make sure that jobs are created mostly outside of current job concentration areas. This way more people will live near their job locations and have a higher level of job accessibility, especially by bicycle.

To exploit the potential level of accessibility provided by Cicloruta, several interventions are possible. These interventions will contribute to the level of accessibility.

- Seperating Ciclorutas physically from the pavement will prevent pedestrians to accidentally walk on Ciclorutas. This can be achieved, for example, by situating the cycle path slightly lower than the pedestrian zone. This way Cicloruta is more like a small street than a pedestrian zone, so pedestrians will avoid it like they avoid the street right now.
- Turn Cicloruta in a consistent network without interruptions will improve the cycling speed. There are several possible interventions to achieve this (Teunissen, 2012). This will not only result in higher cycling speed but also in a better cycling experience because less interruptions equal a smoother cycling trip.
- It is currently not possible to cycle to a TM station and travel on by TM, because there are no bicycle parking facilities at most TM stations. This can be overcome by building compact bicycle parkings at TM stations, but also by introducing bicycle sharing programs.
- There are plans for a metro in the future, connecting the south-western and north-eastern parts of Bogotá with the job concentrations in the east (Metro en Bogotá, 2013). This is a great opportunity to promote and stimulate multimodal transport from the beginning. Before the system opens, the Cicloruta network must be focussed on the stations. Furthermore, people need to be encouraged to use their bicycle to travel to metro stations, for example by promotion or a discount on the train ticket when they use the bicycle parking facilities at a metro station.

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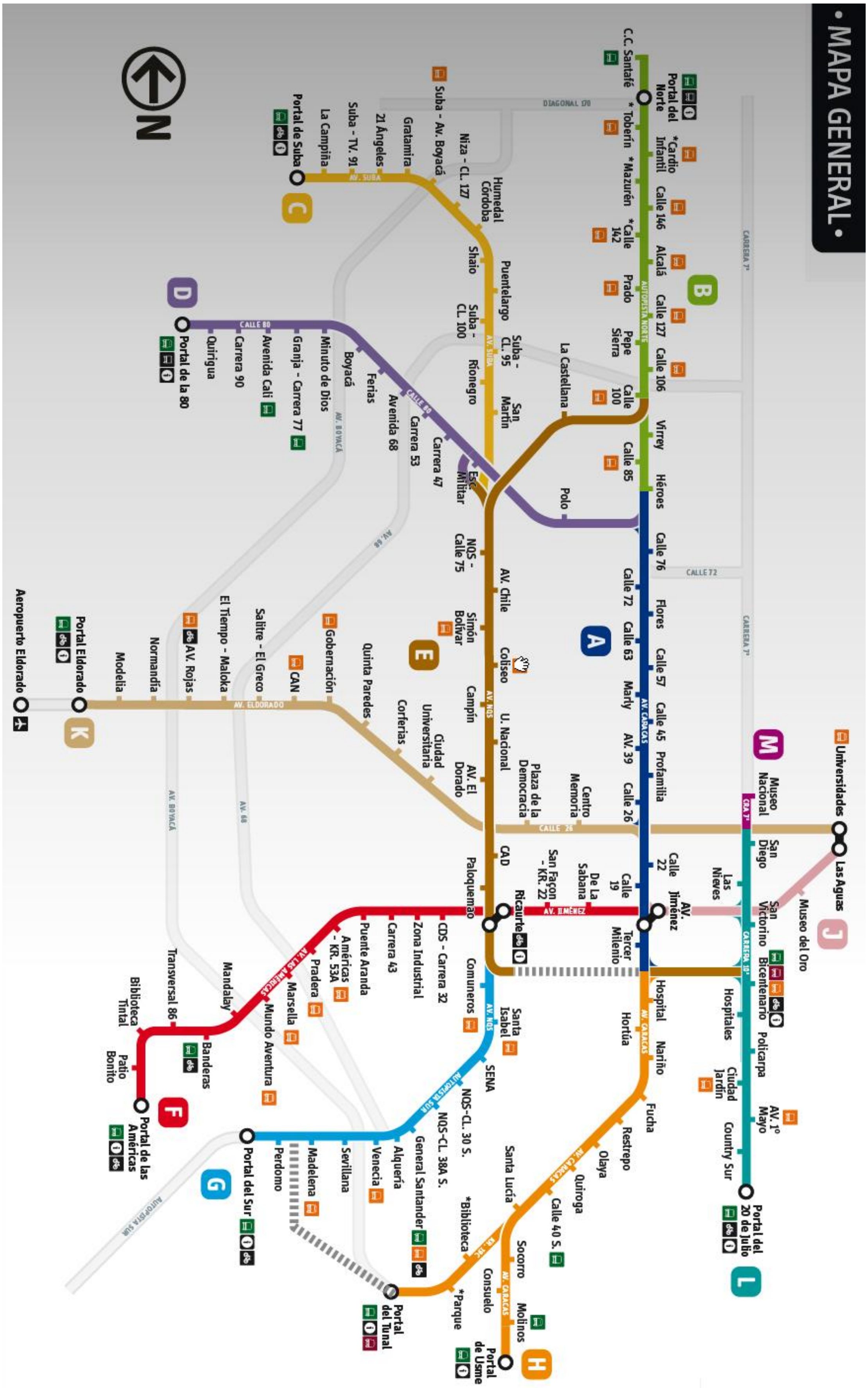
# APPENDICES

