Contribution of the Metro de Bogotá to the city's accessibility

Rogier Busscher
S1341367

1. Preface

This document forms the research performed for my bachelor thesis for the program of civil engineering at the University of Twente. I seized the opportunity to perform my thesis abroad, resulting in an interesting internship at the University Piloto Colombia in Bogota. The opportunity to do my research here in Bogota lead to me learning a lot about both (public) transport in Bogota, as well as the Colombian way of living.

However, without the support of several people, I would never have been able to take on this challenge.

First of all, I would like to thank Mark Brussel, who provided the contacts with the UPC and invested a large amount of time in reviewing and giving feedback on both this bachelor thesis as well as the thesis proposal. I also would like to say that I enjoyed or regular Skype meetings. Also, I would like to thank Karst Geurs for finding time is his agenda to provide me with the occasional feedback.

Furthermore, I would like to thank my colleagues at the Gestion Urbana at the Piloto University. Especially Carlos Moreno deserves my gratitude. Next to the provided feedback, help, discussion about my work and the occasional translating, he also made my time here in Bogotá really fun, by taking me along for trips outside the city and enjoying the occasional dinner.

Lastly, I would like to thank my family for supporting my journey to Bogotá.

2. Abstract

In Bogotá, Colombia's largest city and capital, a new metro will be build. El Metro de Bogotá. This project that will cost several hundreds of million US dollars, is expected to be ready in 2022. Right now, the city and its more than seven million inhabitants have to rely on BRT and conventional buses as their only source of motorized public transport. A metro may be a very big step forward, albeit, there are certain phenomena that raise suspicion whether or not the benefits of the metro will be distributed equally among the socio-economic classes.

In this research, a multimodal GIS analysis has been performed to analyze the effects on travel times and generalized travel costs. This was done by building an ArcGIS model with the most important public transport modes and non-motorized transport. Then the metro was added into this model and a before and after analysis was done.

With this data, three different measures of accessibility have been performed. Although results vary with the different measures, in general, the lowest socio-economic classes seem to profit the least from the metro on average. However, a slightly higher class, which still can be seen as poor, does show a large increase.

Then, an equity assessment done. A solid conclusion on the equitability of the metro proved to be difficult nonetheless, because a feasible quantitative measure of equity was not available.

Contents

3. List of figures

4. List of Tables

5. List of abbreviations

SES	-	Socio-economic Strata
PT	-	Public Transport
TM	-	Transmilenio
VTT	-	Value of Travel Time
GTC	-	Generalized Travel Costs
COP	-	Colombian Pesos
GDP	-	Gross Domestic Product
TT	-	Travel Time
BRT	-	Bus Rapid Transit
TAZ	-	Transport Analysis Zone

6. Introduction

Bogotá, the capital of Colombia is the largest city of Colombia, with more than 10 million people living in the Bogota metropolitan area (greater Bogotá)(The Data Team (The Economist), 2015). Meanwhile, around 45 million people live in Colombia. Most of the people living in Colombia live in cities, around 78%. Well known cities besides Bogotá are among others Medellin and Cali. But even though Medellin is the second largest city in Colombia, its 2,5 million inhabitants are in no proportion to the 10 million inhabitants Bogotá has.

With a share of the GDP of Colombia that is 1,5 times higher than its share of inhabitants, Bogotá is the center of economic activity in Colombia. Also, the GDP per capita is around 50% higher than that of Colombia (Wessels, Pardo, & Bocarejo, 2012). However, wealth is distributed among the people unequally, as indicated by Bogotá's relatively high Gini-Coefficient of 0,599 (Wessels et al., 2012).

In such a large city, it is almost inevitable that problems with transportation occur. In Bogotá in 1999, 95% of all road space was used by private vehicles, moving only 19% of all motorized trips. (Folmar, 2015) (D Hidalgo, 2002). Later on, several ways of sustainable transport were introduced to Bogota. The most well-known example is the Transmilenio Bus Rapid Transit (BRT) system. It is 84 km long, has 9 lines and 115 stations. It set the gold standard for BRT (Cervero, 2005). In 2010, the Transmilenio served 1.5 million people every day (Munoz-Raskin, 2010) and increased the bus speeds from 12km/h to 26km/h. (Teunissen, Sarmiento, Zuidgeest, & Brussel, 2015). Next to the Transmilenio, two cycling initiatives have been executed, the first of which is the Dutch-advised plan 'Cicloruta'. Cicloruta led to the increase of cycling as a part of all trips from 0,9% in 1996 to 4% in 2003 (Cervero, 2005). The last initiative is a series of car free days, called Ciclovía. During such events more than 120 km of road is closed to motorized transport, each time leading to large numbers of people using the infrastructure for walking and cycling. These events raised awareness about car-use and also had the positive side-effect of numerous people performing physical activities (Torres, Sarmiento, Stauber, & Zarama, 2012).

Although these measures proved to be effective, the governments of Colombia and Bogotá have decided that a next step is required to keep Bogotá accessible. After all, as mayor Peñalosa said: "*Mobility in the developing cities is a very peculiar challenge. Because, different from health, education or housing, it tends to get worse as the society becomes richer. Clearly an unsustainable model*" (Peñalosa 2013) as cited by (Matuszewski, 2015). This next step will be the realization of the metro de Bogotá. This project consists of a new metro line, the Metro de Bogotá. The metro line has been subject of research and discussion since the late 1950's. Right now, Bogotá is losing 0.5%-3% of its GDP on congestion, around 0.8-5 billion dollars annually. A metro might be able to bring this number down. Furthermore, a metro will likely be faster, have more capacity and pollute much less than the buses running in Bogotá right now (Margolis, 2015). And, not the least important, the metro will likely raise accessibility for the people of Bogotá.

7. Problem context

The realization of the long-discussed metro in Bogotá seems like a great step forward for the city of Bogotá and its people. There are, however, indications that the realization of the Metro de Bogotá will not be profitable for everybody. The earlier stated relatively high Gini-Coefficient is an indication of this possibility, but there are more factors that justify doubting the equity of the Metro de Bogotá. For example, the poorest stratum of Bogotá tends to spend 17% of their income on transport (C Rodriguez & Peralta, 2016), where the policy threshold limit of affordability for developing countries is between 6-15% (Echenique Gómez-Lobo, 2007). With metro fares expected to be equal to, or even higher than, the current fares of public transport in Bogotá, this might get even worse, or the poorest people will simply not use the metro, which would lead to an increase of the gap in accessibility between the rich and poor. Furthermore, recent increase in the Transmilenio fares going from 1800 COP in the beginning of 2016 (Buckley, 2016) to 2200 COP now ((Transmilenio), 2017), may have worsened the situation.

These developments raise suspicion that not every social-economic group in Bogotá will profit equally from the realization of the metro. In other words, the *equity* of the metro may be in danger. In the meantime, few to none studies have been performed on the effect of the metro on the levels of accessibility for the different socio-economic strata (SES). The fact that so little is known about this topic, makes research on the equity of the metro necessary.

8. Research objectives

This chapter will attend the research gap, aim and research questions this thesis will address. Firstly, the research gap will be assessed. Then, the research aim will be elucidated, after which the research questions derived from the aim, will follow.

8.1 Research gap

At this moment, it is unclear if and to what extent accessibility will rise after realization of the Metro de Bogotá for each socio economic strata. This means the raise in accessibility will likely vary among socio economic strata, which could lead to a decrease in transport equity. Subsequently, the effects of the metro on transport equity are also not clear. The effects of the metro on both Bogotá's accessibility and transport equity, are to large extent influenced by the metro's effect on travel time and (generalized) travel costs, which are also unknown.

8.2 Research aim

This research aims to predict the effects of the realization of the Metro de Bogotá on travel costs, accessibility and transport equity, for each socio-economic stratum specifically.

8.3 Research questions

The research questions are derived from the research aim. The answers to the research questions together, will fulfill the aim of this research.

8.3.1 Main research question

What are the effects of the metro de Bogotá on (generalized) travel costs, accessibility and equity for the different socioeconomic strata (SES)?

8.3.2 Sub questions

1. What is equity? What are good ways to measure equity in the context of Bogotá?
    a. What is equity?
    b. How can equity be defined/measured in the context of the metro de Bogotá?
2. What are the predicted effects of the metro de Bogotá on travel time, travel costs and generalized travel costs on transport in Bogotá for each socioeconomic stratum?
    a. What are the predicted effects on travel time?
    b. What are the predicted effects on monetized travel costs?
    c. What are the predicted effects on generalized travel costs?
3. What are good ways to measure accessibility in the context of Bogotá?
    a. What are, given the context, good measures of accessibility?
    b. What data is available?
4. How will accessibility change for each SES with travel time as an impedance?
5. How will accessibility change for each SES with generalized travel costs as an impedance?
6. What do the outcomes, and the differences in the outcomes, of the previous three questions, mean for the equity of the Metro de Bogotá?
    a. What do the outcomes of the questions 4 and 5 mean for the accessibility provided by the metro de Bogotá for all SES?
    b. Is this equitable?

9. Literature review

9.1 Equity

In order to answer the main research question, first the concept of equity has to be defined. Simple as this may seem, transport equity can be difficult to evaluate because there are various types, impacts, measurement units, and categories of people to consider (Litman, 2005). Equity is often described as 'fairness' or justice (van Wee & Geurs, 2011) (Martens, 2012) (Garcia-Zamor, 2014). The Oxford Dictionary defines equity as "The quality of being fair and impartial". Equity is also often seen as a substitute for sustainability, or the two are mixed up (Litman, 2003), while rather, in the generally accepted model of sustainability founded on the three pillars of social, economic and environment, as often used by the United Nations (*UNEP ENVIRONMENTAL, SOCIAL AND ECONOMIC SUSTAINABILITY FRAMEWORK*, 2015), equity is the interface of the social and economic pillars. A graphic explanation can be found below in Figure q.

Figure 1: Classic Sustainability Model

Also, there is a lot of discussion whether or not equity is the right term to base policy making decisions upon. For example, (Savvides, 2013) defines transport equity as "*transportation equity has the goal to provide equal access to social and economic opportunity by providing equitable levels of access for all people to all places*". But in the United States, equal chance to economic and social opportunity is often analyzed by making use of what is nowadays called 'the spatial mismatch hypothesis' (Sanchez, Stolz, & Ma, 2004). Meanwhile in the United Kingdom, researchers and policymakers often use a broader view of social inequity. Here, the term social in- or exclusion is often used to address the equal access to opportunity (Sanchez et al., 2004) (Savvides, 2013). According to K. Geurs, Boon, & Van Wee (2009), "*distinguishing between 'social differences' and 'social (in)justice'/ '(in)equity' has the advantage of separating judgement and actions, and objectivity and subjectivity.*" However, according to Martens (2012), "*each of these terms may refer to different concepts in certain contexts, in common usage the terms strongly overlap and are used interchangeably.*" Summarizing, one can deduce that choosing the right term is mainly a matter of setting the right definition.

But how do Bogotán policy and policy makers address equity in general? They view access to social protection as a constitutional right. "*Article 48 of the Constitution of Colombia (1991) states that "Social Security is a mandatory public service which will be delivered under the administration, coordination, and control of the State, subject to the principles of efficiency, universality, and cooperation within the limits established by law. All the population is guaranteed the irrevocable right to Social Security.*" (Rosero, Castanó, & Sarmiento, 2012). According to the Colombian law, social spending should be assigned to *those groups more vulnerable and poor*. (Law 60 of 1993 art. 30).

For translating these relatively vague goals into a definition of equity, a framework by Litman (2017) is used. This framework defines three types of equity. The first is horizontal equity, which assesses equity as the '*equal treatment of equals*'. This type of equity propagates that government policy should not favor any group over another. An example of this is a flat rate tax system. The second type is 'vertical equity with regard to income and social class'. This approach assesses equity as a way of favoring socially and economically disadvantaged groups by government policy. Policy is progressive if it favors disadvantaged groups and regressive if it harms them. The third type of equity is 'vertical equity with regard to mobility need and ability'. This means that policy should adapt an inclusive design, which means that all users, including those with special needs (e.g. handicapped persons), should be comprised. The goal of Colombian policy to assign social spending to the most vulnerable and poor groups fits best within the type of equity defined as 'vertical equity with respect to income and social class'.

Another question that arises when addressing this issue is how Colombians view transport equity specifically. According to Camila Rodriguez, Gallego, Martinez, Montoya, & Peralta-quiros (2016) the general Colombian policy is that public transport systems should be "*self-sufficient with fares set at 'cost-recovery' levels"*. This has been administered in 'Law 86 of 1989' (Diario Oficial No. 42.853, de 12 de agosto de 1996). Ideally, a system would both be able to operate at cost-recovery levels and in the meantime be able to serve everyone by being affordable for all socioeconomic classes. However, optimizing for both values would be an impossible challenge. Therefore the Plan Nacional de Desarrollo. Departamento Nacional de Planeación (DNP), Bogotá, Colombia has for the first time explicitly allowed provision of subsidies in public transport (Pojani & Stead, 2017). However a broad policy on how to implement this specifically has not been adopted yet. Indications that measures like these are necessary are present. For example figure 3 shows that the very poor (Strata 1+2) people living in Bogota spend on average 17% of their income on transport, while only taking 0,9 motorized trip per day.

Figure 2: Number of trips and individual income intended for the transport, Source: *(C Rodriguez & Peralta, 2016)*

The previous paragraph and figure 2 indicate that there's a close relation between equity and affordability. This is also argued by Litman (2017). When an increase in potential accessibility is provided by for example a new toll road or metro, this increase is only met when the infrastructure is affordable to someone. Falavigna & Hernandez (2016) put it like this: "*a person can live close to several transit routes, but if he is not able to afford the fare, he is vulnerable in terms of accessibility*". In other words, the raise in accessibility due to a policy measure such as new infrastructure is compromised by factors such as out of pocket costs.

Summarizing these findings, it can be deduced that a policy measure can be viewed as equitable when it favors the lower socio-economic strata over the higher ones. This way of defining is backed both by the general view on equity which aims to assign government (social) spending on the groups that are most vulnerable and poor, as well as the recent allowance of targeted subsidies on public transport. In the case of the metro de Bogotá, this means that *the metro should raise accessibility for* *the lower strata more than for the higher ones*, or at least with the same extent. The raise in accessibility has to be measured in terms of relative increase, since the absolute increase will not tell us much about profits for each SES, whereas the total amount of suitable jobs differs for each stratum.

Obviously, a well-established qualitative answer to the question on the effect of the metro is possible with this definition. However, a quantitative measure of equity would contribute to the validity of the conclusion to great extent. According to Litman (2017), the Gini-index, Theil coefficient and coefficient of variation are often used to quantify (in)equity. Meanwhile, Bertolaccini (2013) stresses the importance of choosing the right scale and right measures in order to make a good comparison. Furthermore, because of the clear spatial component this research has, a spatial equity measure will also contribute to the meaning and validity of this research. An example that is often used in GIS-based studies is an (extended) Moran's I approach (Rahman & Neema, 2015) (Wismadi, Zuidgeest, Brussel, & van Maarseveen, 2014). However, on the case of the spatial equity of the BRT system of the Colombian city Santiago de Cali, a simpler approach comparing z-values is adopted (Delmelle & Casas, 2012). Both approaches have pro and contra arguments. In case of this research, a Moran's I approach may turn out to be less suitable, because the metro will likely have large local spatial impacts, while the Moran's I results into a more global spatial equity value. The z-score approach, which benefits in terms of simplicity and does assess the local impacts, however, may also not be the best approach since there will be no single quantitative result with which to assess the spatial equity, and one would have to fall back on qualitative assessment.
For this research specifically, this will mean that the equity of the metro de Bogotá will have to be calculated by using different methods (Gini, Theil, Moran's I, etc.) and for different measures of accessibility. With these different measures and an extensive qualitative assessment, a robust image of the equity of the metro de Bogotá will be created.

9.2 Accessibility

Accessibility plays an important role in this research. However, accessibility is often hard to define, understand and measure (K. T. Geurs & van Wee, 2004). Often people think of accessibility in terms of travel time and lost vehicle hours. While these variables certainly make up for parts of accessibility, they do not represent the whole concept. There are many ways to define accessibility. Song (1996) discusses 9 different ways to measure accessibility ranging from simply defining accessibility as the distance to a central business district, to cumulative opportunity accessibility measures and gravity-type indices.

Additionally, Geurs (2006) provides a broad framework, in which four basic perspectives on measuring accessibility are identified:

1. Infrastructure based measures. Analyzing the performance of transport infrastructure in terms of 'level of congestion' or 'average speed on the network'.
2. Location based measures. Measuring the level of accessibility of spatially distributed activities. (e.g. the amount of jobs reachable within 30 minutes)
3. Person based measures: Focusing accessibility at the individual level.
4. Utility based. Focusing on the benefits that people get from access to activities.

Then, Geurs (2006) also defines four components of accessibility.

1. The *land-use* component. This component reflects "*the amount, quality and spatial distribution of opportunities supplied at each destination"*. This can for example mean jobs.
2. The *transportation* component. Expressed as the amount of discomfort or disutility a person has to overcome in order to reach his destination. This can be time (travel time, waiting time), costs (out of pocket costs, generalized travel costs) or effort (amount of discomfort, risk of accidents) or a combination of these factors.
3. The *temporal* component, which assesses the constraints caused by time. This can mean the availability of opportunities (such as jobs) during the different times of the day.
4. The *individual component* which *"reflects the needs, abilities and opportunities of individuals*."

