APPLYING ACCESSIBILITY MEASURES TO EXPLORE THE INTEGRATION OF BICYCLE AND TRANSMILENIO SYSTEM IN THE CITY OF BOGOTÁ

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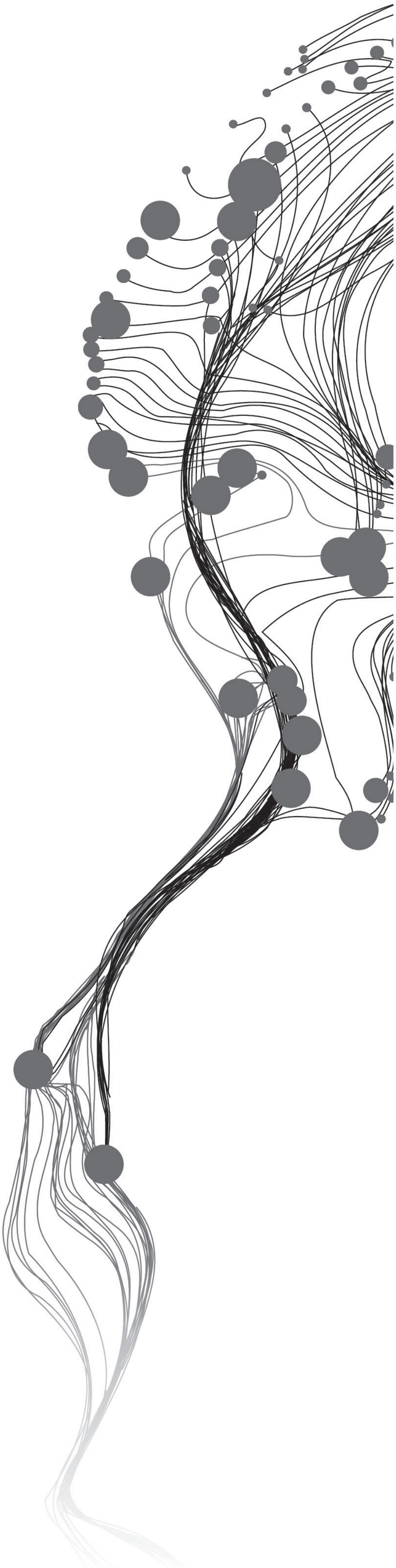

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ZAHRA HAMIDI
Enschede, The Netherlands, March, 2014

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ABSTRACT

The integration of public transport and cycling is important to promote modal shift under sustainable transport policies. The city of Bogota, aiming for more sustainability has developed massive infrastructure for each of these modes, such as TransMilenio and Cicloruta. The main objective of this study is to investigate the potential for integration of these two subsystems through accessibility measures. This measure included social factor to estimate the impact of bicycle integration policies across five social groups in this city.

The accessibility was estimated under three scenarios with combination of TransMilenio, bicycle and walking. Each scenario simulated a different level of bicycle integration in a multimodal trip. To explore the resulting accessibility within each level of income, for each social group, decay functions were calculated by using the travel survey data for each mode. The final accessibility for each residential location was calculated as the sum of the jobs indicator, discounted by the corresponding decay function.

The resulting accessibility showed variation across the space in relation to distance from the city center, and across the social groups in relation to their income. In the scenario without bicycle integration, the origins with higher strata and closer distance to the center had the better accessibility through combination of TransMilenio and walking. Integrating bicycle created positive effects for all social groups in the city. It was found that involving bicycle in the trips from origins to TransMilenio stations creates a larger impact, and benefits the poorest groups the most. On the other hand, full integration would improve the accessibility for the middle strata which are located relatively close to the city center.

In addition to accessibility measures, the current integration of bicycle and TransMilenio was investigated through field surveys. The surveys results revealed that integration policies should go beyond provision of only physical infrastructure. Creating a safe image of cycling and changing citizens attitude toward cycling is important to encourage the use bicycle as a daily transport mode.

Keywords

Accessibility, Intermodality, Network Analysis, Non-motorized Transport, Bogotá

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Zahra Hamidi
Enschede, 2014

What was all my life about? ...
I was raw, I cooked, then I burned ... "Rumi"

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Chapter 1
Introduction

1.1 BACKGROUND

Urban population has been increasing and it is expected exceed to 70% of world population by 2050 (Lerner & Van Audenhove, 2012). In recent decades, rapid urbanization is characterized by motorization and development of car based cities. Statistics show that in Latin America for every new born child, 2.5 new motor vehicles were registered in 2010 (Hidalgo & Huizenga, 2013). Indeed, motorization to some extent could provide mobility for citizens, but it is also associated with heavy economic and environmental issues in current cities.

Insufficient investment in infrastructure, increases the seriousness of the above discussed in developing countries. Negative externalities of motorization are exacerbated by urban poverty and social exclusion. Cities of developing countries are facing a broad range of problems such as: inequality, urban sprawl, spatial mismatches between corresponding urban activities, unhealthy environmental conditions, urban decay, unplanned or poorly designed transport systems, overcrowded urban centers and economic losses due to traffic congestion. Uncontrolled motorization makes policymakers and governments to face greater challenges in providing all citizens with a good quality of life.

An extensive body of research embraces the idea that sustainable urban development could considerably alleviate the mentioned problems. The ultimate goal of sustainable movement is to improve living and working conditions in an economically efficient, and environmentally and socially sustainable manner. Accordingly, it seeks for a coordination between transport and urban developments (Cervero, 2013). Transport is a key in reaching this goal. In urban areas, individuals and businesses need to reach opportunities in different location; transport system affect those opportunities. Therefore, actions and solutions in the transport sector contribute positively to sustainable urban development.