# 1 MAP OF TRANSMILENIO




(TransMilenio S.A., 2012)

# 2 ESTIMATIONS OF DISTANCE DECAY FUNCTIONS

## 2.1 POSSIBLE DISTANCE DECAY FUNCTIONS

(Skov-Petersen, 2001)

### 2.1.1 TRESHOLD

$$f(d_{ij}) = \begin{cases} 1, & d_{ij} \leq treshold \\ 0, & d_{ij} > treshold \end{cases}$$

### 2.1.2 POWER

$$f(d_{ij}) = \frac{1}{{d_{ij}}^{\lambda}}$$

### 2.1.3 EXPONENTIAL

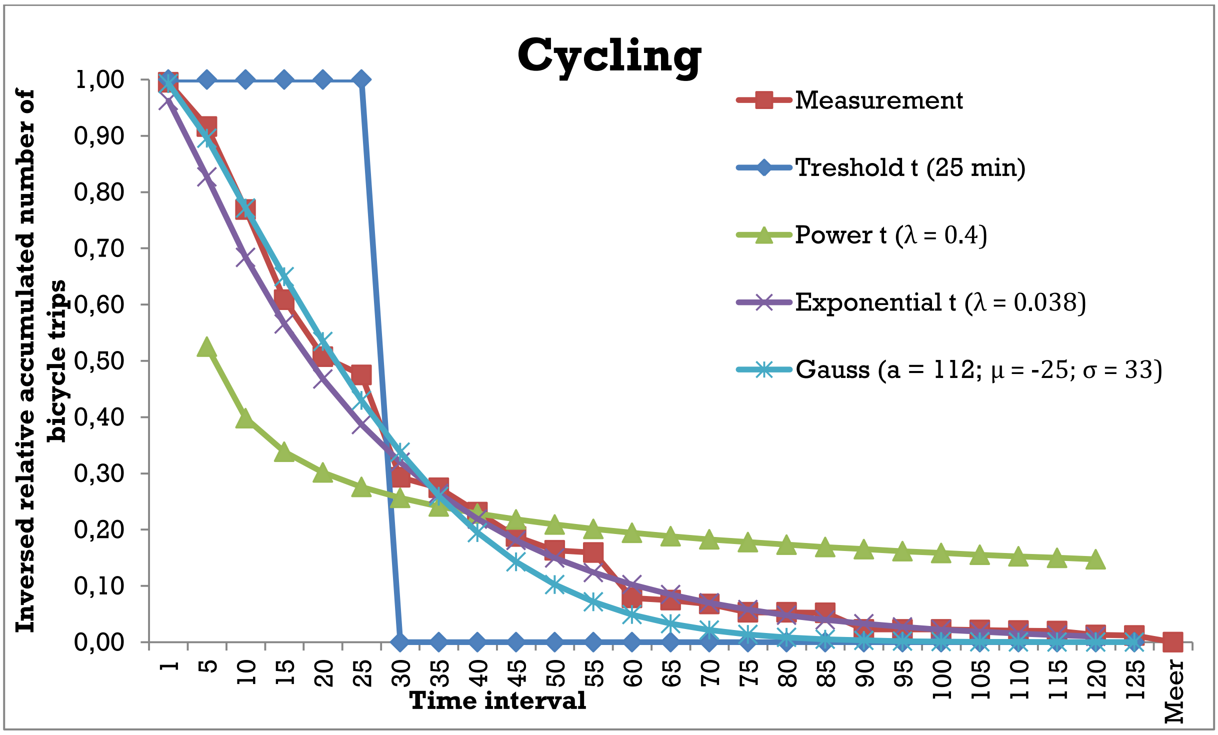
$$f(d_{ij}) = e^{-\lambda * d_{ij}}$$

### 2.1.4 GAUSS

$$f(d_{ij}) = a * \frac{1}{\sigma\sqrt{2\pi}} * e^{-\frac{1}{2}\left(\frac{d_{ij-\mu}}{\sigma}\right)^2}$$