Figure 3 shows the relations between these components. An ideal measure of accessibility would be able to take all of these components and its underlying relations into account. However, in practice, this would rapidly prove to be difficult.

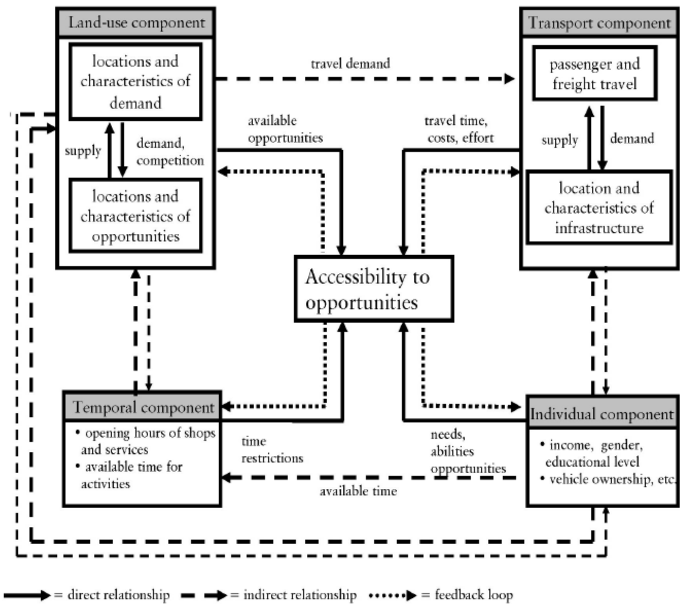

Figure 3: Accessibility framework Source: *(Geurs, 2006)*

From the four basic perspectives and the four components of accessibility, Geurs then comes to a matrix, presenting perspectives focusing on each component, which ignores other aspects of accessibility. This matrix is presented in Figure 4.

Given the case, model and data available, a location based measure seem to be the best fit for the accessibility measure of this study. After all, the part of the stratification of the population in this research is clear, covering the individual component. The amount of jobs per strata is also known, taking care of the land-use component and the model will be able to calculate travel costs between locations of activities, adding a transport component to the measure. Only the temporal component will be hard to add to an accessibility measure, since data on availability of opportunities during the different times of the day is not available.

	Transport component	Land-use component	Temporal component	Individual Component
Infrastructure-based measures	Travelling speed; Vehicle-hours lost in congestion		Peak-hour period; 24-hr period	Trip-based stratification, e.g. home-to-work, business
Location-based measures	Travel time and/ or costs between locations of activities	Amount and spatial distribution of the demand for and/or supply of opportunities	Travel time and costs may differ, e.g. between hours of the day, between days of the week, or seasons	Stratification of the population (e.g. by income, educational level)
Person-based measures	Travel time between locations of activities	Amount and spatial distribution of supplied opportunities	Temporal constraints for activities and time available for activities	Accessibility is analysed at individual level
Utility-based measures	Travel costs between locations of activities	Amount and spatial distribution of supplied opportunities	Travel time and costs may differ, e.g. between hours of the day, between days of the week, or seasons	Utility is derived at the individual or homogeneous population group level

Figure 4: Accessibility perspectives Source: *(Geurs, 2006)*

A widely excepted and widely used location-based accessibility measure is that of the *gravitational* or the *potential* accessibility measure, this especially applies for GIS studies (Geertman & Ritsema Van Eck, 1995). The most commonly used potential accessibility measure follows the following outline:

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

- A_i is the level of accessibilities of opportunities at location i
- S_j is the amount of specific opportunities at location j, also called the 'attraction'.
- $f(d_{ij})$ is the distance-decay function between origin i and destination j.
- d_{ij} are the costs associated with the movement from i to j.

The mobility survey of Bogotá will be able to provide a good indication of the amount of jobs as well as the data for the formulation of a distance-decay function. However, data on other 'opportunities' will be much harder to distill from the mobility survey, or other sources. Therefore, the opportunities component of the formula will consist exclusively of jobs. Therefore, our accessibility measure ultimately becomes:

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

- A_i is the level of job accessibility at location i
- S_j is the amount of suitable jobs at location j, also called the 'attraction'.
- $f(d_{ij})$ is the distance-decay function between origin i and destination j.
- d_{ij} are the costs associated with the movement from i to j.

10. Case description

10.1 Metro

Figure 5: Metro characteristics

The Metro de Bogota will be a metro line starting at station Portal de Las Americas and ending at Calle 72. In total, it will be 25 km long and it will for a large part cover the economic center of Bogota. The metro will have 14 stations, with around 1,4 kilometers between every station. The metro is set to be operative in 2022. The metro will move around 656 thousand people every day. The commercial speed of the metro will be at least 41 km/h and the frequency will be three minutes. The metro fare will be integrated with the Transmilenio BRT system Bogota has and the price will be 2200 COP. This means that as long as one stays inside the system of BRT and metro, a single flat fare of 2200 pesos is the fare for each and every trip. The metro will not be a replacement for the existing BRT lines that are at this moment present at its location, but will exist next to it. Above in figure 5, the characteristics of the metro have been summarized. Please keep in mind that this figure includes phase three of the metro, which will not be operational until 2030 and therefore is negated in this research.

10.2 Transmilenio

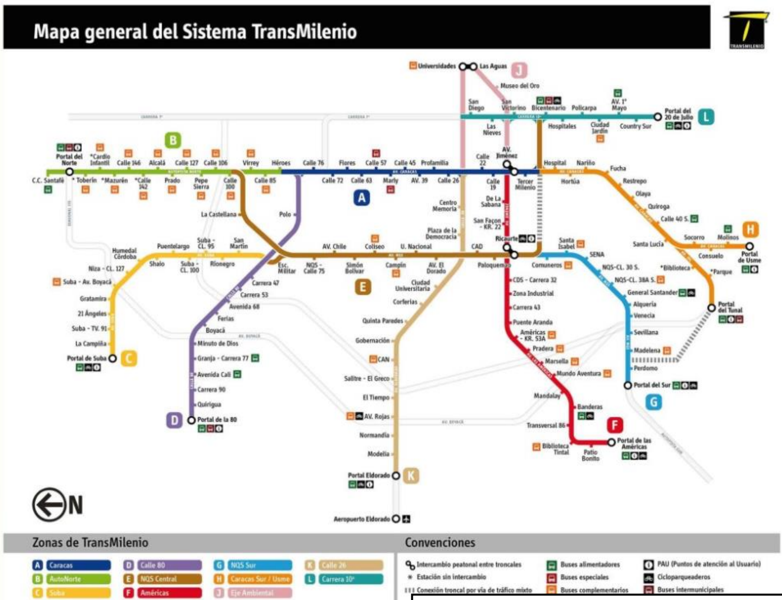

Figure 6: Transmilenio lines

The Transmilenio (TM) is Bogotá's bus rapid transport (BRT) system. It opened to the public with just two routes covering Bogotá's Caracas, and Calle 80. Nowadays, it's a rather large system, with 113 km of BRT routes and 147 stations. The maximum speed on the BRT system is around 60 km/h but in practice, the commercial speed is around 29 km/h. The frequency of the buses is 5 minutes in the peak hours and the fare is 2200 COP. The Transmilenio started as an enormous success and was praised by urban planners all over the world. However, later, the approval rates for the TM dropped, because of dropping speeds and over crowdedness at the buses and its stations (Gilbert, 2008).

10.3 Cicloruta

Cicloruta is the bicycle route network in Bogotá. It started out as a Dutch advised plan to raise bicycle use in the city. Nowadays, the network consists of around 400 km of bike paths and thirty routes. This makes it the largest cycling network of Colombia. However, the network has its flaws. Average speed is only around 9 km/h (Hamidi, 2014). This is because the network is interrupted at almost every intersection, often, pedestrians walk on the bike paths and the condition of the infrastructure is bad. Also, safety issues play a role in whether or not people choose to use the bike for transportation (Andiarios, 2015). There is some integration with the public transport network at the moment, but not to large extent. Only 12 of all TM stations have a bike parking facility.

Figure 7: People walking on Cicloruta (Ter Braake, 2013)

Figure 8: The Cicloruta infrastructure is often in bad state

10.4 Characteristics of the strata

Bogotá has a stratification system which divides its people into socio-economic classes. The so called Social Economic Strata (SES) system. It is based on a combinations of the geographic location of people's houses, their construction and construction materials and the access to utilities such as a connection to the city's water supply. The Mobility Survey of Bogotá 2011 tells us the job and home locations of the different strata. This is an open accessible database of a large number of trips performed by Bogotáns. The set consists among other data of trips with socio-economic data of the commuter included with it. This can be SES, car possession, but also data on the trips such as travel times and main mode. This data on residential locations is displayed per strata in this paragraph, marked in red. Also, the job locations per strata are displayed. When a closer look is taken at the data, one can see that not every zone is a residential location for just one strata group. This is due to the fact that the both the stratification system and the zone system that are used are relatively old. The stratification system dates from 1994 (Esbjørn & Fjalland, 2012), and the zonas de análisis de transporte (ZAT), or Transport Analysis Zone (TAZ) system, dates from around 2010. Originally, the TAZ system was used to divide Bogotá into zones where around the same amount of people live, with the same SES, but developments over time have altered this classification to a small extent. Table 1 shows the population specified for the strata-groups that this research works with, whereafter the residential and job-locations for the SES are presented. Concerning the job-locations, for each SES specifically, the amount of times a certain TAZ was named as a destination of a job related trip, was counted. This will not tell us the actual amount of jobs in a TAZ, but it is a nice indication, since the data from the mobility survey will represent the actual real life situation. In other words, the chosen indicator will follow the same pattern as the actual amount of jobs in Bogotá.

Population per Strata in Bogotá			
SES 1+2	SES 3	SES 4	SES 5+6
51,68%	35,27%	8,65%	4,40%

Table 1: Percentage per strata of total population

SES1&2

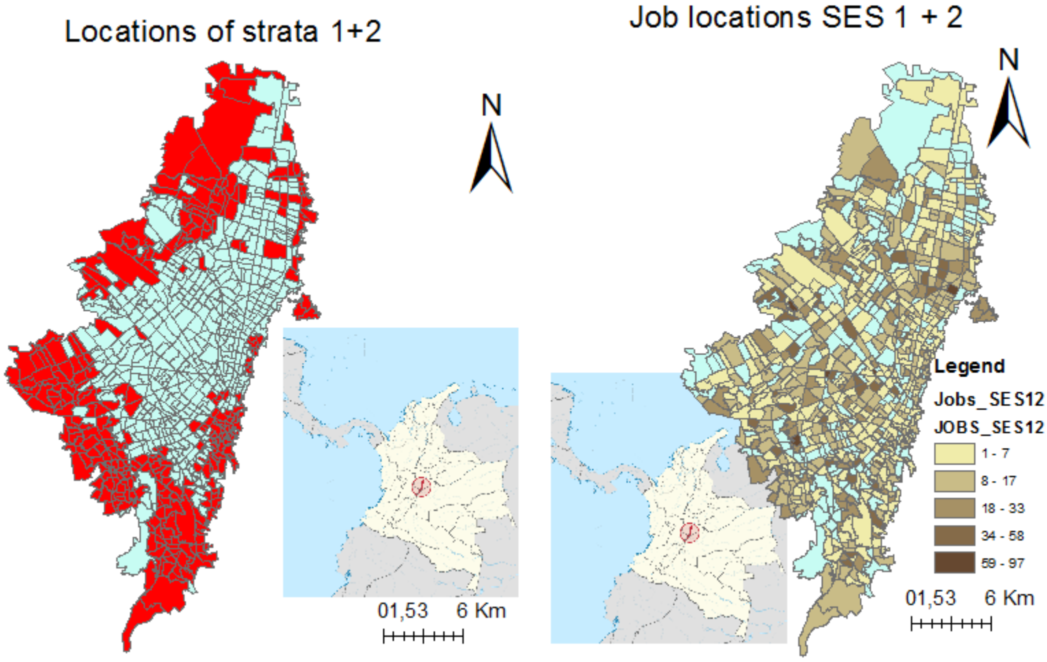

Figure 9: Residential and job locations for strata 1+2

SES3

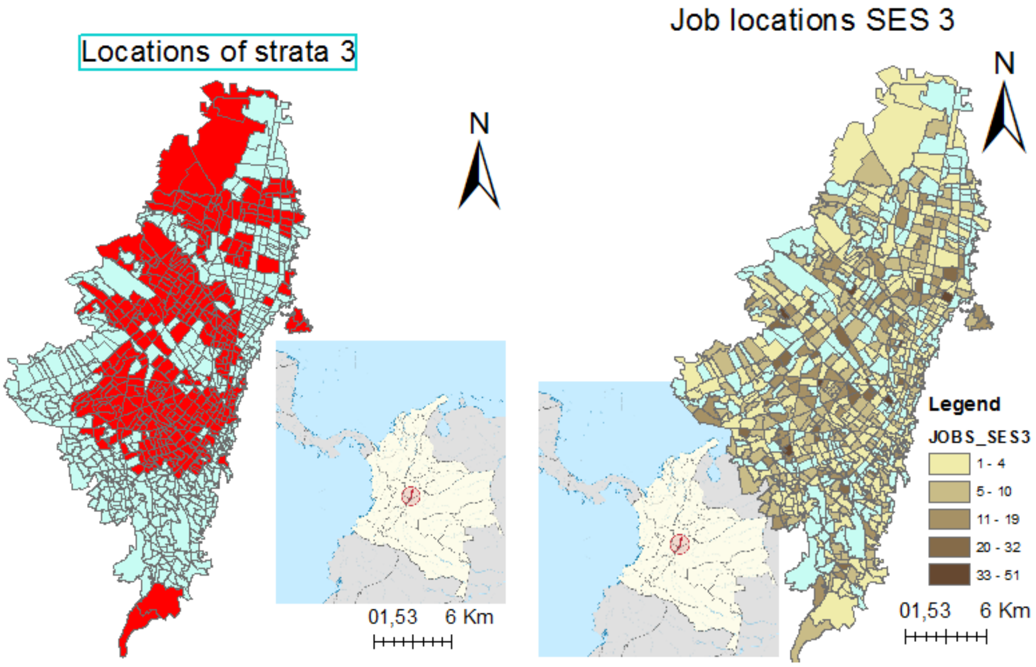

Figure 10: Residential and job locations for stratum 3

SES4

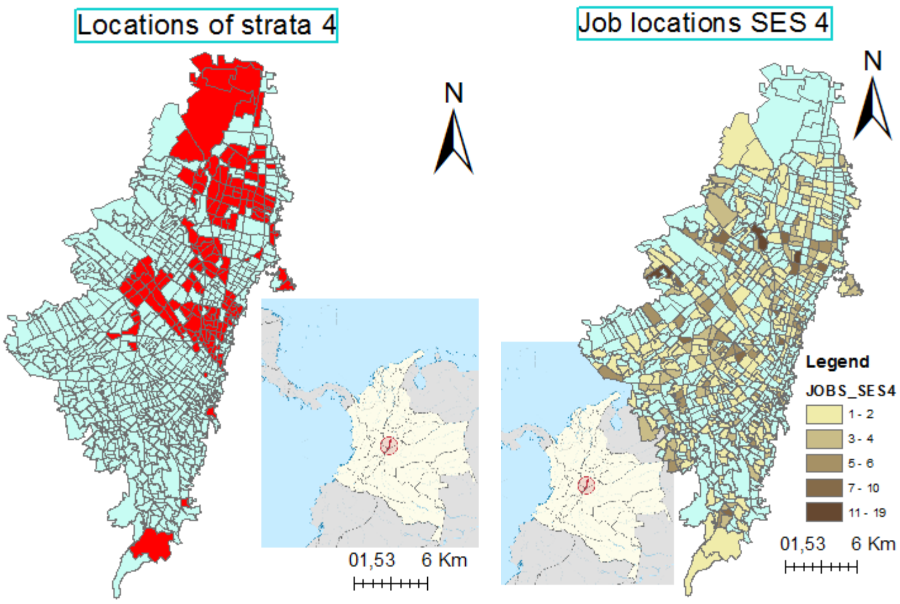

Figure 11: Residential and job locations for stratum 4

SES5&6

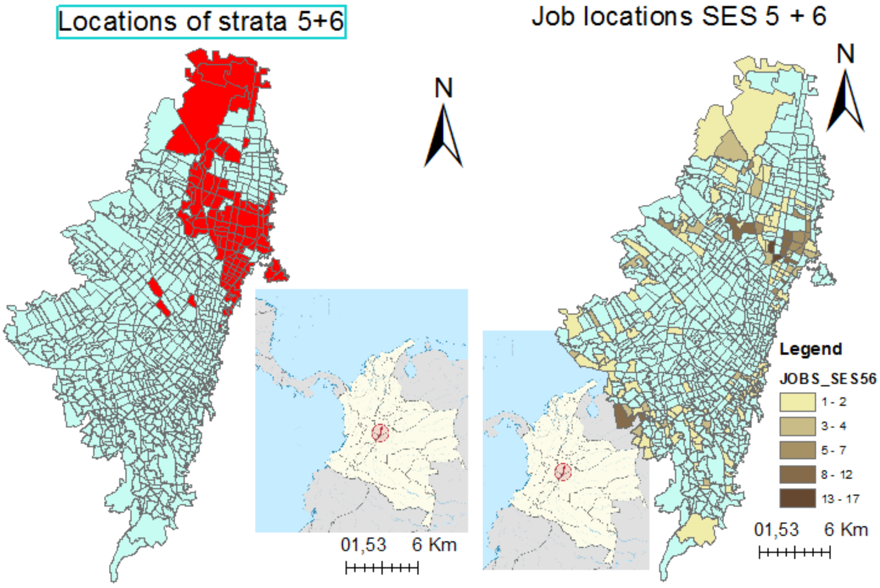

Figure 12: Residential and job locations for strata 5+6

11. Model and methodology

This chapter will explain the model that is used to conduct this research with, as well as other important methodological aspects.

11.1 ArcGIS multimodal network dataset

ArcGIS' network analyst tool provides a powerful tool to solving network-based multiple O-D routing problems. The network analyst is able to calculate the shortest route for *different impedances* between multiple origins and destinations using *multiple transport modes*. This tool will thus be very helpful in finding the effects of the realization of the metro (adding a *mode*) on travel times and generalized travel costs (*impedances*).

11.1.1 Modelled commuting scenarios.

In order to model the effects of the metro on the travel impedances, three commuting scenarios were considered:

1. Biking directly – In this scenario, the distance between the origins and destinations is overcome by using the bike only. In cases of short distance, this mode will likely be the fastest.
2. Walking – Public Transport – Walking. This scenario makes use of three different modes to get from origin to destination. Walking to a metro or Transmilenio station, wherefrom one takes the public transport (either metro, Transmilenio, or, in some cases, both), after which the final part of the movement is done by walking again.
3. Biking – Public Transport – Walking. In this scenario, four different modes are used to conquer the travel impedances. 'A commuter' bikes to a station which has a bike parking facility, then uses the public transport (TM, metro), after which he or she walks the rest of the trip to the destination.
   It is imported to note that the network analyst does not allow analyses that end on a different mode than the one they start. Therefore, this scenario has to be calculated in two parts. First a matrix with all possible combinations between first origin, then station (with bike parking facility) and lastly destination is generated. Then, the travel costs between all origins and all stations by bike is calculated. After this, the travel costs between each station and destination, by PT and walking, are calculated. At this point, the data on costs between Origin and every possible bike station and the data on costs between each possible bike station and destination is known. The data on both parts is added to the generated combination matrix. Then, the total travel time for each of these possible combinations can be calculated, after which a simple formula can find the lowest value for each unique O-D relation. The MATLAB code used to perform this workaround can be found in Appendix C.

Other scenarios, such as walking directly or bike-PT-bike were not considered for several reasons. Walking directly would never be faster than biking directly, so this scenario is not useful for our analysis. Bike-PT-Bike is deemed to be an unrealistic scenario, since people are not allowed to bring their bike on the Transmilenio or metro and bike sharing systems are non-existent in Bogotá.

When all O-D impedances are calculated for each SES, the scenarios are compared to each other, after which the fastest mode is chosen, for both a situation in which the model ís present and a situation in which it is not. With such a before-after analysis, the effects of the metro can be found and presented clearly.

11.1.2 Preparation of data

With four different modes that together make up the model, a great deal of data preparation has to be done. On all four modes, preparation of data was necessary, as well as the transfers between the modes.

Walking infrastructure

Walking infrastructure was modelled by downloading the shape files of the car (road) infrastructure of the city. Then, unwalkable infrastructure like the 'autopistas', the ring road of Bogotá, were removed. Also, passes over these autopistas were added to the model, by carefully checking Google Earth footage of the city on these locations. Furthermore, the connectivity policy has to be set, which determines how interconnected segments are modeled. Here, one can chose between endpoint connectivity and any-vertex connectivity. If you can be relatively sure that your data is close to perfect, endpoint connectivity is the best policy, since it takes into account non-intersecting, but still overlapping infrastructure, such as bridges and viaducts. The any-vertex policy does not do this. The difference is illustrated in figure 13. Since the huge amounts of data that are associated with the walking infrastructure, we cannot be very sure about the 'perfectness' of our data. So the connectivity policy is set to any-vertex. This however means that there will be 'mistakes' in the model in the case of a viaduct where in the real world, no connectivity between the layers exist. Introducing a small error.

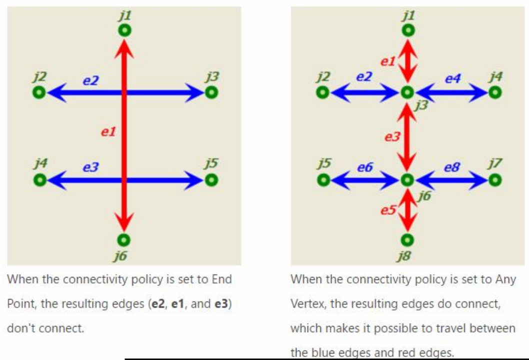

Figure 13: Connectivity policies

Biking infrastructure.

The biking infrastructure took the walking infrastructure as a base layer. Then, data on the ciclorutas of Bogotá was added to this infrastructure. This makes is done because of the fact that in principle, all pedestrian space can be used by bikers as well, which is also frequently done, together with the specific bike infrastructure, the total supply of infrastructure for the bikers is known. Also, because of the way the walking infrastructure has been modelled, infrastructure that is not suitable for bikers, such as highways are kept out of the modelled bike infrastructure. The speed of the non-cicloruta was set on 8 km/h, while the cicloruta speed was set to 10 km/h. These characteristics are derived from Hamidi (2014). The connectivity policy is set to any-vertex as well.

Transmilenio (BRT) infrastructure

The Transmilenio infrastructure and stations had to be updated to the latest data. The speed for the Transmilenio was set at 27 km/h (Darío Hidalgo, Pereira, Estupiñán, & Jiménez, 2013). Because the data on the Transmilenio is not nearly as much as the data on for example the walking infrastructure, it is relatively easy to check the quality of the data. In this case, it is decided that the connectivity policy can be set to endpoint, since the endpoints of the segments are the TM stations.

Metro infrastructure

The shape files of the metro system were provided in a different coordinate system than the one used for the other infrastructure. Therefore, it had to be converted to the coordinate system that is used by the model. The speed of the metro was set at 45 km/h, as stated in the interview with David Mendelez (Appendix A). The connectivity policy for the metro is set to endpoint connectivity as well, for the same reason as with the BRT-system.

Transfers Walking-PT

Between the walking infrastructure and the public transport stations, so called *transfer edges* had to be created. This was done by using a tool that draws a line on the closest distance between a point and a polyline. The transfer time modelled for the transfer from walking to public transport was set at two minute station access time, plus half the frequency of the PT as additional waiting time, in case of access of the PT. In case of egress, the component of half the frequency was left out.

Transfers Biking-PT

The transfer from biking to public transport was a bit more difficult to model. Since not every TM station has a bike parking facility, the ones that do have one had to be filtered, and transfers from the bike infra exclusively to the stations with a bike parking facility had to be drawn. The transfer time for bike to PT was set at again, two minutes access time and half the frequency of the PT, but now, an additional two minutes were added for the time it takes to park a bike at a TM station (Braake, 2013). For the egress time, again, the half-the-frequency component was left out. The figure 14 on the right illustrates this concept.

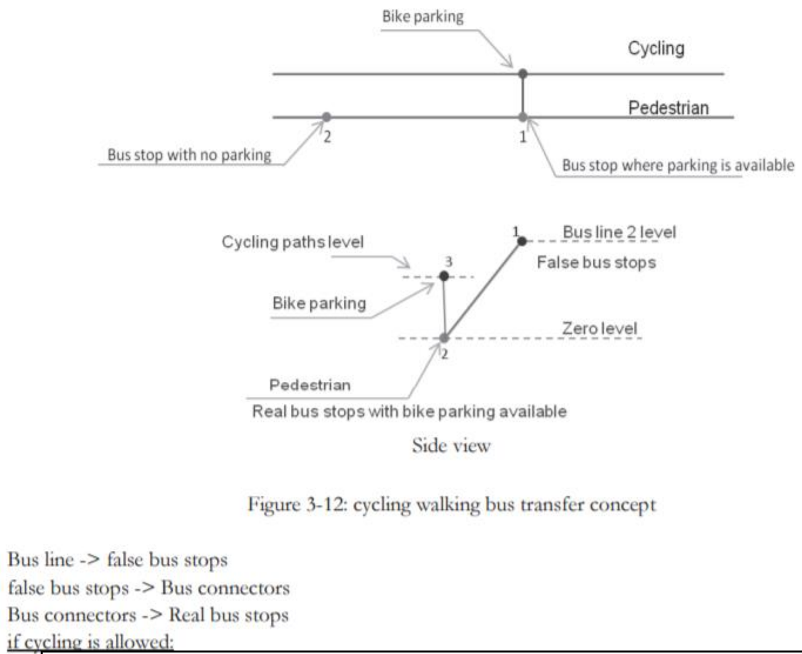

Figure 14: Conceptual model of 3D multimodal network modelling, Source: *(Mahrous, 2012)*

Transfers Metro-TM

For the transfers from the metro to TM and the other way around, the transfer time was set at again two minutes access time plus half the frequency of the infra to which one transfers ~~to~~. This means that the opposite directions have different transfer times, because the frequency of the metro and Transmilenio are different. Respectively, they are three minutes, as stated in the interview with David Mendelez (Appendix A) and five minutes (Hamidi, 2014).

Connectivity between the modes

In order to make the transfers from for example walking to PT only possible at the locations where it is supposed to (the stations), the modes are set on different 'connectivity levels' this way, one can make sure that a transfer will only happen when it is supposed to. The example below shows the connectivity levels for the Walk-PT-Walk scenario. The walking infrastructure is on the first connectivity level, the metro on the second and the transfers are on level four. The 'false stations' make sure the transfer between level one and four is possible, after which the real stations serve as the connection between level four and level two. This way, one can be absolutely sure that transfers between modes only happen at the designated points.

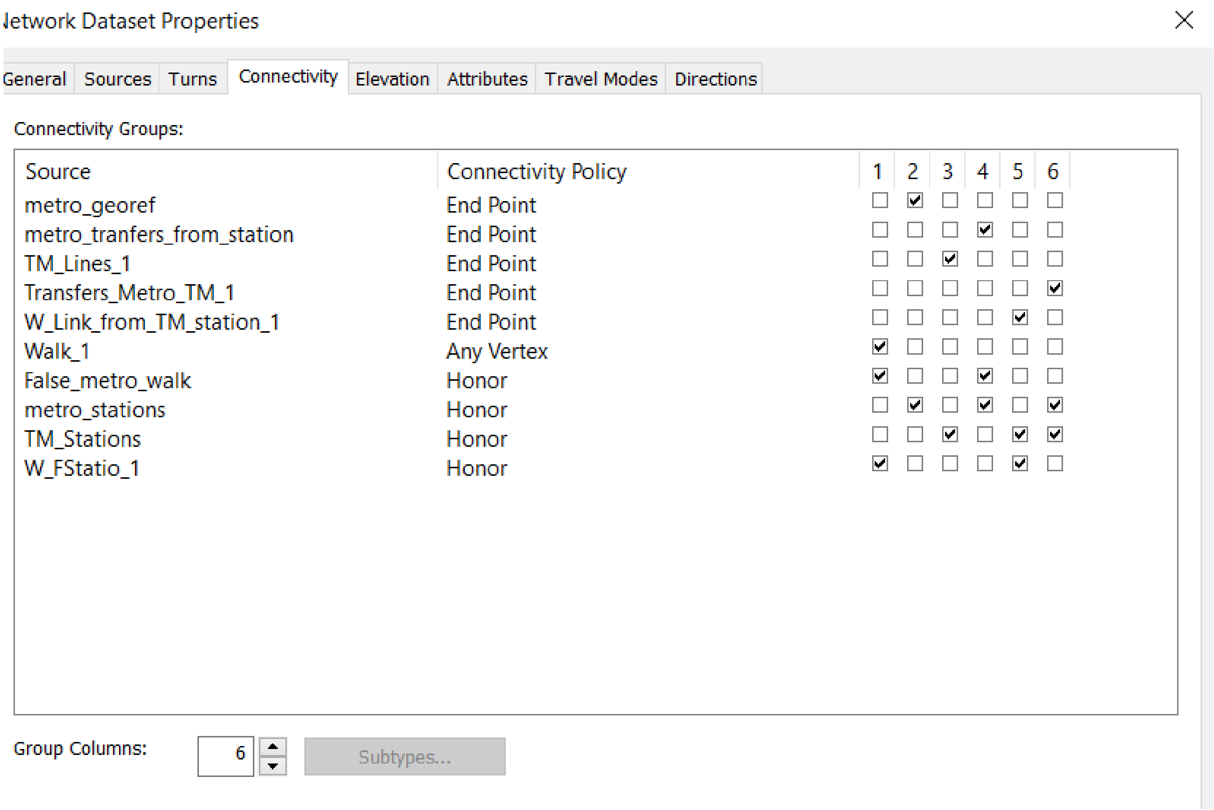

Figure 15: Connectivity policies and levels in the model

Additional data preparation

With the length and speed of each part of infrastructure known, the amount of time for each part of the model could be calculated. Furthermore, this amount of time, multiplied by the value of travel time (VTT) for each SES, would tell us the generalized costs. At the transfers entering the PT system, the PT fare of 2200COP had to be added. Also, the values in the different directions (access/egress) of the transfers from and to the PT were different, so they had to be calculated for each direction. This leads to a table like in figure 15. The big differences in the GTC between on and off can be explained by the fact that it takes more time to access PT than it takes time to egress it. Furthermore, the actual fare of the PT is also added to the GTC-field of the access transfer.

With all this data available for each piece of infrastructure the network analyst is able to calculate the lowest cost movement between each origin and destination in both terms of travel time and GTC, for each applicable mode scenario and for all different socio-economic strata.

11.2 Important assumptions, abstractions and idealizations

11.2.1 Rational behavior

This research and specifically the model used to perform it assume rational behavior in the transport choices of commuters. This means that it is assumed that a person traveling between a certain origin and destination will use the route of the smallest resistance for the chosen impedance. This means for example that when the impedance is set to travel time, all O-D movements will be based on the lowest travel time possible. In real life, this may be different because the users of a network are limited by bounded rationality. This means that in the real world, especially in movements that are more complex, i.e. making use of multiple transport modes, commuters cannot possibly always know which route has the smallest resistance, or, in other words, the smallest travel time or GTC.

11.2.2 Biking and Walking assessed together

The realization of a metro will not influence the walking and biking time between origins and destinations. Therefore, in the case that a trip is completed faster by using one of these modes in both the cases with and without the metro present in the system, no effect is caused by the metro. For the fact that this research focusses on the effect of the metro, it is not interesting whether the commuter actually bikes or walks to his destination. Therefore, the accessibility measure assumes that the bike is taken to the destination. This also complies with the fact that rationally is assumed for the commuters. In real life, a modelled trip may actually have been completed by foot, but this is irrelevant for this research.

11.2.3 Generalized travel costs based on two parameters

In this research and therefore in the model, uses a definition of generalized travel costs, based on two parameters. The actual fare of the public transport taken for a movement added to the value of the travel time specified for each movement and each SES. Or in a mathematical representation: $GTC = Fare_{PT} + \frac{VTT_{SES(x)}}{minutes} * minutes$, with GTC as generalized travel costs, $Fare_{PT}$ as the fare of public transport, $VTT_{SES(x)}$ as the value of travel time per minute for stratum x (1-6) and minutes as the travel time in minutes between an origin and destination.

The Values of Travel Time have been provided by David Mendelez from the Bogotá metro company and are as displayed in table 2. According to this data, stratum four has the highest VTT, while one would expect strata 5 and 6 to have the highest VTT, because higher income groups tend to have higher VTT's. The fact that according to this data, in Bogotá this is not the case can be caused by the problem that SES 5+6 are very small groups, so they may have been underrepresented in the research, especially since car-ownership is relatively high for SES5+6 (Secretaría Distrital de Movilidad), 2015) and PT-preference may be very low in general.

Values of travel time per SES in COP/min				
	SES 1+2	SES 3	SES 4	SES 5+6
Value of Travel Time (COP/min)	25,5	36	52	49,9

Table 2: VTT per strata

However, one can choose to add more factors to generalized travel costs. The amount of (dis)comfort when using a certain mode can for example be expressed in a monetized value, and can be added to the GTC. However, this particular research focusses just on travel time and out of pocket costs as components forming the GTC. This is because of the fact that in most cases, travel time and out of pockets costs are the major components influencing travel behavior of commuters. Also, a component like comfort would simply play a small role in the total GTC, since in a developing country like Colombia, luxury like comfort is simply valued significantly less than in more developed countries where the money spend on transportation in absolute terms is significantly higher.

11.3 Origins and Destinations

11.3.1 Origins

Bogotá and its surrounding municipalities are divided into 999 TAZ's or *Transport Analysis Zones*. Every TAZ represents around the same amount of inhabitants per zone, with roughly people of the same stratum living in it. Therefore each TAZ represents a certain stratum, or in some rarer cases, two or more strata. The centroids of these zones are chosen as the origin locations of the different strata. The mobility survey of 2011 provided the data on the location of the zones, their ID and the strata living in them. This way, origins are linked to a geographical location in a manner that is sound and easy to model and understand. Furthermore, since this research focusses on mobility for the city of Bogotá, the TAZs located in the surrounding municipalities were removed from the data.