## 2.2 Distance decay estimations

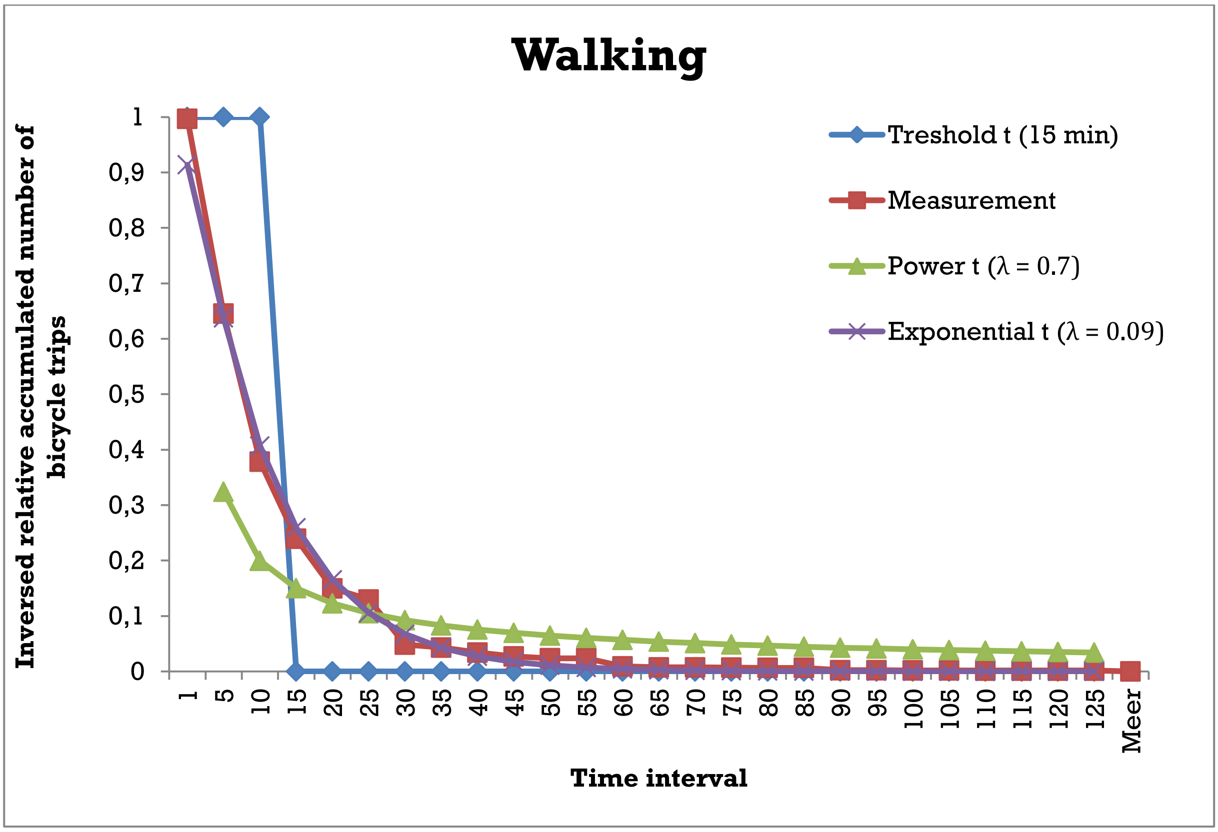
### 2.2.1 Bicycle




$$f(d_{ij}) = \begin{cases} a * \frac{1}{\sigma\sqrt{2\pi}} * e^{-\frac{1}{2}\left(\frac{d_{ij}-\mu}{\sigma}\right)^2}, & d_{ij} < 35\ minutes \\ e^{-\lambda * d_{ij}}, & d_{ij} \geq 35\ minutes \end{cases}$$

$$f(d_{ij}) = \begin{cases} 112 * \frac{1}{33\sqrt{2\pi}} * e^{-\frac{1}{2}\left(\frac{d_{ij}+25}{33}\right)^2}, & d_{ij} < 35\ minutes \\ e^{-0.038 * d_{ij}}, & d_{ij} \geq 35\ minutes \end{cases}$$

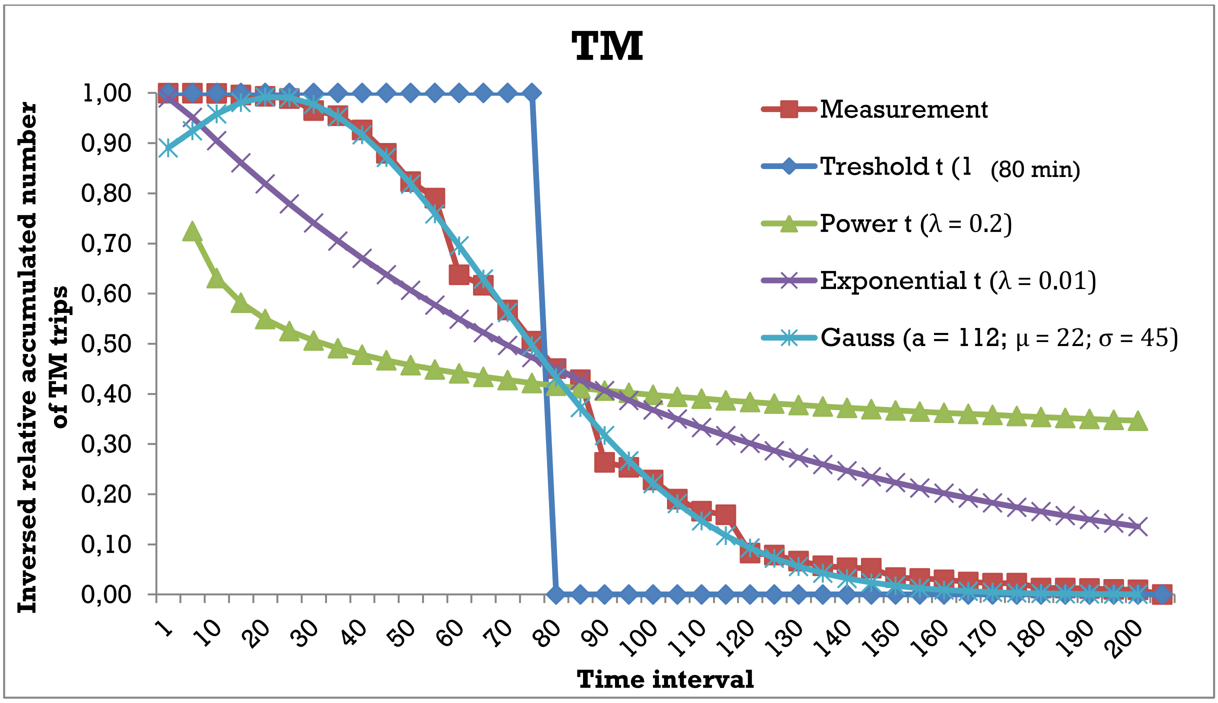
### 2.2.2 WALKING




$$f(d_{ij}) = e^{-\lambda * d_{ij}}$$

$$f(d_{ij}) = e^{-0.09 * d_{ij}}$$

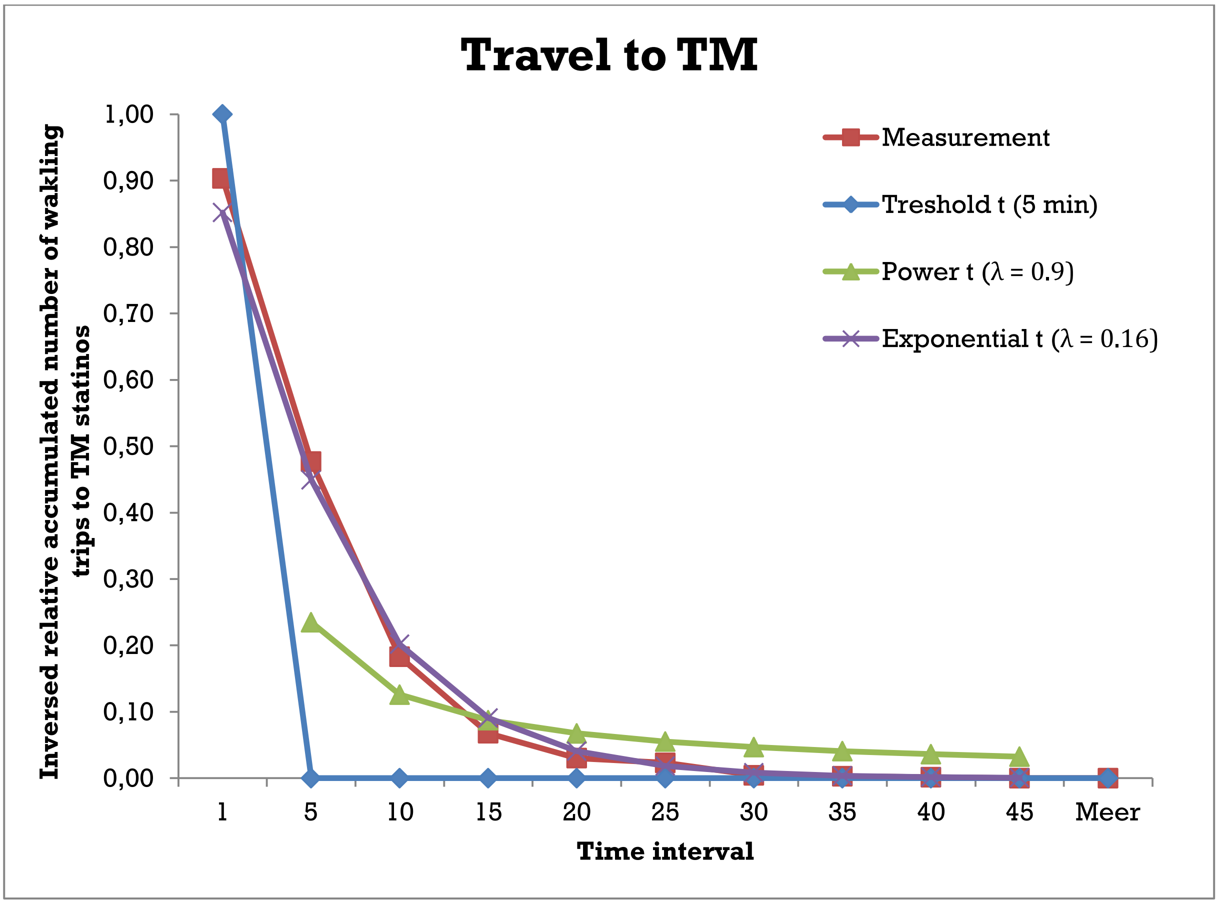
### 2.2.3 TransMilenio




$$f(d_{ij}) = \begin{cases} 1, & d_{ij} < 20\ minutes \\ a * \frac{1}{\sigma\sqrt{2\pi}} * e^{-\frac{1}{2}\left(\frac{d_{ij}-\mu}{\sigma}\right)^2}, & d_{ij} \geq 20\ minutes \end{cases}$$

$$f(d_{ij}) = \begin{cases} 1, & d_{ij} < 20\ minutes \\ 112 * \frac{1}{45\sqrt{2\pi}} * e^{-\frac{1}{2}\left(\frac{d_{ij}-22}{45}\right)^2}, & d_{ij} \geq 20\ minutes \end{cases}$$