11.3.2 Destinations

In order to model the destinations, data from the mobility survey of 2015 is used. Here, the destination TAZs of job related trips have been used to model the destinations and the amount of jobs at a certain destination. For each SES specifically, the amount of times a certain TAZ was named as a destination of a job related trip, was counted. This will not tell us the actual amount of jobs in a TAZ, but it is a nice indication, since the data from the mobility survey will represent the actual real life situation. In other words, the chosen indicator will follow the same pattern as the actual amount of jobs in Bogotá.

11.4 Distance-decay functions

As stated in the paragraph on accessibility, the measure of accessibility of this research is:

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

- A_i is the level of job accessibility at location i
- S_j is the amount of suitable jobs at location j, also called the 'attraction'.
- $f(d_{ij})$ is the distance-decay function between origin i and destination j.
- d_{ij} are the costs associated with the movement from i to j.

This means that a distance-decay function has to be found. These distance-decay functions are often different for different modes and also the socio-economic status of people are of influence in their decay curves. For example because lower strata have lower VTT's and therefore are willing to travel longer, or because the lowest strata live relatively far away from their jobs and therefore have to travel longer trips in general.

The idea of a distance-decay function is to quantify the fact that the chance that a person will make a short trip (with low costs in terms of time or GTC) is bigger than that of the same person taking a longer trip (with higher costs in terms of time or GTC). Or "*the interaction between two locales declines as the distance between them increases"* (Bjelland, Montello, Getis, Fellmann, & Getis, 2013).

The decay functions that use travel time as an impedance are found in Hamidi (2014). The functions follow the pattern of: $e^{(-\beta * d_{ij})}$. The β values can be found in Figure 16. In this research, SES 1 and SES 2 are taken together, so for the β-parameter of that group, the weighted average is used. As said, the model uses three possible scenarios how a trip can be done. The first is walk-PT-walk, the second bike-PT-walk and the third is bike directly. For the trips that use public transport, this is automatically assumed to be the main mode. Furthermore, since data on the travel times or decay functions of the metro are clearly not

	TM		Bicycle		Walking	
	β	Max Travel Time	β	Max Travel Time	β	Max Travel Time
SES 1	0.028	180 min	0.038	90 min	0.072	60 min
SES 2	0.030	190 min	0.053	75 min	0.104	50 min
SES 3	0.037	150 min	0.054	70 min	0.131	35 min
SES 4	0.039	130 min	0.053	50 min	0.179	25 min
SES 5&6	0.047	90 min	0.078	25 min	0.134	25 min

Figure 16: Bèta values and maximum travel time per SES and mode, Source: Hamidi, (2014)

available yet, the distance-decay function for the metro is assumed to be equal to that of the Transmilenio. This leaves us with two possible β-values that can be applied to calculate the accessibility, which have to be linked to the corresponding trip-scenario. This is done with the help of a vertical lookup function in excel.

These are the distance-decay functions with travel time as the impedance. However, this research also tries to clarify the effects of the metro on accessibility with generalized travel costs as the impedance. Since the GTC-value is different from the travel time values, the decay functions are different as well. For each mode, the travel time can be converted into GTC. For walking and biking, the travel time is simply multiplied by the Value of Travel Time. Mathematically, this means: $GTC_{SESx} = TT * VTT_{SESx}$. With GTC_{SESx} as the generalized travel costs for the specific SES. TT as the applicable travel time and VTT_{SESx} as the value of travel time associated with the SES.

For public transport, however, the travel time is also multiplied by the value of travel time. But, in addition, the fare of the TM or metro is added (both COP 2200). Mathematically, this leads to: $GTC_{SESx} = TT * VTT_{SESx} + Fare_{PT}$. With GTC_{SESx} as the generalized travel costs for the specific SES. TT as the applicable travel time. VTT_{SESx} as the value of travel time associated with the SES and $Fare_{PT}$ as the public transport fare, currently set at COP 2200 for both the metro and the Transmilenio.

To come to a GTC-decay function is relatively easy for the scenario of the commuters biking directly. If the function is $e^{(-\beta * d_{ij})}$, with a constant β-value and d_{ij} as the travel time between i and j, and the d_{ij} is multiplied by the VTT to come to the GTC, one can simply divide the β-value by this VTT in order for the function to remain constant. The GTC-decay function for this scenario therefore becomes: $e^{(-\frac{\beta_{SESx}}{VTT_{SESx}} * d_{ij})}$. With β_{SESx} as the β-value for the specified SES and mode, VTT_{SESx} as the value of travel time for the corresponding SES and d_{ij} as the costs in GTC between origin i and destination j.

For the scenarios where public transport is involved, however, getting to a GTC-decay function is a little less self-evident. Because of the way the GTC are calculated for these scenarios, with the cost parameter added to the equation, one can't simply convert the time-decay to a GTC-decay function. Therefore, a different approach is chosen to find the GTC-decay function for the public transport modelling scenarios.

For the four different SES-groups, all job-related Transmilenio trips are isolated from the Bogotá mobility survey 2015. Then, the invested GTC for each trip is calculated with the formula presented earlier in this paragraph. Then the trips are ranked from the smallest GTC (around COP 2200, the flat fare for the PT), to the highest. Then an inversed accumulated frequency of travel time was calculated. Then a function was

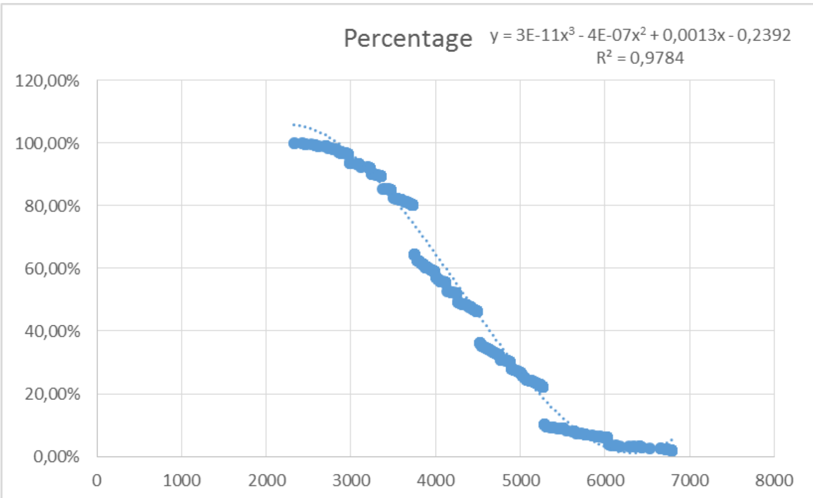

Figure 17: GTC-decay function for SES1+2

fitted to the pattern. At first, a function in the style of the other decay functions was tried in order to fit the pattern, but this proved to be unfeasible. Therefore, a polygon function was chosen, since it was the best fit to the data, both visually and in terms of the R^2-value. The result for socio-economic strata 1 and 2 is given in Figure 17. The rest of the fits can be found in Appendix B. Additionally, a table of the functions is presented in Table 3. When a closer look is taken at the scatter plots, gaps, where no values are observed, occur. This can be explained by the hypothesis that people, when answering such questions in the survey, will likely have a preference for rounding their trips to 'nice' values, such as a whole hour, or three quarters of an hour.

Socio-economic strata	Decay function	R^2-value
SES 1 + 2	$y = 3E\text{-}11x^3 - 4E\text{-}07x^2 + 0{,}0013x - 0{,}2392$	0,9784
SES 3	$y = 1E\text{-}11x^3 - 2E\text{-}07x^2 + 0{,}0009x - 0{,}0566$	0,9776
SES 4	$y = 5E\text{-}12x^3 - 1E\text{-}07x^2 + 0{,}0004x + 0{,}482$	0,9697
SES 5 + 6	$y = 7E\text{-}12x^3 - 1E\text{-}07x^2 + 0{,}0007x + 0{,}0642$	0,9808

Table 3: GTC-decay functions and R^2-values per strata

Equal maximum travel time contour measure

In the earlier approach, the accessibility and gains in terms of accessibility have been determined on the basis of access to suitable jobs, corrected with a decay function. These decay functions have been specified for each mode and SES separately. However, these decay functions are based on travel behavior in the past. Due to geographical characteristics and the possibility for a *spatial mismatch,* a discrepancy in the residential locations and working locations of people in a city, a potential accessibility measure as applied is not always the best way to assess equity of a transport system. Due to residential locations far away from job locations, which specifically apply for strata 1 and 2, a decay function may imply that lower socio-economic groups have a preference for traveling longer, which might not be the actual case. Therefore, a second way to measure job-accessibility is used to focus more on the equity part of this research. The measure used is a contour measure, which uses a maximum amount of travel time. This maximum amount is determined by taking the weighted average of all maximum travel times as determined by Hamidi (2012), resulting in a so called threshold. The weights of this average are determined by the share of the total population for each SES. Because the travel times to jobs for strata one and two are almost all within the contour, both with and without the metro, this maximum travel time is divided by two, resulting in the maximum time that around half of the people of Bogotá are willing to spend as a minimum. Not applying this measure would result in a measure that is not able to make a distinction between the scenarios with and without the metro. The values are 83 minutes for public transport and 35 for the bike/walk mode. The measure of accessibility now becomes:

$$A_i = \sum J_j \; (TT < Threshold) + 0 \;\; (TT > Threshold)$$

With

- A_i as the amount of Job-equivalents
- TT as the travel time between Origin i and destination j
- J_j as the amount of jobs in destination j
- $Treshold$ as the threshold value that is equal to the maximum travel time.

Results of this approach can be found in chapter 12.3.

Next to this approach of sufficientarism, other more common measures of equality have been tried to contribute to an assessment of equity. The Gini-coefficient was tried, but negates the spatial component. Also, the way the accessibility is measured, with *suitable jobs*, makes it hard to compare levels of accessibility. The Theil-index showed to have the same flaw. Furthermore, the accessibility levels do not add to the total amount of accessibility in a city, which would apply when the Gini-index is used for distribution of income, for example. Also, a Spearman's rank measure was tried, but the ranks of accessibility do not change after the intervention, even though progress in amount of travel times and generalized travel costs is noticed. The fact that the ranks do not change, even though the measure shows an effect, makes it a measure that is not applicable.

11.5 Equal decay function measure

Since every measure so far seems to be not applicable or inconclusive, more information is needed to come to a good judgement of the equitability of the metro. Therefore, another opportunity-based measure is executed.

This specific opportunity-based measure takes the weighted average Bèta values for travel time, and consequently, travel time as an impedance, so that characteristics of the city such as a possible spatial mismatch, which could lead to a figurative preference for longer travel times of lower strata, are ruled out. The weighted average of the β-values are 0,034 for public transport and 0,053 for biking/walking. This leads to the following accessibility measure

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

- A_i is the level of job accessibility at location i
- S_j is the amount of suitable jobs at location j, also called the 'attraction'.
- $f(d_{ij})$ is the decay function between origin i and destination j.
- d_{ij} are the costs associated with the movement from i to j.

With the decay function$f(d_{ij})$:

$$f\left(d_{ij}\right) = \exp(-\beta * d_{ij})$$

With:

- exp() as the e exponential function.
- β as the β-parameter for the function, 0,034 for public transport and 0,053 for biking/walking;
- d_{ij} as the costs in terms of travel time

It will be interesting to take a look at the difference for this accessibility measure itself for the scenarios with and without the metro. After all, it will be interesting to assess the accessibility for the different strata with the exact same accessibility measure, resulting in an equal approach for all the strata. The results can be found in chapter 12.4.

12. Results

In this chapter, first, the predicted effects of the realization of the metro on modal split, travel time and generalized travel costs are addressed. Then, the effects of the metro on three accessibility measures will be shown and discussed. The first of these measures is the specified distance decay measure, whereafter the results with the equal contour measure will be presented. And lastly, the effects of the metro in terms of accessibility with an equal decay function will be elucidated.

12.1 Effects on modal split, travel time and GTC

In the tables below, the overall effects of the metro on modal split, travel time and GTC are shown. The tables show all trips between every possible origin and destination for that stratum, so no maximum travel time is applied. The blue part of each table shows the amount of trips per mode, while the red part of each table presents the effects on average GTC or TT.

SES 1 + 2

Overall changes caused by metro with GTC as impedance						
	Change in modal split					***Change in GTC***
	Bike_PT_Walk & Walk_PT_Walk	Bike_PT_Walk	Walk_PT_Walk	Bike Directly	Total	Average GTC
Without Metro	26673	10207	16466	246783	273456	2899
With Metro	28118	11545	16573	245338	273456	2898
Increase	5,42%	13,11%	0,65%	-0,59%	0,00%	-0,04%

Table 4: Changes caused by metro with GTC as impedance SES 1+2

Overall changes caused by metro with TT as impedance						
	Change in modal split					***Change in TT***
	Bike_PT_Walk & Walk_PT_Walk	Bike_PT_Walk	Walk_PT_Walk	Bike Directly	Total	Average TT
Without Metro	209680	93624	116056	63776	273456	79
With Metro	213472	105567	107905	59984	273456	78
Difference (%)	1,81%	12,76%	-7,02%	-5,95%	0,00%	-1,58%

Table 5: Changes caused by metro with TT as impedance SES 1+2

The average decrease in travel times and GTC does not show very significant results. Especially the difference caused by the metro in terms of GTC is very low. Meanwhile, the difference with GTC as the impedance in terms of PT-use does show an increase of 5,4%. The fact that the difference in terms of average GTC is so low can be caused by several things. First of all, this table is based on all trips. The fact that the strata 1 and 2 mostly live on the outside of the city and the jobs are distributed all over the city can be one cause of this. This table also takes into account the trips from the very north to the very south of the city for example. Trips that would normally never or rarely occur. Furthermore, the fact that the GTC-approach ads the fee of 2200 COP when public transport is used, can lead to a smaller decrease in terms of GTC. In the case of travel time as the impedance, the average change in travel time is showing better results, while the change in modal split is smaller. This can be caused by the fact that the costs between an origin and destination is based solely on travel times. This leads to the people taking the public transport faster, since the costs are not taken into account. This means that also in the situation without the metro, people would choose the public transport as their main mode, leading to a smaller difference in modes when the metro is added to the system.

SES 3

Changes caused by metro with GTC as impedance						
	Change in modal split					***Change in GTC***
	Bike_PT_Walk & Walk_PT_Walk	Bike_PT_Walk	Walk_PT_Walk	Bike Directly	Total	Average GTC
Without Metro	69624	50085	19539	180993	250617	3282
With Metro	78003	59753	18250	172614	250617	3235
Increase	12,03%	19,30%	-6,60%	-4,63%	0,00%	-1,41%

Table 6: Changes caused by metro with GTC as impedance SES 3

Changes caused by metro with TT as impedance						
	Change in modal split					***Change in TT***
	Bike_PT_Walk & Walk_PT_Walk	Bike_PT_Walk	Walk_PT_Walk	Bike Directly	Total	Average TT
Without Metro	223894	101337	122557	26723	250617	59
With Metro	226958	113416	113542	23659	250617	55
Increase	1,37%	11,92%	-7,36%	-11,47%	0,00%	-5,23%

Table 7: Changes caused by metro with TT as impedance SES 3

For strata 3, the results are already more hopeful. A change in GTC of -1,4% and -5,2% in terms of travel time at least are better results than for strata 1 and 2. The effects of the total amount of trips being taken into account already gets smaller because of the people of strata 3 living closer to the center of the city. When GTC is taken as the impedance, the total share of public transport increases by more than 12%. The amount of trips where a bike is used to get to a PT-station even increased by more than 19%. The fact that with TT as the impedance the increase in PT-use is smaller, can be attributed to the presumption that with exclusively travel time as an impedance, people will take the public transport in more occasions, as explained earlier in the discussion of the results for strata 1 and 2.

SES 4

Changes caused by metro with GTC as impedance						
	Change in modal split					*Change in GTC*
	Bike_PT_Walk & Walk_PT_Walk	Bike_PT_Walk	Walk_PT_Walk	Bike Directly	Total	Average GTC
Without Metro	28228	16209	12019	35114	63342	4603
With Metro	30525	20446	10079	32817	63342	4490
Increase	8,14%	26,14%	-16,14%	-6,54%	0,00%	-2,45%

Table 8: Changes caused by metro with GTC as impedance SES 4

Changes caused by metro with TT as impedance						
	Change in modal split					*Change in TT*
	Bike_PT_Walk & Walk_PT_Walk	Bike_PT_Walk	Walk_PT_Walk	Bike Directly	Total	Average TT
Without Metro	56655	22062	34593	6687	63342	62
With Metro	56851	27531	29320	6491	63342	58
Increase	0,35%	24,79%	-15,24%	-2,93%	0,00%	-4,99%

Table 9: Changes caused by metro with TT as impedance SES 4

Strata 4 shows a larger effect in terms of decrease in travel time, than in GTC. This can be caused by the public transport fare weighing significantly less in the eyes of the strata 4 people. They value benefits in travel time more than the costs of the transport compared to the lower strata.