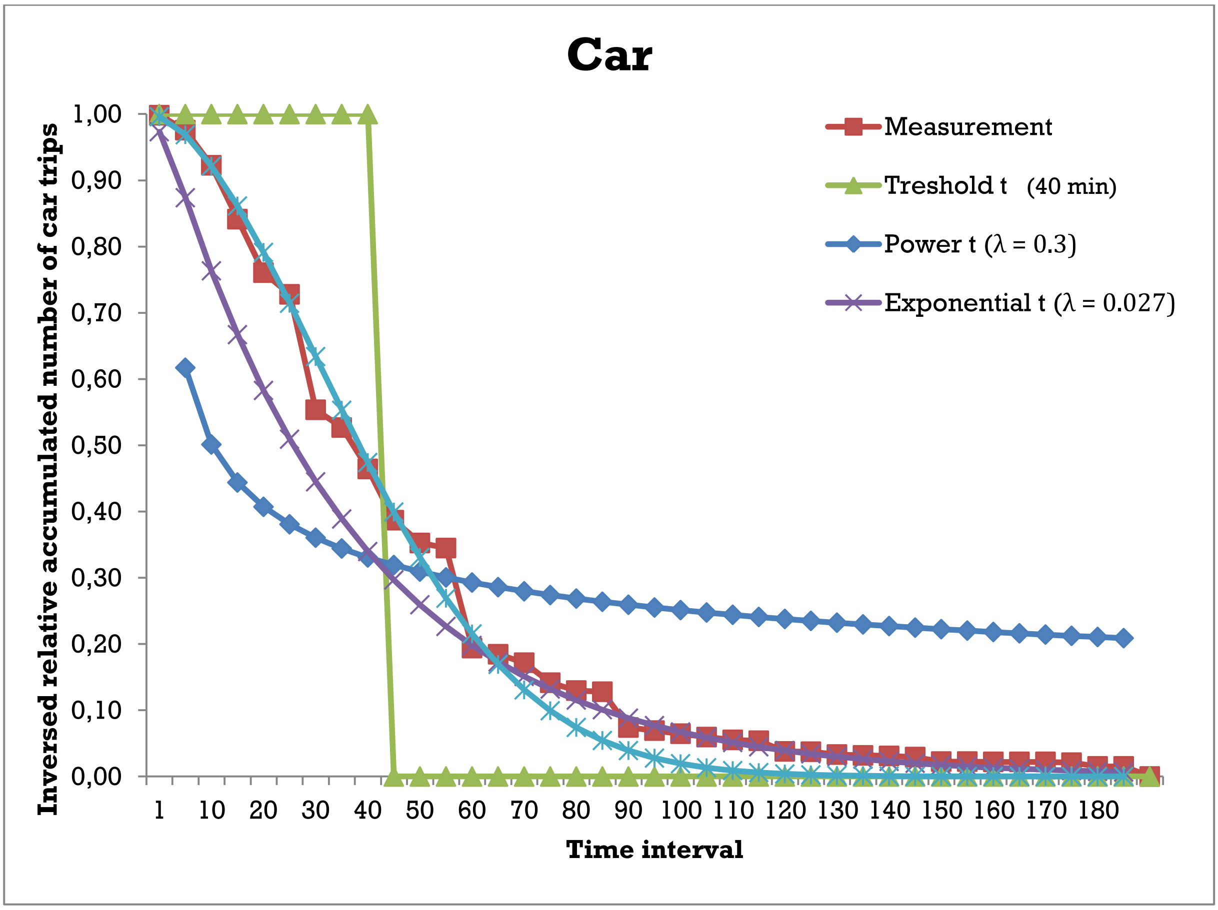
### 2.2.4 Walking to TransMilenio




$f(d_{ij}) = e^{-\lambda * d_{ij}}$

$f(d_{ij}) = e^{-0.16 * d_{ij}}$

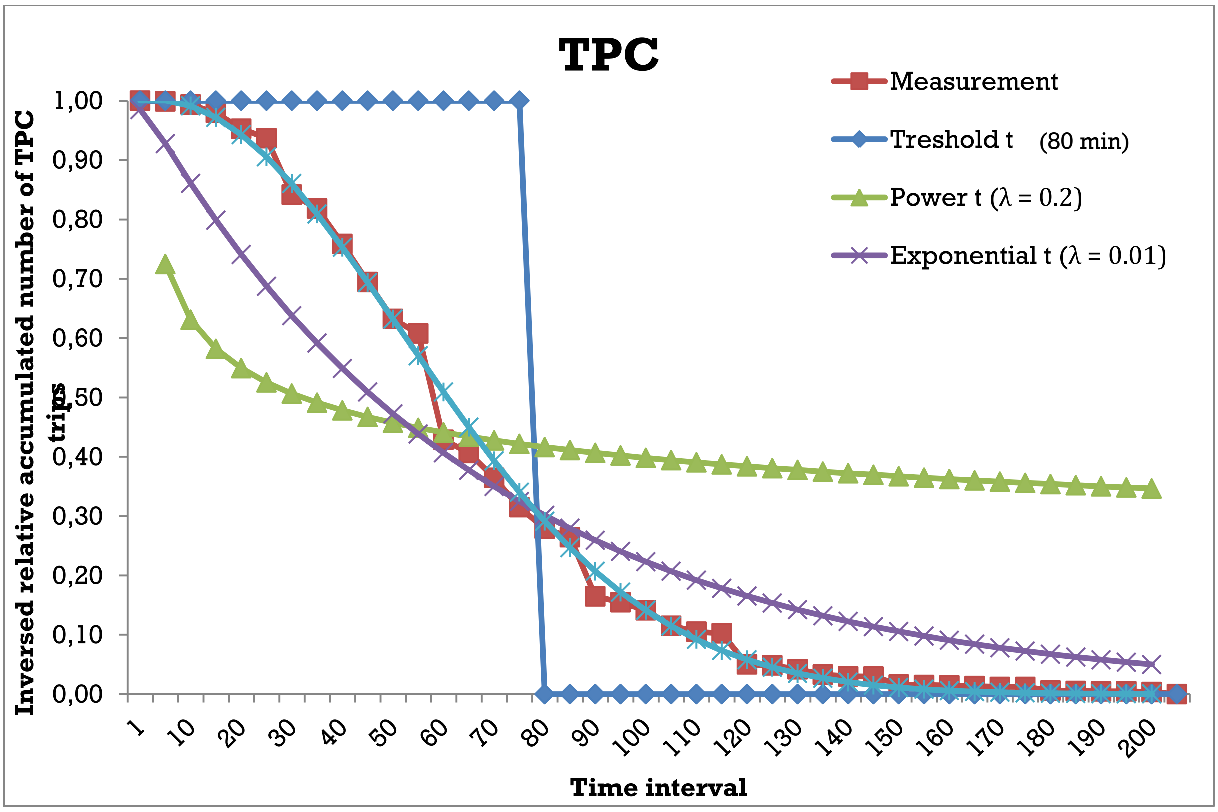
### 2.2.6 Car




$$f(d_{ij}) = \begin{cases} a * \frac{1}{\sigma\sqrt{2\pi}} * e^{-\frac{1}{2}\left(\frac{d_{ij}-\mu}{\sigma}\right)^2}, & d_{ij} < 60 \ minutes \\ e^{-\lambda * d_{ij}}, & d_{ij} \geq 60 \ minutes \end{cases}$$

$$f(d_{ij}) = \begin{cases} 95 * \frac{1}{37\sqrt{2\pi}} * e^{-\frac{1}{2}\left(\frac{d_{ij}+7}{37}\right)^2}, & d_{ij} < 60 \ minutes \\ e^{-0.027 * d_{ij}}, & d_{ij} \geq 60 \ minutes \end{cases}$$

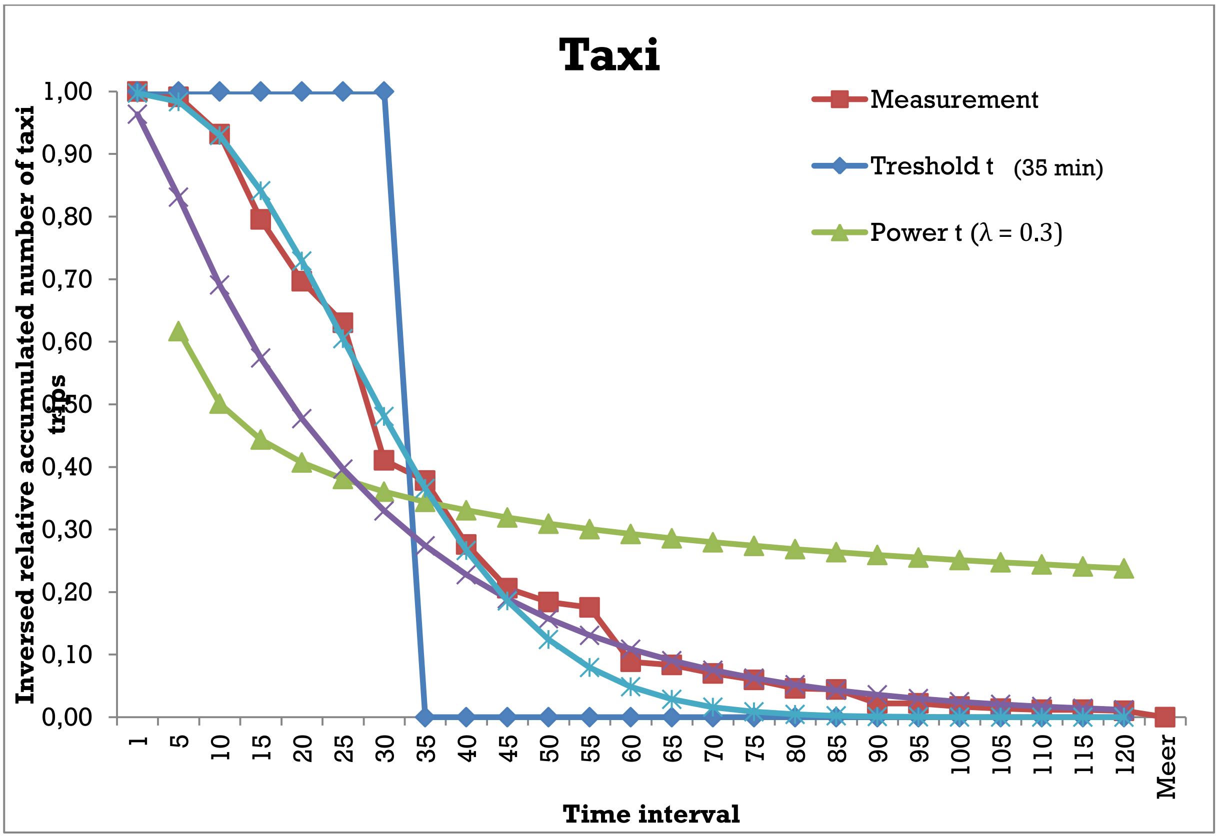
### 2.2.7 TPC (I.E. REGULAR BUSES OR COLECTIVOS)




$$f(d_{ij}) = a * \frac{1}{\sigma\sqrt{2\pi}} * e^{-\frac{1}{2}\left(\frac{d_{ij-\mu}}{\sigma}\right)^2}$$

$$f(d_{ij}) = 123 * \frac{1}{49\sqrt{2\pi}} * e^{-\frac{1}{2}\left(\frac{d_{ij-3}}{49}\right)^2}$$

### 2.2.8 Taxi




$$f(d_{ij}) = \begin{cases} a * \frac{1}{\sigma\sqrt{2\pi}} * e^{-\frac{1}{2}\left(\frac{d_{ij}-\mu}{\sigma}\right)^2}, & d_{ij} < 40\ minutes \\ e^{-\lambda * d_{ij}}, & d_{ij} \geq 40\ minutes \end{cases}$$

$$f(d_{ij}) = \begin{cases} 60 * \frac{1}{24\sqrt{2\pi}} * e^{-\frac{1}{2}\left(\frac{d_{ij}-1}{24}\right)^2}, & d_{ij} < 40\ minutes \\ e^{-0.027 * d_{ij}}, & d_{ij} \geq 40\ minutes \end{cases}$$