SES 5 + 6

Changes caused by metro with GTC as impedance						
	Change in modal split					*Change in GTC*
	Bike_PT_Walk & Walk_PT_Walk	Bike_PT_Walk	Walk_PT_Walk	Bike Directly	Total	Average GTC
Without Metro	7411	3808	3603	8789	16200	4846
With Metro	7974	5366	2608	8226	16200	4720
Increase	7,60%	40,91%	-27,62%	-6,41%	0,00%	-2,60%

Table 10: Changes caused by metro with GTC as impedance SES 5+6

Changes caused by metro with TT as impedance						
	Change in modal split					*Change in TT*
	Bike_PT_Walk & Walk_PT_Walk	Bike_PT_Walk	Walk_PT_Walk	Bike Directly	Total	Average TT
Without Metro	12942	5276	7666	3258	16200	72
With Metro	13018	7297	5721	3182	16200	68
Increase	0,59%	38,31%	-25,37%	-2,33%	0,00%	-4,88%

Table 11: Changes caused by metro with TT as impedance SES 5+6

For strata 5 and 6, a similar explanation probably applies. However, not a great amount of data from the mobility survey was available on this group. This could mean that the results produced for strata 5 and six could very well be not-representative.

Summarizing

For strata 1 and 2, the effects of the metro seem to stay behind in terms of modal split, GTC and travel time. The fact that it happens for generalized costs may not seem as a surprise, but, the conclusion that also the accessibility with travel time as the impedance does not improve, does come as a surprise. With GTC as the impedance, effects on the modal split seem to be spectacular, but with TT as the impedance, effects are much lower. For strata 5 and 6 results seem especially nice, but this may be because of the small amount of data available.

12.2 Accessibility for opportunity-based measure with specified decay functions.

SES 1 + 2

Travel Time

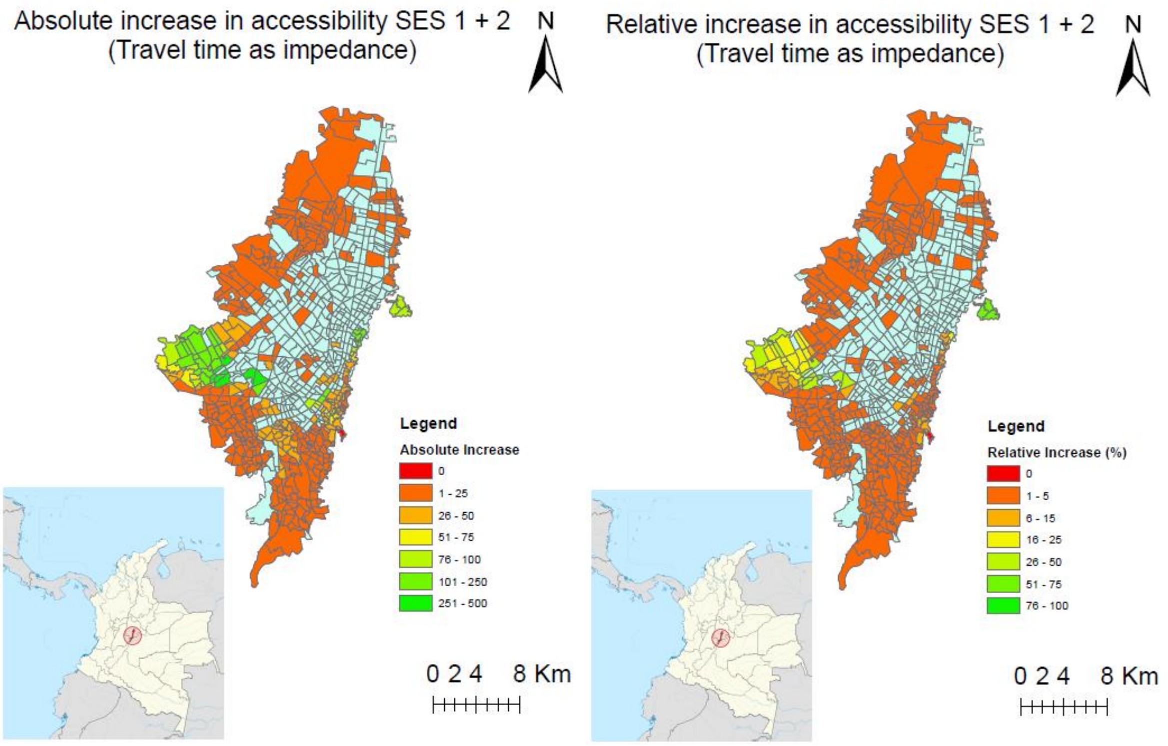

Figure 18: Absolute and relative increases in accessibility SES1+2, Travel time as the impedance

GTC

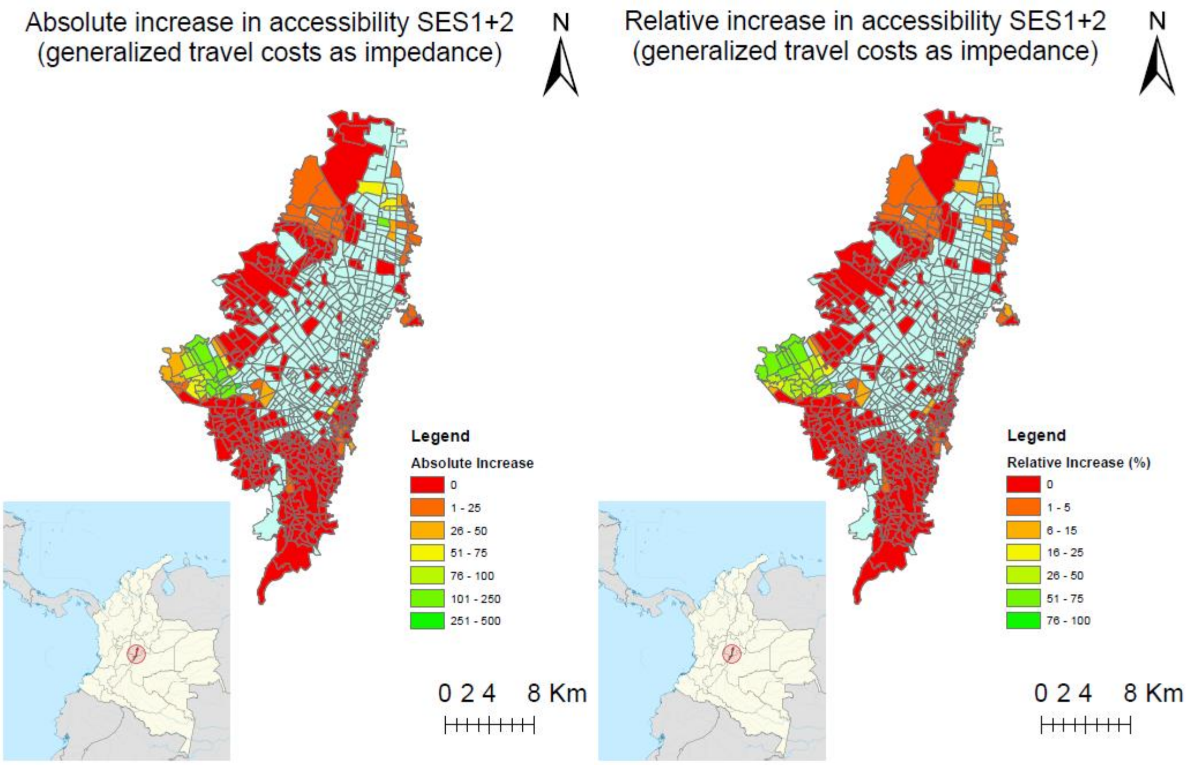

Figure 19: Absolute and relative increases in accessibility SES1+2, GTC as the impedance

The effects of the metro in terms of both absolute and relative gain in accessibility for both travel time and generalized travel costs as the impedance, seem poor at first sight. The larger part of the SES1+2 residential areas are colored either red or orange, representing a (very) small effect. However, in the very western part of the city, the Kennedy neighborhood, the effects of the metro are (very) noticeable. Several TAZs in this neighborhood show more than 75% increase, or more than 251 job-equivalents absolute increase. However, overall average gains in terms of accessibility are small because of the large amount of zones that show a very low effect. This can be viewed in Table 12 and 13.

SES 3

Travel Time

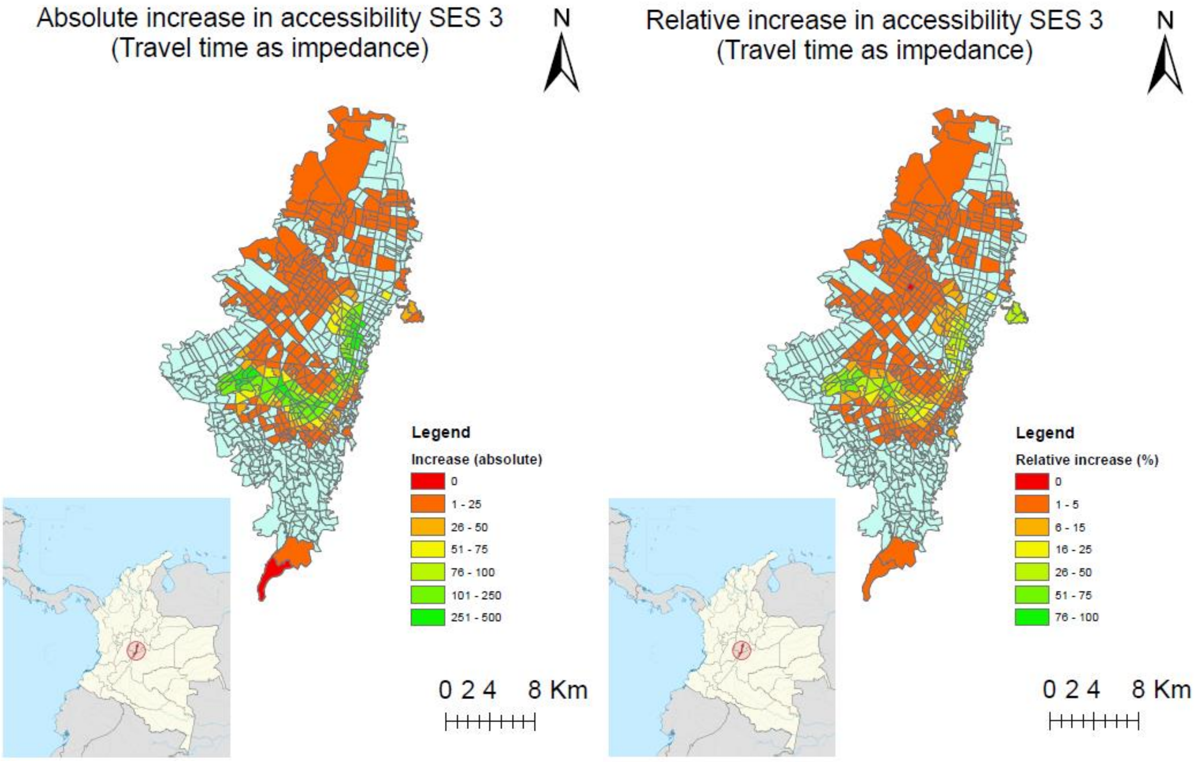

Figure 20: Absolute and relative increases in accessibility SES3, Travel time as the impedance

GTC

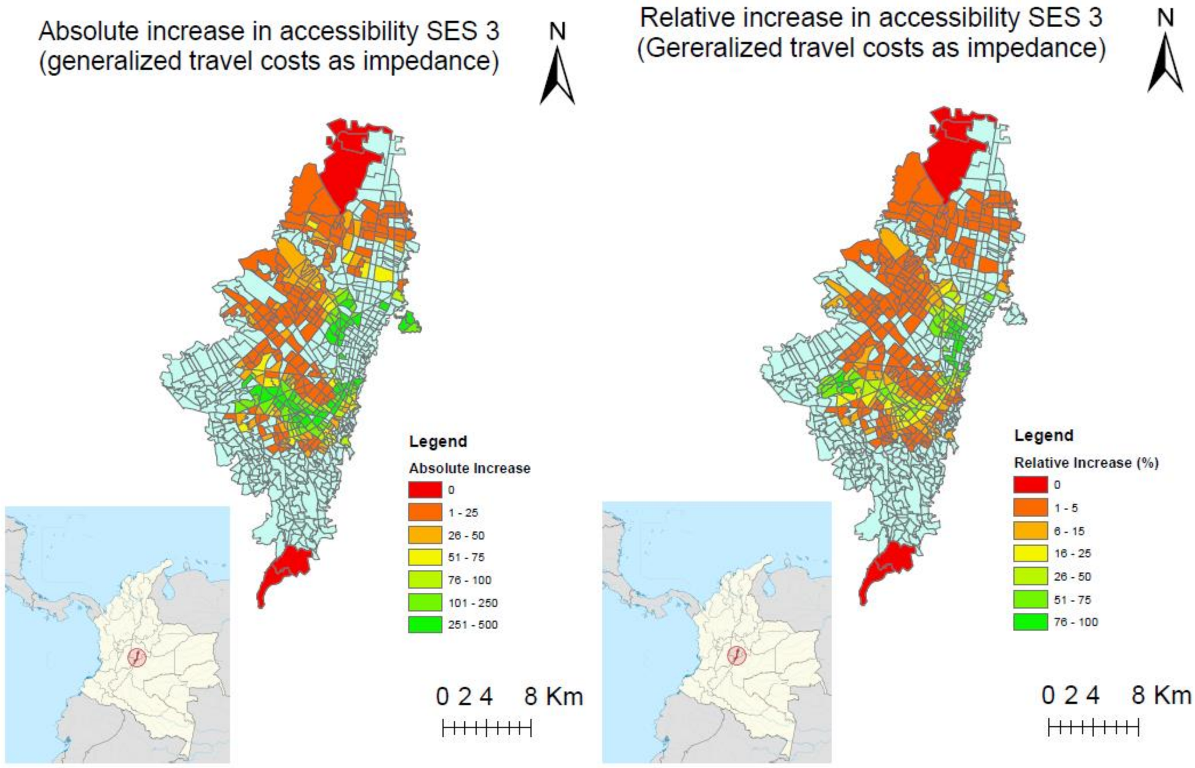

Figure 21: Absolute and relative increases in accessibility SES 3, GTC as the impedance

For strata 3, the effects of the metro seem to be higher compared to strata 1 and 2. Much more TAZ's are colored green, especially in terms of absolute gains in accessibility, both for GTC and TT as the impedance. Also, in relative increase, the effects also seem good for strata 3. Many TAZ's have either a yellow or green color, indicating at least a 16% increase in accessibility. The average gains in accessibility are high, especially in comparison to strata 1 and 2.

SES 4

Travel Time

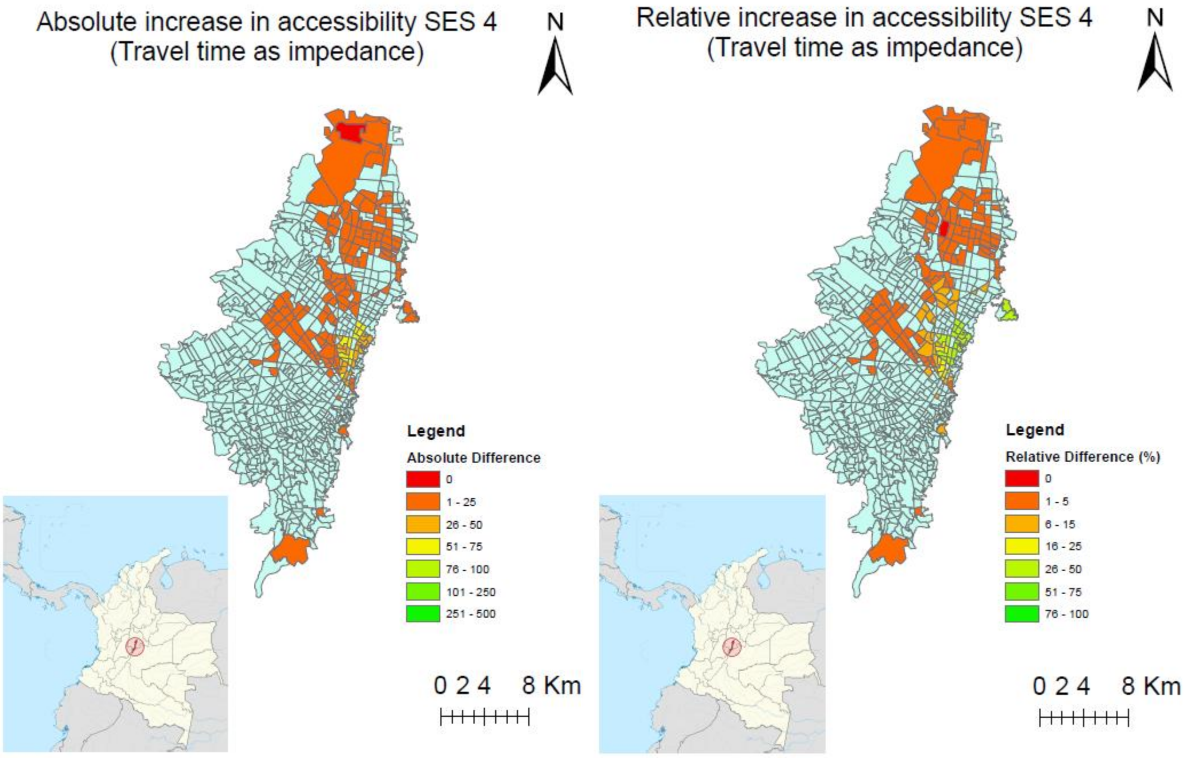

Figure 22: Absolute and relative increases in accessibility SES4, Travel time as the impedance