## 3 INCOMPLETE TABLE OF ACCESSIBILITY CALCULATION

(SES6, with Cicloruta)

| TAZ_O | TAZ_D | Minutes | Jobs_TAZ_D_SES6 (inquiry) | f(dij)bike | Sj | Aij |
|---|---|---|---|---|---|---|
| **83** | 60 | 25 | 2 | 0,421 | 525 | 221 |
| **83** | 854 | 30 | 2 | 0,333 | 525 | 175 |
| **83** | 86 | 31 | 2 | 0,314 | 525 | 165 |
| **83** | 59 | 32 | 1 | 0,311 | 262 | 82 |
| **83** | 71 | 42 | 1 | 0,202 | 262 | 53 |
| **83** | 58 | 43 | 1 | 0,193 | 262 | 51 |
| **83** | 153 | 45 | 4 | 0,182 | 1050 | 192 |
| **83** | 63 | 46 | 2 | 0,171 | 525 | 90 |
| **83** | 69 | 47 | 1 | 0,169 | 262 | 44 |
| **83** | 51 | 47 | 1 | 0,168 | 262 | 44 |
| **83** | 147 | 50 | 10 | 0,152 | 2625 | 398 |
| **83** | 87 | 51 | 4 | 0,142 | 1050 | 149 |
| **83** | 155 | 56 | 2 | 0,117 | 525 | 62 |
| **83** | 53 | 56 | 1 | 0,117 | 262 | 31 |
| **83** | 88 | 59 | 3 | 0,108 | 787 | 85 |
| **83** | 152 | 63 | 2 | 0,091 | 525 | 48 |
| **83** | 852 | 63 | 4 | 0,090 | 1050 | 95 |
| **83** | 156 | 63 | 2 | 0,090 | 525 | 47 |
| **83** | 148 | 66 | 1 | 0,083 | 262 | 22 |
| **83** | 146 | 66 | 2 | 0,080 | 525 | 42 |
| **83** | 149 | 67 | 2 | 0,080 | 525 | 42 |
| **83** | 851 | 67 | 2 | 0,079 | 525 | 41 |

The complete table consists of 6150 rows and is available on request, as well as the tables for other scenarios and SES.

# 4 ACCESSIBILITY LEVEL PER ORIGIN TAZ (SES6, WITH CICLORUTA)

| TAZ_O | Ai | Z_score |
|---|---|---|
| **83** | 3145 | -1,32 |
| **85** | 5961 | -1,01 |
| **87** | 11273 | -0,42 |
| **144** | 14850 | -0,02 |
| **145** | 16442 | 0,16 |
| **147** | 12967 | -0,23 |
| **148** | 18300 | 0,36 |
| **150** | 25310 | 1,14 |
| **154** | 8378 | -0,74 |
| **155** | 12149 | -0,32 |
| **156** | 14834 | -0,02 |
| **164** | 24314 | 1,03 |
| **165** | 24569 | 1,06 |
| **166** | 23557 | 0,95 |
| **243** | 25897 | 1,21 |
| **244** | 14309 | -0,08 |
| **245** | 26027 | 1,22 |
| **248** | 15408 | 0,04 |
| **250** | 10726 | -0,48 |
| **252** | 13625 | -0,16 |
| **253** | 17270 | 0,25 |
| **257** | 25861 | 1,20 |
| **258** | 24970 | 1,10 |
| **259** | 27909 | 1,43 |
| **260** | 23317 | 0,92 |
| **261** | 22588 | 0,84 |
| **262** | 24435 | 1,04 |
| **263** | 26736 | 1,30 |
| **264** | 16390 | 0,15 |
| **265** | 9613 | -0,60 |
| **720** | 144 | -1,66 |
| **736** | 1005 | -1,56 |
| **743** | 535 | -1,61 |
| **745** | 474 | -1,62 |
| **756** | 272 | -1,64 |
| **849** | 11996 | -0,34 |
| **850** | 23270 | 0,91 |
| **851** | 19560 | 0,50 |
| **852** | 16311 | 0,14 |
| **958** | 1387 | -1,52 |
| **960** | 747 | -1,59 |

The other tables are available on request

# 5 Distribution of TM trip lengths

Trip lengths are in minutes

| SES | P10 | P50 | Average | Modal |
|---|---|---|---|---|
| **1** | 60 | 90 | 102 | 90 |
| **2** | 52 | 90 | 88 | 90 |
| **3** | 45 | 65 | 74 | 60 |
| **4** | 40 | 60 | 67 | 60 |
| **5** | 30 | 55 | 61 | 60 |
| **6** | 25 | 60 | 80 | 60 |