GTC

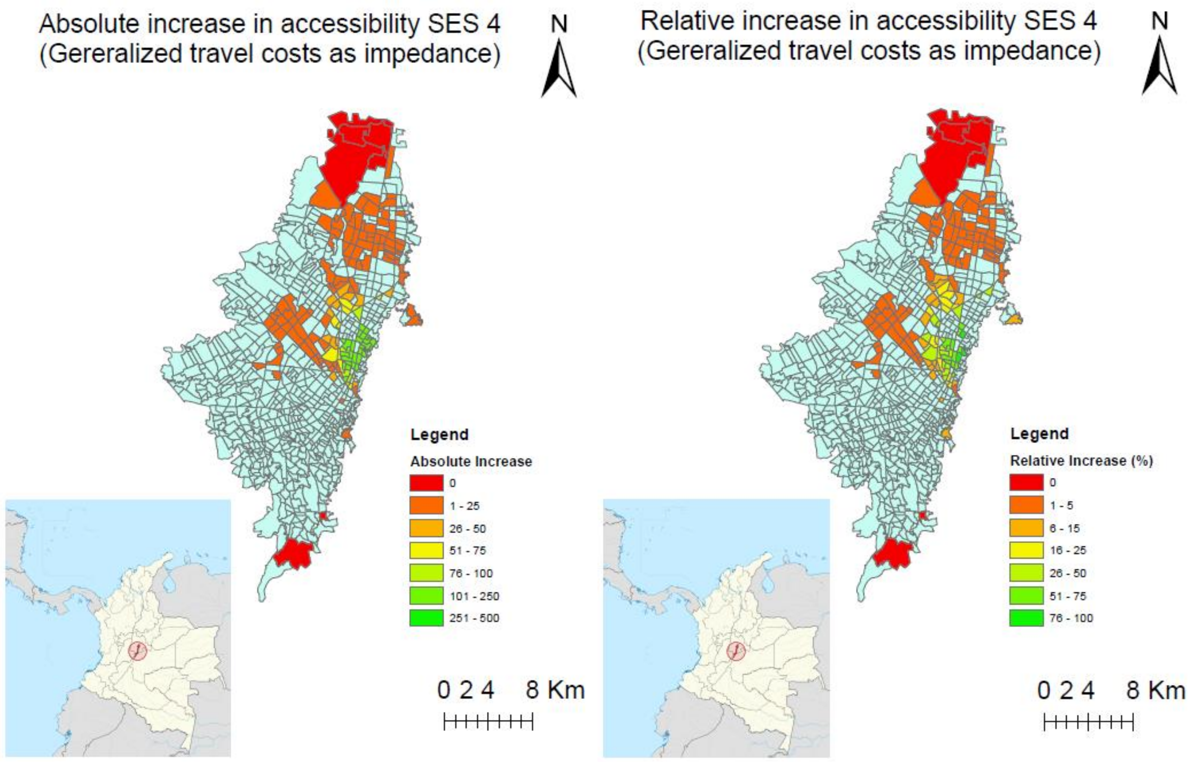

Figure 23: Absolute and relative increases in accessibility SES 4, GTC as the impedance

For stratum 4, raise in accessibility in absolute terms with travel time as an impedance, are meager. Relatively, however, they already seem better, with many TAZ's showing an increase of at least 26%. In terms of GTC, the results show a higher effect, with relative increases of more than 75% in certain instances.

SES 5 + 6

Travel Time

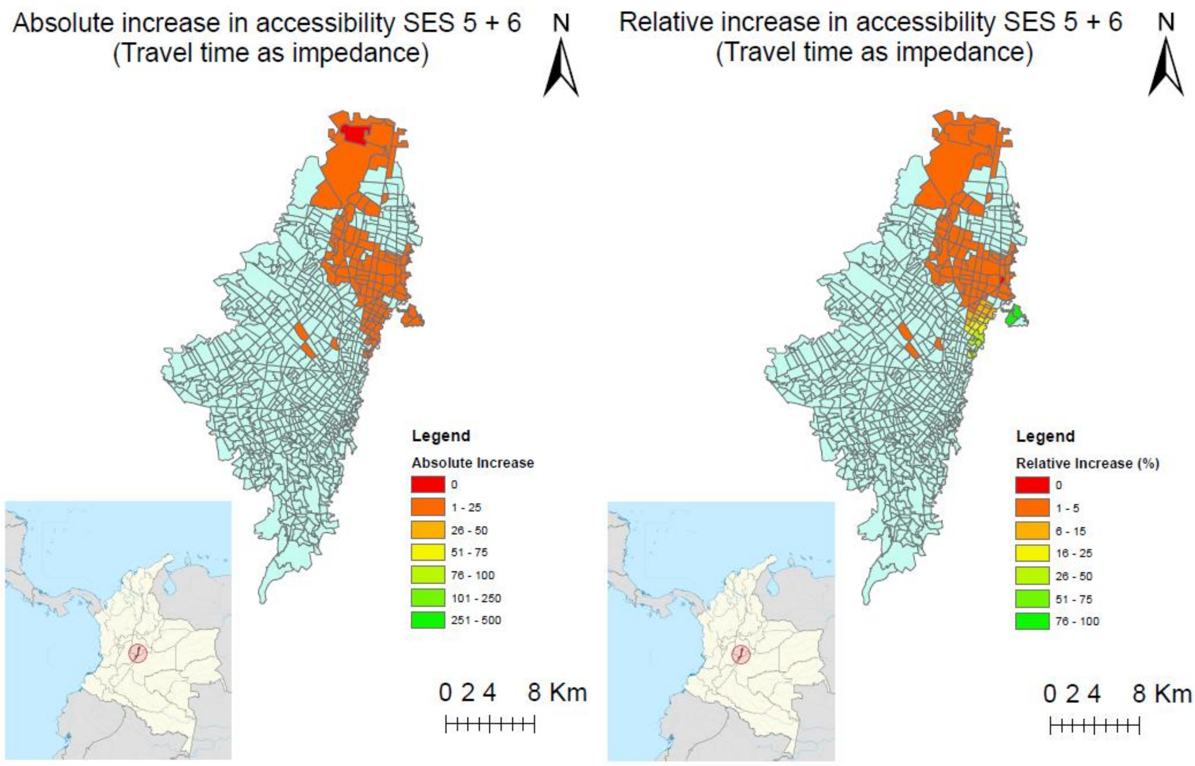

Figure 24: Absolute and relative increases in accessibility SES5+6, Travel time as the impedance

GTC

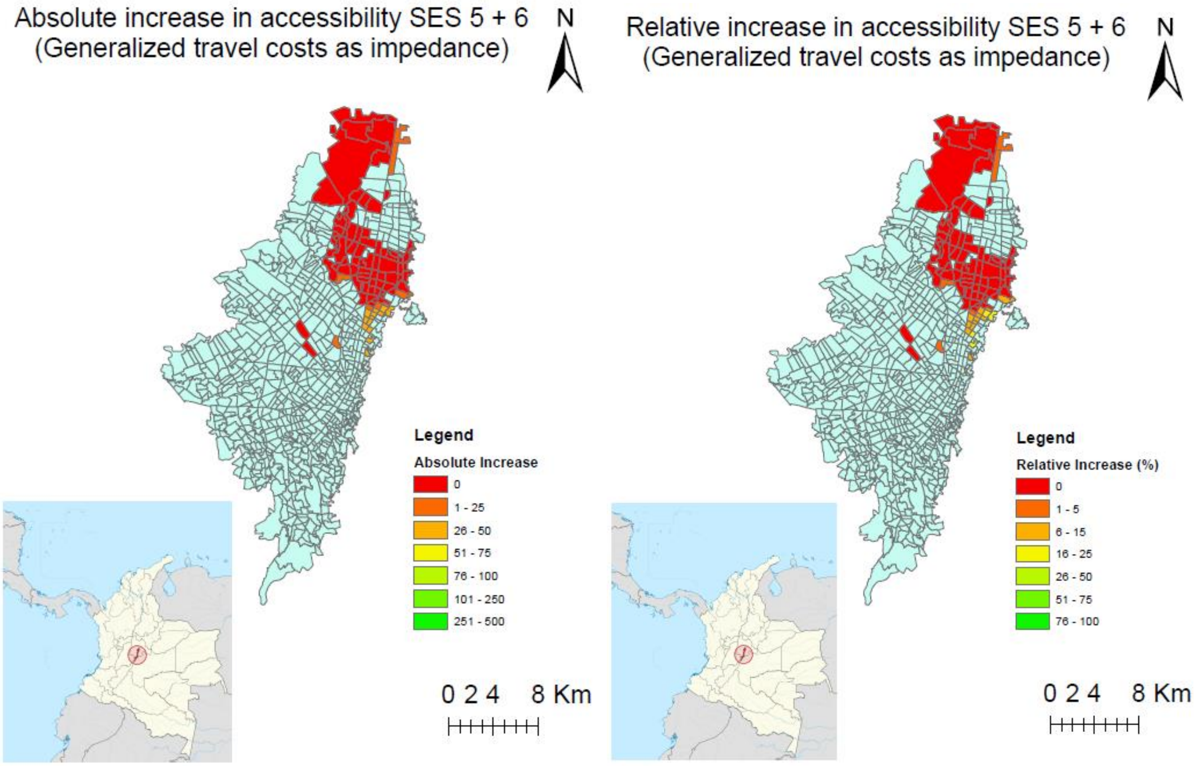

Figure 25: Absolute and relative increases in accessibility SES 5+6, GTC as the impedance

For strata five and six, the maps seem to show the lowest gains in accessibility after realization of the metro. Except for outliers, strata five and six seem to profit very little, specifically in absolute terms. However, since the accessibility was already low (in absolute terms) for strata 5 and 6 and they make up for a very small part of the total population, Table 12 and 13 still show a higher relative increase than strata 1 and 2 manage to achieve.

Summary

Changes in accessibility with GTC as the impedance				
	SES12	SES3	SES4	SES56
Average Absolute Increase	10,9	148,8	38,9	16,8
Average Relative Increase (%)	3,94	21,8	20,2	9,8
Absolute Increase	4596	62033	6302	1815
Total Jobs Travel Survey	3092838	1653405	157302	42120
Absolute Increase Corrected Total Jobs	0,0014	0,037	0,04	0,04

Table 12: Changes in accessibility, GTC as the impedance

Changes in accessibility with Travel Time as the impedance				
	SES12	SES3	SES4	SES56
Average Absolute Increase	34,5	61,6	12,7	1,7
Average Relative Increase (%)	4,3	9,5	8,4	7,5
Absolute Increase	14556	25681	2057	186
Total Jobs Travel Survey	3092838	1653405	157302	42120
Absolute Increase Corrected Total Jobs	0,004	0,015	0,013	0,004

Table 13: Changes in accessibility, TT as the impedance

In terms of overall effects of the metro, SES 3 seems to show the most effect. It scores best on both relative increase and corrected increase for the case of travel time as the impedance, as well as relative increase with GTC as the impedance. Only on corrected increase with GTC as the impedance, the higher strata score better. Also remarkable is, while the maps showed a relatively positive image of the gains for strata 1 and 2, the summarizing table shows that SES 1+2 score the worst on all points. Stratum 4 shows overall good increases as well, while for strata 5 and 6 the scores seem to vary a lot. Especially when comparing the summarizing table to the maps of strata 1 and 2, curiosities seem to occur. The maps seem to show a relatively good outcome, while the table with the averages shows a much more negative image. This can be caused by, although quite a few SES 1+2 neighborhoods show high increases, the average result is overshadowed by the also large amount of zones that do not notice a (high) increase. This implies that to just look at the table of averages and conclude that strata 1 and 2 profit less from the metro and the metro plans are therefore not equitable, may be too hasty.

12.3 Equal contour-based accessibility

This analysis results into the following table:

	SES12	SES3	SES4	SES56
Total Jobs With Metro	1482815	1397364	128214	27194
Total Jobs No Metro	1459540	1356596	124535	25788
Total Jobs Travel Survey SES	3092838	1653405	157302	42120
Increase Jobs	23275	40768	3679	1406
Relative Increase	1,59%	3,01%	2,95%	5,45%
Increase Jobs Normalized Total Jobs	0,0075	0,0247	0,0234	0,0333

Table 14: Changes in accessibility for equal contour-based accessibility, per SES

Clear are the total jobs with and without the metro present in the model, as well as the (relative) increase in jobs after the metro has been inserted into the model. The field with 'Total Jobs Travel Survey' shows the total amount of jobs deducted from the travel survey, per SES. Then, the results are normalized for this total amount of jobs, to make them comparable with each other among the different SES.

Now, several papers suggest a level of minimum sufficient job accessibility that everyone should have in order for a transport system to be equitable (Lucas, Wee, & Maat, 2016) (Martens, 2017). However, it is difficult to define how many jobs exactly would be sufficient for a socio-economic class. A possibility is to base the threshold of sufficient jobs based on the distribution of income (Martens, 2015). However, since the division of wealth and income in Bogotá is rather unfair, with a high Gini-coefficient, as discussed earlier in this research, applying this method would not result in an equity measure that would actually assess the equality of the transport system and the intervention that is applied.

Still, it is possible to compare the relative increases in accessibility that this measure implies, as well as the absolute normalized increase in jobs. Looking at the table 14, it becomes clear that SES 3 and SES 4 profit most from the metro in terms of a contour accessibility measure. They get an increase of around 3%, while SES 1+2 only notice an 1,6% increase. In addition to that, in terms increase in normalized jobs, SES 3 and SES 4 see an even bigger increase compared to SES 1+2. Meanwhile, SES 5+6 shows the biggest increase, both relatively and in terms of jobs normalized to the total amount of jobs deducted from the Bogotá travel survey. However, it is doubtful if these numbers for SES 5+6 will ever be reached, since practice shows that they have a far smaller maximum travel time, compared to the one that is worked with in this analysis. Altogether, the results from this analysis could imply that the intervention of the realization of the metro does not make the system more equitable, rather even more inequitable. However, to conclude such a statement based on merely this small part of the puzzle would be dangerous and rash.

12.4 Equal decay function opportunity based accessibility approach.

SES 1 + 2

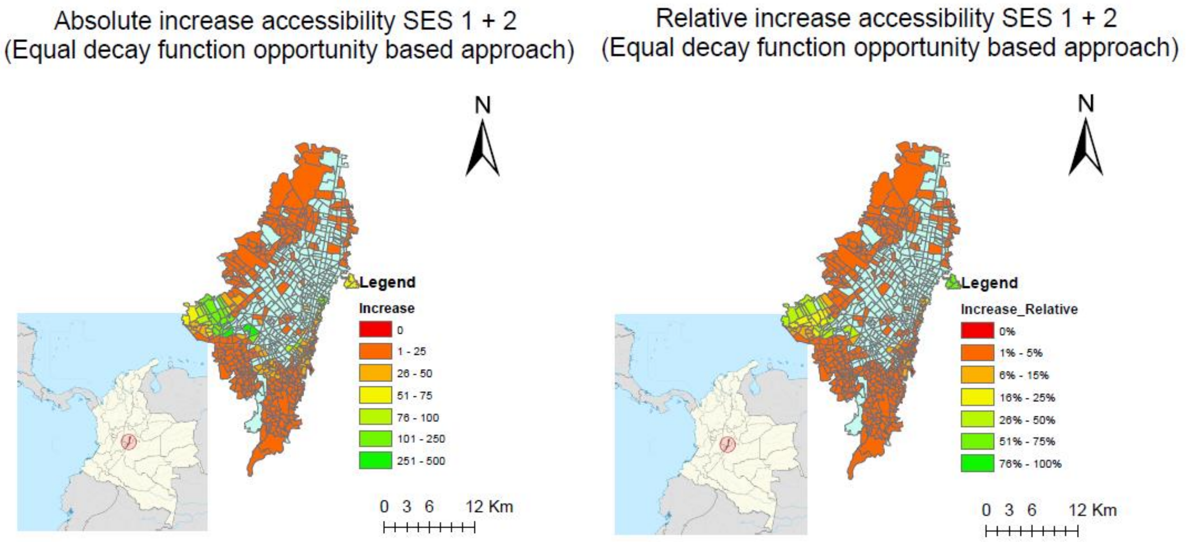

Figure 26: Absolute and relative increases in accessibility SES 1+2. Equal decay function approach

SES 3

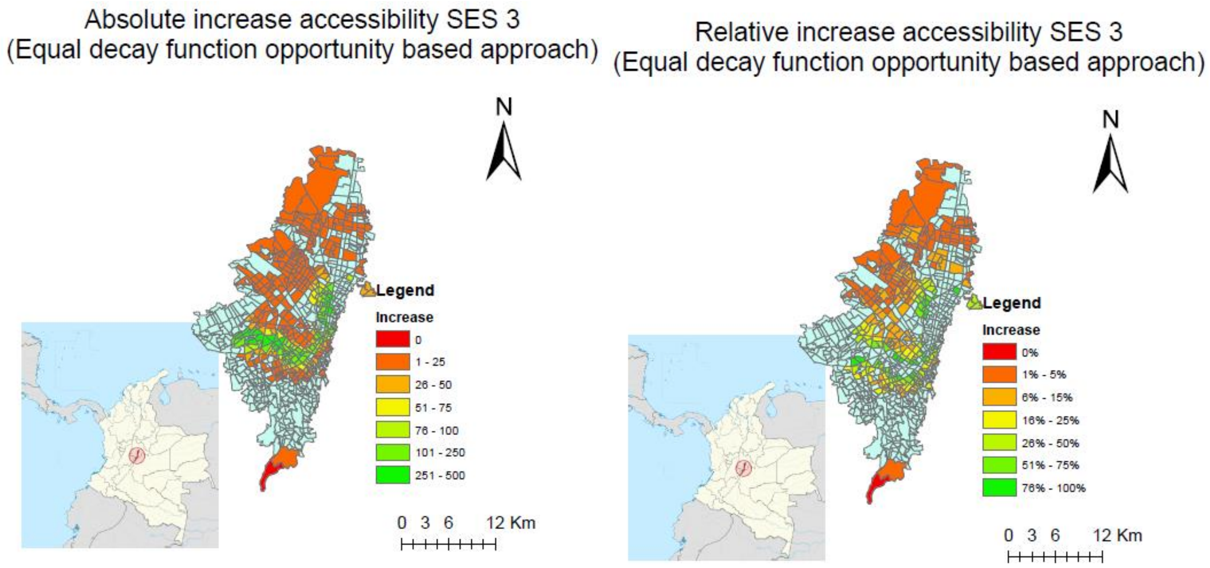

Figure 27: Absolute and relative increases in accessibility SES 3. Equal decay function approach

SES 4

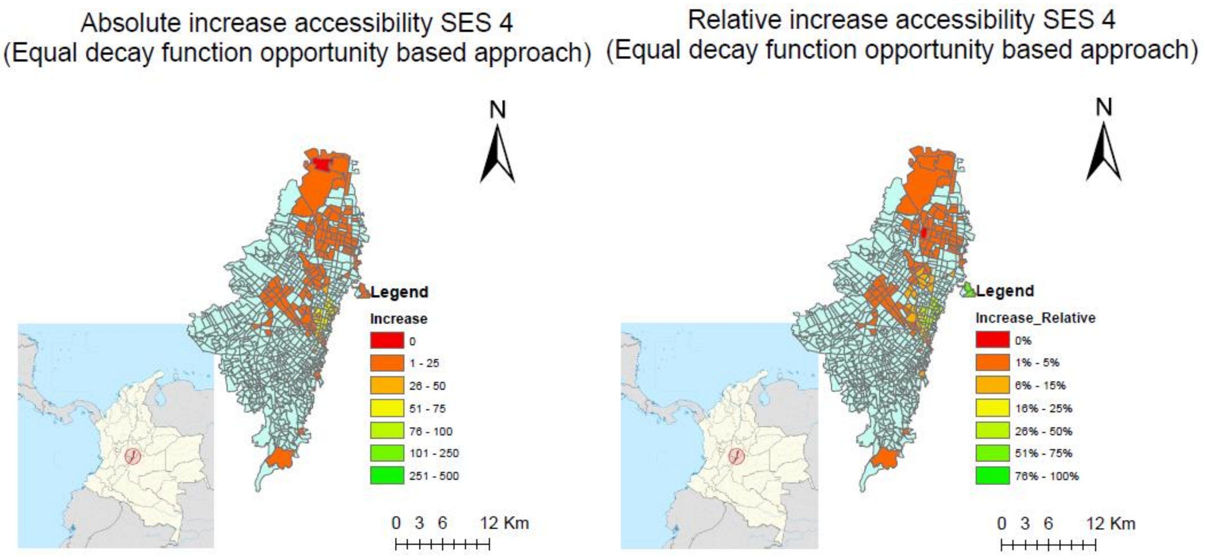

Figure 28: Absolute and relative increases in accessibility SES 4. Equal decay function approach

SES 5 + 6

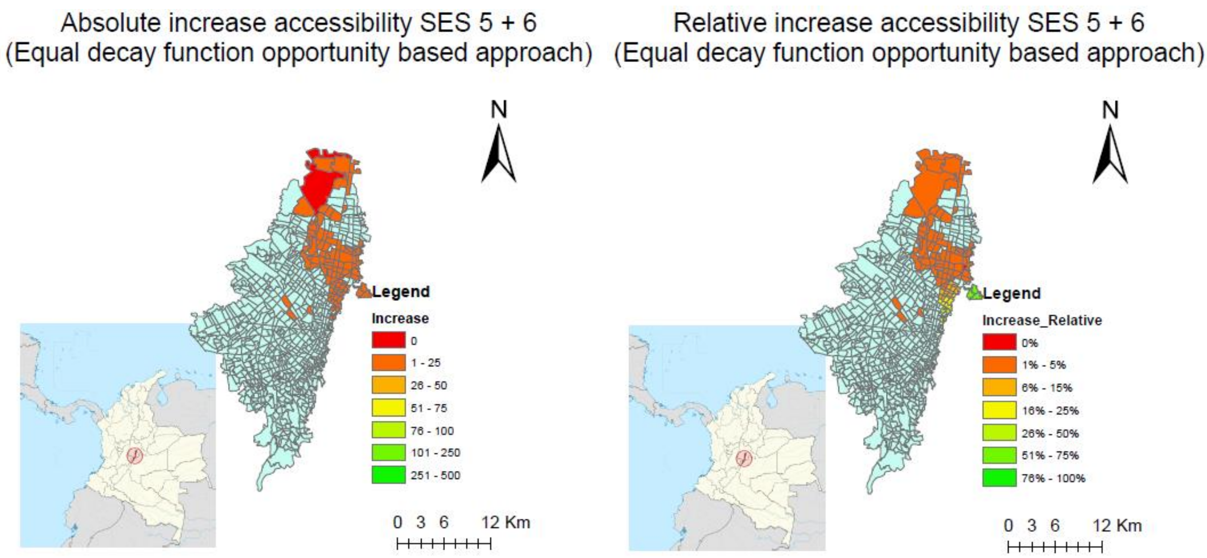

Figure 29: Absolute and relative increases in accessibility SES 5+6. Equal decay function approach

Summary

Accessibility for equal decay function opportunity based accessibility

	SES12	SES3	SES4	SES56
Average Absolute Increase	29	71	14	3
Average Relative Increase (%)	4,2	10,4	9,1	4,8
Absolute Increase	12218	29703	2328	306
Total Jobs Travel Survey	3092838	1653405	157302	42120
Absolute Increase Corrected Total Jobs	0,004	0,018	0,015	0,007

Table 15: Changes in accessibility for equal decay function approach, per SES

The approach where a decay function with equal Bèta values and equal maximum travel times are applied, shows the same results as the earlier approaches. Again, the strata 1 and 2 show the smallest amount of profits, both in relative and absolute normalized increase. Still the Kennedy part of SES 1+2 gains decent benefits. Noticeable is the difference in the equal-contour based accessibility measure and the equal decay function approach for strata 5 and 6. In the first of these approaches, they show to have the biggest profits, while with the second measure, they only score better than strata 1 and 2. Still, as pointed out earlier, the results for strata 5 and 6 should be looked at with great care, because of the small amount of data available.

13. Discussion

This research tried to assess the equity of the metro of Bogotá by comparing accessibility, measured in three different ways, among different socio-economic strata. In order to do this, the effect of the metro on travel times and (generalized) travel costs had to be found. This was done by making a multi-modal network analysis of the city, in ArcGIS. Almost in any case of modelling, assumptions, and generalizations have to be made. This also applies to this research.

An important one that has most likely resulted into the largest error was the choice between the connectivity policies for the walking and biking infrastructure. A decision had to be made between the endpoint or any-vertex policy, where in the end, any-vertex was chosen. This introduced an error in the case of for example viaducts, where the model assumed connectivity between levels, while in the real world, this is not the case. However, because of the large amount of trips and the small amount of cases where this discrepancy would apply, the error will not result in to large differences between the model and the real world. Another error in the model is caused by the assumption of rational behavior. Due to bounded rationality, the commuters choosing the fastest route in any case is simply impossible, and will also result into a discrepancy between the model and the real world. However, the assuming of rational behavior is widely accepted within these kinds of researches. Furthermore, it is simply the only feasible method within the amount of time available, and the differences between the modelled world and the real world will not be very big. A last remark that can be made on the modelling and data of this research is that for strata five and six, a very small amount of data was available. Therefore, outcomes concerning this group have to be treated with great suspicion, since the small amount of data may have influenced the outcomes.

As discussed, three measures have been used to assess the accessibility among the SES. The first accessibility measure is one with specified time and GTC-decay functions. These kind of accessibility measures are widely accepted and applied within the field of traffic and mobility policy studies. However, several experts on equity argue that such a measure is not the best way to assess equity, because preferences in the past may be due to spatial mismatch instead of actual preference. Therefore, two measures of accessibility that are more fit for an equity assessment are also used. With three different measures of accessibility, of which two are specified for an equity assessment and the other is widely used and accepted in accessibility researches, a robust view of the accessibility among the SES can be realized. Also, the different measures seem to show more or less the same results, which contributes to the robustness of the total research.

Still, even with robust levels of accessibility, it is hard to conclude on the equitability of the metro. A good quantitative measure of equity has not been found so the conclusion on equity will have to rely on qualitative arguments. This will to some extent compromise the strength of the conclusion concerning the equity part of this research.

However, even though the model and the equity assessment showed to have their flaws, I think this research is to large extent reproducible and the results from this results on travel times, travel costs and accessibility levels will very closely approach the real world situation.

14. Conclusion

With three measures of accessibility, a robust conclusion on accessibility can be drawn. Remarkable is that strata 1 and 2 get the smallest increase in accessibility in all measures, except for one, where they are the second lowest group. The poorest people of Bogotá seem to get the smallest (relative) increase in accessibility. Kennedy, a neighborhood where a lot of strata 1&2 people live, shows nice effects, but other strata 1 and 2 areas often show small of no effects at all. However, stratum three, still a group with people that live below the standard of poverty, shows very good results. With results mainly around 10% increase and even a staggering 20% increase in one case, they will be the group that is predicted to profit the most from the metro. For stratum four, that are middle incomes and richer people, also nice results are predicted, although not as good as for stratum three. The results for strata five and six vary a lot among the different measures. Therefore it is hard to conclude something for strata 5&6's accessibility. Also, doubts the low amount of data available for this group, already made this hard, so an accessibility conclusion for strata five and six will not be drawn.

When looking back at the definition of equity of this research it may be possible to conclude about the equity of this distribution of accessibility benefits. The definitions is: *"the metro should raise accessibility for the lower strata more than for the higher ones in terms of relative increase"*. When thinking about the conclusion on accessibility increase for strata one and two that has just been drawn, this does not seem to be the case. After all, strata one and two show the smallest relative increase in accessibility.

However, strata three can also be viewed as one of the lower strata and they get the highest accessibility increases. Here a quantitative assessment of equity would have been very helpful because it would have been an objective way to discuss the equity. However, such a measure proved unfeasible for this research, which makes an assessment about the equity of the metro problematic. However, the least thing that can be said is that the relatively poor people from stratum three profit well from the metro. They gains for strata one and two seem to fall behind. Still, around one million people of strata one and two living in the Kennedy neighborhood will profit to large extent by the metro's realization.

For future research, I would recommend finding a feasible and applicable quantitative measure of accessibility. Furthermore, a larger amount of data on the travel behavior of strata five and six would have benefitted this study.

15. References

(Andiarios). (2015). Las dificultades de un ciclista en Bogotá. Retrieved from http://www.elespectador.com/noticias/bogota/dificultades-de-un-ciclista-bogota-video-540555

(Transmilenio). (2017). Tarifas. Retrieved from http://www.transmilenio.gov.co/Publicaciones/ZONALES/informacion_general_zonales/Tarifas

Bertolaccini, K. L. (2013). Assessing the Equity of Transit Supply Distribution in Metropolitan Areas Using Lorenz Curves and Gini Coefficients, 1–39.

Bjelland, M., Montello, D., Getis, A., Fellmann, J., & Getis, J. (2013). *Human Geography: Landscapes of Human Activities (WCB Geography)*.

Braake, S. J. ter. (2013). The Contribution of Cicloruta on Accessibility in Bogotá: A spatial analysis on Cicloruta's contribution to job accessibility for different social-economic strata, (September).

Buckley, E. (2016). TransMilenio, SITP fare hikes cost Bogotá commuters. Retrieved from https://thecitypaperbogota.com/bogota/bogota-hikes-fares-for-public-transportation/11601

Cervero, R. (2005). Progressive Transport and the Poor: Bogotá's Bold Steps Forward. *Access*, 24–30. Retrieved from http://bit.ly/115xnDZ

Delmelle, E. C., & Casas, I. (2012). Evaluating the spatial equity of bus rapid transit-based accessibility patterns in a developing country: The case of Cali, Colombia. *Transport Policy*, *20*, 36–46. https://doi.org/10.1016/j.tranpol.2011.12.001

Echenique Gómez-Lobo, A. (2007). AFFORDABILITY OF PUBLIC TRANSPORT : A METHODOLOGICAL CLARIFICATION. *Serie Documentos de Trabajo*, *N 261*, 34. Retrieved from http://www.econ.uchile.cl/uploads/publicacion/db395ea5-f323-448c-b00a-935049986dcb.pdf

Esbjørn, A., & Fjalland, E. L. P. (2012). COLOMBIA - SOCIAL STRATIFICATION BY LAW. Retrieved from http://www.ifhp.org/ifhp-blog/colombia-social-stratification-law

Falavigna, C., & Hernandez, D. (2016). Assessing inequalities on public transport affordability in two latin American cities: Montevideo (Uruguay) and C??rdoba (Argentina). *Transport Policy*, *45*, 145–155. https://doi.org/10.1016/j.tranpol.2015.09.011

Folmar, C. (2015). Bogotá ' s Transportation Renewal : Exemplary sustainable transportation systems for policymakers, (April).

Garcia-Zamor, J.-C. (2014). *Strategies for Urban Development in Leipzig, Germany: Harmonizing Planning and Equity*. https://doi.org/10.1007/978-1-4419-6649-0

Geertman, S. C. M., & Ritsema Van Eck, J. R. (1995). GIS and models of accessibility potential: an application in planning. *International Journal of Geographical Information Systems*, *9*(1), 67–80. https://doi.org/10.1080/02693799508902025

Geurs, K., Boon, W., & Van Wee, B. (2009). Social Impacts of Transport: Literature Review and the State of the Practice of Transport Appraisal in the Netherlands and the United Kingdom. *Transport Reviews*, *29*(1), 69–90. https://doi.org/10.1080/01441640802130490

Geurs, K. T. (2006). Accessibility, land use and transport : accessibility evaluation of land-use and transport developments and policy strategies, 1–247. Retrieved from http://dspace.library.uu.nl/handle/1874/9299

Geurs, K. T., & van Wee, B. (2004). Accessibility evaluation of land-use and transport strategies: Review and research directions. *Journal of Transport Geography*, *12*(2), 127–140.

https://doi.org/10.1016/j.jtrangeo.2003.10.005

Gilbert, A. (2008). Bus Rapid Transit: Is Transmilenio a Miracle Cure? *Transport Reviews*, *28*(4), 439–467. https://doi.org/10.1080/01441640701785733

Hamidi, Z. (2014a). Applying Accessibility Measures To Explore the Integration of Bicycle and City of Bogot a Applying Accessibility Measures To Explore the Integration of Bicycle and.

Hamidi, Z. (2014b). *APPLYING ACCESSIBILITY MEASURES TO EXPLORE THE INTEGRATION OF BICYCLE AND TRANSMILENIO SYSTYEM IN THE CITY OF BOGOTA*. Retrieved from https://www.itc.nl/library/papers_2014/msc/upm/hamidi.pdf

Hidalgo, D. (2002). TransMilenio: A high capacity–low cost bus rapid transit system developed for Bogotá, Colombia. *Proceedings of the Second International Conference, April 14-18, 2002, Alexandria, Virginia, USA*. Retrieved from http://www.codatu.org/wp-content/uploads/Transmilenio-A-high-capacity-low-cost-bus-rapid-transit-system-developed-for-Bogota-Colombia-D.-HIDALGO.pdf

Hidalgo, D., Pereira, L., Estupiñán, N., & Jiménez, P. L. (2013). TransMilenio BRT system in Bogota, high performance and positive impact – Main results of an ex-post evaluation. *Research in Transportation Economics*, *39*(1), 133–138. https://doi.org/10.1016/j.retrec.2012.06.005

Litman, T. (2003). Social Inclusion As A Transport Planning Issue in Canada. *Transport Policy*, 1. Retrieved from http://www.vtpi.org/soc_ex.pdf

Litman, T. (2005). Evaluating Transportation Equity: Guidance for Incorporating Distributional Impacts in Transportation Planning. *Victoria Transport Policy Institute, Victoria, British …*, *8*(2), 50–65. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Evaluating+Transportation+Equity+Guidance+For+Incorporating+Distributional+Impacts+in+Transportation+Planning+by#2

Litman, T. (2017). Evaluating Transportation Equity: Guidance for Incorporating Distributional Impacts in Transportation Planning. *Victoria Transport Policy Institute, Victoria, British …*, *8*(2), 50–65. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Evaluating+Transportation+Equity+Guidance+For+Incorporating+Distributional+Impacts+in+Transportation+Planning+by#2

Lucas, K., Wee, B., & Maat, K. (2016). A method to evaluate equitable accessibility : combining ethical theories and accessibility-based approaches. *Transportation*, 473–490. https://doi.org/10.1007/s11116-015-9585-2

Mahrous, R. F. (2012). Multimodal Transportation Systems : Modelling Challenges. *Msc Thesis , Faculty of Geo-Information Science and Earth Observation.*, 85.

Margolis, J. (2015). can-modern-megacity-bogot-get-without-subway @ www.pri.org.

Martens, K. (2012). Justice in transport as justice in accessibility: Applying Walzer's "Spheres of Justice" to the transport sector. *Transportation*, *39*(6), 1035–1053. https://doi.org/10.1007/s11116-012-9388-7

Martens, K. (2015). Accessibility and Social Equity in Tel-Aviv Metropolitan Area - examination of the current conditions and ... ביבא - הניחב לש בצמה םייקה יטירסתו תושיגנ תוינויוושו תיתרובחת ןילופורטמב - חותיפ םיידיתע לת Accessibility and Social Equity in Tel- Aviv Metropolitan Area - examination of the current conditions and, (April). https://doi.org/10.13140/RG.2.1.4141.3284

Martens, K., Martens, K., & Martens, K. (2017). Transport Justice, (January).

Matuszewski, B. (2015). *BRT AS A WAY TOWARDS MORE SUSTAINABLE CITIES? : BOGOTA'S*

TRANSMILENIO. Retrieved from http://projekter.aau.dk/projekter/files/223227294/BRT_as_a_way_towards_more_sustainable_cities_Bogota_s_Transmilenio_Bartosz_Matuszewski.pdf

Movilidad)), ((Secretaría Distrital de. (2015). Datos abiertos. Retrieved from http://www.movilidadbogota.gov.co/web/?q=node/1654

Munoz-Raskin, R. (2010). Walking accessibility to bus rapid transit: Does it affect property values? The case of Bogotá, Colombia. *Transport Policy*, *17*(2), 72–84. https://doi.org/10.1016/j.tranpol.2009.11.002

Pojani, D., & Stead, D. (2017). *The Urban Transport Crisis in Emerging Economies*. https://doi.org/10.1007/978-3-319-43851-1

Rahman, M., & Neema, M. N. (2015). A GIS Based Integrated Approach to Measure the Spatial Equity of Community Facilities of Bangladesh. *Aims Geosciences*, *1*(November), 21–40. https://doi.org/10.3934/geosci.2015.1.21

Rodriguez, C., Gallego, J. M., Martinez, D., Montoya, S., & Peralta-quiros, T. (2016). Examining Implementation and Labor Market Outcomes of Targeted Transit Subsidies. *Transportation Research Record Journal of the Transportation Research Board*.

Rodriguez, C., & Peralta, T. (2016). Balancing Financial Sustainability and Affordability in Public Transport—the Case of Bogota, Colombia, (18), 1689–1699.

Rosero, L. M., Castanó, L., & Sarmiento, A. (2012). SISBEN : A unified vulnerability assessment and identification system for social assistance Social Protection in Action : *International Labour Office*, *2012*(202). Retrieved from http://www.social-protection.org/gimi/gess/RessourcePDF.action?ressource.ressourceId=51857

Sanchez, T., Stolz, R., & Ma, J. (2004). Inequitable Effects of Transportation Policies on Minorities. *Transportation Research Record*, *1885*, 104–110. https://doi.org/10.3141/1885-15

Savvides, A. (2013). Equity of mobility in sustainable transportation. *WIT Transactions on Ecology and the Environment*, *179 VOLUME*, 1091–1101. https://doi.org/10.2495/SC130932

Song. (1996). Some Tests of Alternative Accessibility Measures: A Population Density Approach. *Land Economics*, 10.

Teunissen, T., Sarmiento, O., Zuidgeest, M., & Brussel, M. (2015). Mapping Equality in Access: The Case of Bogotá's Sustainable Transportation Initiatives. *International Journal of Sustainable Transportation*, *9*(7), 457–467. https://doi.org/10.1080/15568318.2013.808388

The Data Team, (The Economist). (2015). Bright lights, big cities. Retrieved from http://www.economist.com/node/21642053

Torres, A., Sarmiento, O. L., Stauber, C., & Zarama, R. (2012). The Ciclovia and Cicloruta Programs: Promising Interventions to Promote Physical Activity and Social Capital in Bogotá, Colombia. *American Journal of Public Health*, *103*(2), e23–e30. https://doi.org/10.2105/AJPH.2012.301142

UNEP ENVIRONMENTAL, SOCIAL AND ECONOMIC SUSTAINABILITY FRAMEWORK. (2015). Retrieved from https://wedocs.unep.org/rest/bitstreams/14946/retrieve

van Wee, B., & Geurs, K. (2011). Discussing equity and social exclusion in accessibility evaluations. *European Journal of Transport and Infrastructure Research*, *11*(4), 350–367.

Wessels, G., Pardo, C. F., & Bocarejo, J. P. (2012). *Bogotá 21: Towards a World-Class, Transit-Oriented Metropolis*.

Wismadi, A., Zuidgeest, M., Brussel, M., & van Maarseveen, M. (2014). Spatial Preference Modelling for equitable infrastructure provision: An application of Sen's Capability Approach. *Journal of Geographical Systems*, *16*(1), 19–48. https://doi.org/10.1007/s10109-013-0185-4

Appendix A: Interview David Mendelez of Metro Company

Interview David Meléndez – Contract manager of the metro de Bogotá organization

Hello David, thank you for the opportunity to interview you. To start off, I would like to introduce you to my research a little bit. My name is Rogier Busscher I am a student in civil engineering at the University of Twente in the Netherlands. For my bachelor thesis, I am researching the plans of the metro de Bogotá. My research will mainly focus on generalized costs, raise in accessibility and the difference in it among socioeconomic strata, or in other words, the differences in equity.

1. **What is your position with the metro company?**

My position is to manage the integration of the metro and its stations within the streets. I focus on urban development. For example I assess potential land use plot areas for the stations. I also focus on the urban impact of the plans. The effects of an elevated metro in the streets of Bogotá will be large. It is therefore that we try to keep the design of the metro as 'light' as possible.

2. **My research focusses on the accessibility, equity and generalized costs. What will be the tariff structure of the metro?**

A tariff structure integrated with the Transmilenio will be used, for the same price as the Transmilenio is now.

3. **How has this tariff structure been decided on?**

We view the BRT and metro system as one system. Therefore, also one tariff should apply.

4. **To what extent is the travel budget of the different SES known within your organization?**

We have data on this topic. It is mainly based on the multi-purpose survey of Bogotá (Encuesta Multipropositos de Hogares).

5. **To what extent do you think that there are going to be people that will not be able to afford the metro?**

I certainly think that there are going to be people that will not be able to afford the metro. However, I do not know how many. Since the costs are going to be the same as the Transmilenio, maybe you can find research on the affordability of the BRT.

6. **What will be the metro's frequency**

In peak hours, the frequency will be three minutes. The frequency in non-peak hours has not yet been decided on.

7. **What will be the average speed of the metro?**

The average speed between the first and the last metro station, including the stopping time at all stations will be 43km/h.

8. **Which and how many metro stations will have bike parking options?**

Recently it has been decided that all metro stations will have a space to park your bike. The exact details on how big each bicycle shed has to be are not yet known.

9. **Will the users be allowed to bring their bike on the metro?**

We have not decided on this topic yet.

10. When will the metro be ready?

In 2022

11. Are you going to make it in time?

We most certainly hope so. I'm confident that we will be in time.

Appendix B: Scatter plots and fits of GTC-decay functions

SES 1 + 2

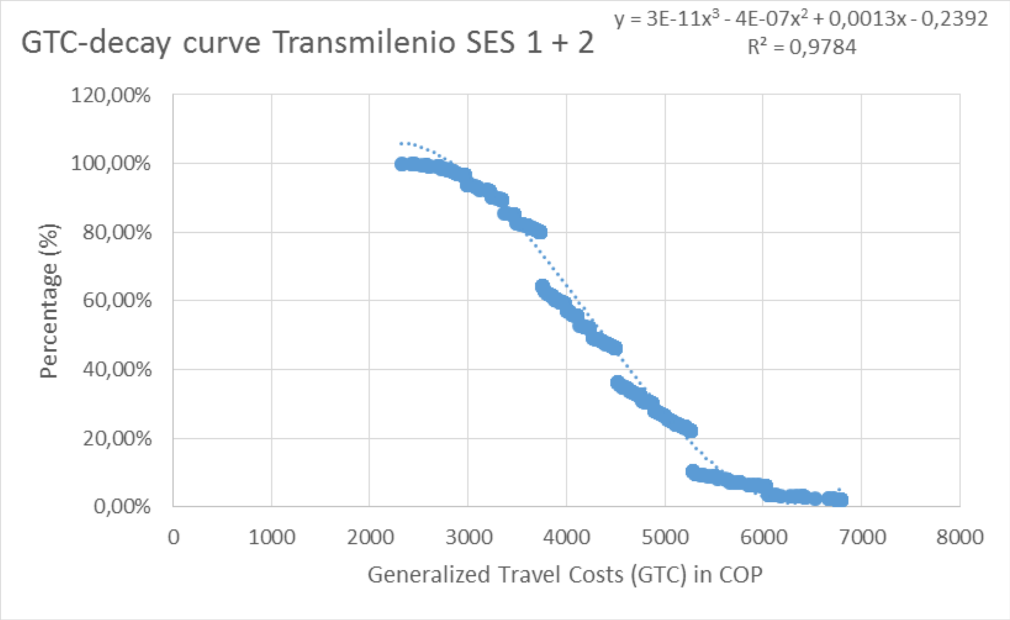

Figure B1: Scatter plots and fits of GTC-decay function SES 1 + 2

SES 3

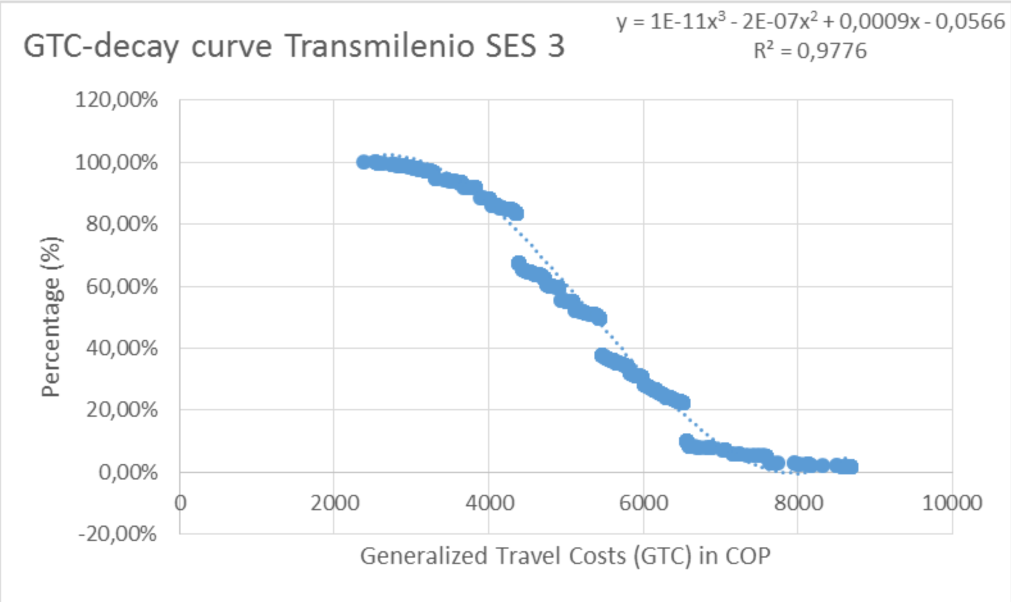

Figure B2: Scatter plots and fits of GTC-decay function SES 3

SES 4

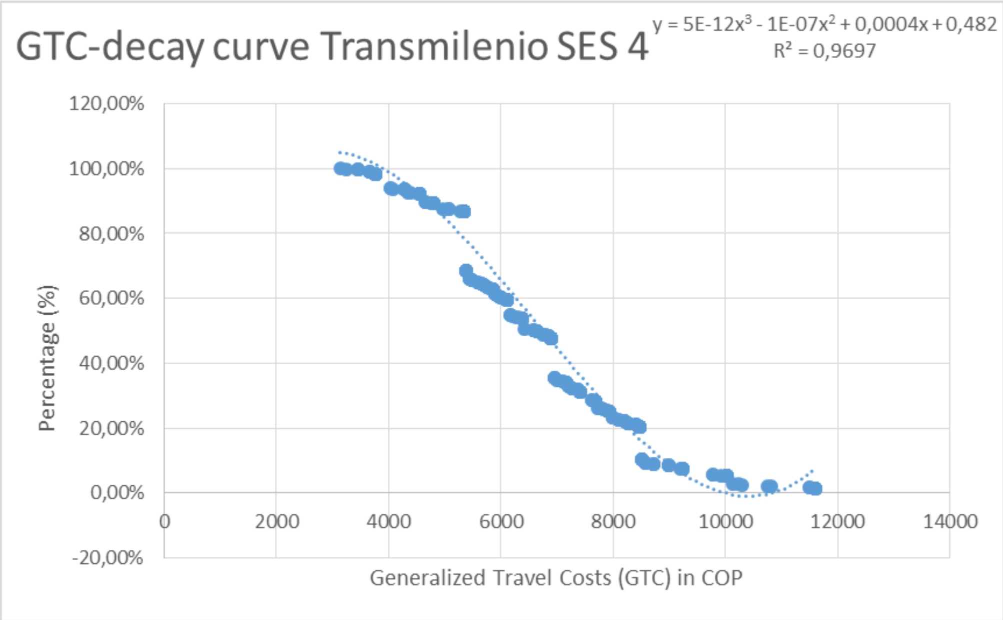

Figure B3: Scatter plots and fits of GTC-decay function SES 4

SES 5 + 6

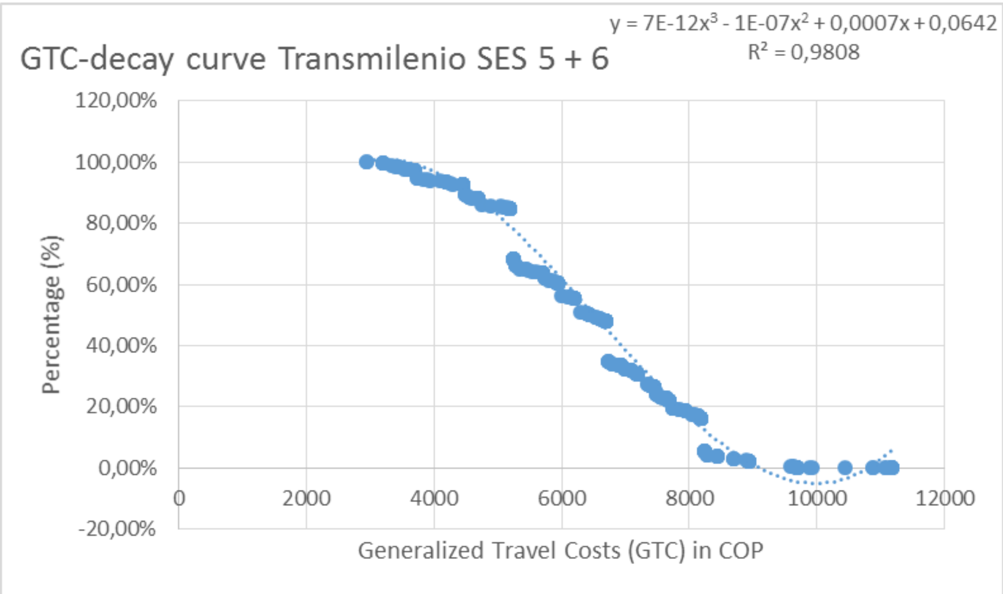

Figure B4: Scatter plots and fits of GTC-decay function SES 5+6

Appendix C: MATLAB code used for Bike-PT-Walk scenario

```
[ca, cb, cc] = ndgrid(OriginsID, StationsID, DestinationID);
combs = [ca(:), cb(:), cc(:)];                                      %creates
matrix of all possible combinations to get from origin to destination via every
station

Load B = Origin_Station (Bike) data: [OriginID StationID TT]

[~, ind] = ismember(combs(:, [1 2]), B(:, [1 2]), 'rows');
C = [A B(ind, 3)];                                                 %finds match
between first two column of both matrices. Then adds travel time to third column
of combinations

                                                                   %Repeat for
Station-Destination (PT&walk) data

[~, ind] = ismember(combs(:, [2 3]), B2(:, [1 2]), 'rows');
combs = [combs B2(ind, 3)];                                        %Now the combs
matrix consists of [OriginID StationID Travel_Time(Origin-Station)
Travel_Time(Station-Destination)]

combs=[combs(:,1) combs(:,3) combs(:,4)+ combs(:,5)];              %Now the combs
matrix only consists of: [OriginID DestinationID Total_Travel_Time] So the OD-
relation via every possible station is now known.



combs = sortrows(combs);                                           % After the
sort unique combinations will be adjacent and with increasing values in 3rd column

[~,ia] = unique(combs(:,1:2),'rows');                              % Find index of
all the unique comb in col 1 & 2, unique only returns the first index

result = combs(ia,:);                                              % These three
rows of code found the lowest possible OD-relation. So now, the fastest travel
time between origin, station and destination is known. This result is the travel
time for the scenario Bike-PT-Walk
```