Urban life involves moving between different urban activities. Lerner et al. (2013) reported that intra urban trips represent 64% of the total travel kilometers. Urban transport as the facilitator of these movements support economic and social development of cities. Therefore, citizens travel behavior and transport choices are an evidence of urban developments sustainability. For instance, increase in the modal share of private vehicles, and citizens car ownership are indications for less sustainability. For similar reason Hidalgo and Huizenga (2013) note that current urban growth patterns in Latin America are not sustainable. Car ownership and use of private motorized vehicles are increasing progressively. Thus, it cancel the effect that nonmotorized and public transport modes have the largest shares in urban transport.

Recently, South American cities have decided to develop plans and guide their urbanization processes towards a sustainable one. In 2011, during Latin America Sustainable Transport Forum (FTS), government representatives of eight South American countries and Mexico defined sustainable transport as:

“ *The provision of services and infrastructure for the mobility of goods and people, needed for economic and social development and for improving quality of life and competitiveness. These services*

and transport infrastructure provide safe, reliable, economical, efficient, equitable and affordable mobility, while mitigating the negative impacts on health and the local and global environment, in the short, medium and long term without compromising the development of future generations.” (Foro de Transporte Sostenible de América Latina, 2011).
Based on this definition and inspired by Avoid-Shift-Improve approach, FTS declared that sustainable transport could be achieved with four groups of strategies. First group includes *Avoid* strategies, which seek to prevent unnecessary motorized trips and reduce the need for travel by demand management. These strategies pursue to improve the efficiency of transport system. *Shift* strategies are the second group, which aim for a modal change from the most energy consuming modes such as private vehicles, to more efficient and environmentally-friendly modes. Trip efficiency is the key for this group. Third group includes *Improve* strategies which focus on developing technology and management of transport services. Their main targets are optimizing transport infrastructure as well as vehicle efficiency (SUTP, n.d.). The last group are *Cross-cutting* strategies that seek for improvements with multidimensional aspects of urban transport including: social, economic, institutional and regulation. They aim to face challenges such as: equity and social inclusion, innovative financing, coordination between institutions, developing knowledge and awareness related to sustainable transport in all levels, promoting mitigation and reducing vulnerability to effects of climate change.

FTS emphasized on modal shift to reach sustainability and they introduced following six specific policies to move towards this goal, Hidalgo and Huizenga (2013): they are as below:

- Encourage walking and cycling as alternatives to car, by providing safe environments.
- Expand and improve public transport modes as more efficient passenger transport modes, aiming for affordable, safe, reliable and of high quality systems.
- Discourage use of private cars, through transport demand management.
- Raising awareness through informative and educative social programs in order to bring change in travel behavior toward sustainable alternatives.
- Promote interurban passenger transport e.g. buses and trains, as alternatives to private cars and air transport.
- Enhance intermodal logistics management and promote use of maritime, river, and railway modes for fright and passenger transport.

Public transport, walking and cycling are the most important modes in modal shift programs. Litman (2011) confirmed this by introducing “The Green Transportation Hierarchy”. He prioritized different transport modes according to their efficiency and afford-ability in terms of space, energy and costs. The hierarchy as presented by Litman (2011) appears below:

1. Walking
2. Bicycles
3. Public transportation
4. Service and freight vehicles
5. Taxis
6. Multiple occupant vehicles (carpools)
7. Single occupant vehicles

Walking and cycling are known as non motorized transport modes (NMT). These modes are clean, low cost, energy saving, non-polluting and low space modes of transport. They can easily be used to travel within local distances, up to some 3.5 km (Rietveld, 2000). They become more important for longer trips, with from a multimodal perspective. Indeed they provide access to other transport modes such as public transport. Recently, transportation planning has become more multimodal and comprehensive. It considers a wider range of alternative modes to private cars. Under this new approach, modal integration is also known as a major component of any urban mobility strategy.

Many studies advocated the positive contribution of NMT modes to multimodal trips. UN-Habitat (2013) reported the practices around the world where the integration of bicycles expanded the service area beyond the walking threshold. Yet, the potentials offered by the context of these practices had a great share for their success. Pucher and Buehler (2008) describe that in every context, factors such as: history, culture, topography, climate and government policies affect bicycle usage. Moreover, the choice of bicycle as a transport mode is a function of trip purpose, transport infrastructure and trip makers characteristics (Hegger, 2007). Therefore, transport policies need to be selected according to local factors.

Each transport mode affects the economic and social welfare of urban inhabitants differently. Mobility and accessibility varies according to transport mode. Mobility, refers to the extent of offered transport opportunities, and accessibility is related to quality of those movements. Accessibility is defined as the ease of reaching urban activities through transport system (Litman, 2008). In other words, accessibility indicates the level of opportunity, taking into account both the existence of opportunities and the transport options available to reach them (Geurs, 2006). This is a concept which links the transport system to urban opportunities (land use) and, at the same time, it can be related to economic goals (access to workers, customers, and suppliers), social goals (access to employment, goods and services, social contacts) and environmental goals (resource-efficiency of the associated activity and mobility patterns). Because of this linking property, improving accessibility has become the main objective of sustainable transport policies (Bertolini, 2005; Janelle & Hodge, 2000).

Banister (2008) introduced the "Sustainable Mobility Paradigm" in transport planning. Table 1.1 presents a comparison of the sustainable mobility paradigm and conventional ideas. According to this paradigm, transport policies should center the focus on accessibility rather than mobility. The most important concern of this approach is providing high quality and easy access to urban services and facilities. He further asserts that planners should aim to create high quality local neighborhoods and concentrate development around public transport-accessible locations.

Many studies translated the accessibility concept into measures to evaluate transport policies effectiveness. Handy and Niemeier (1997) remarked that these measures assist decision makers in facing a wide range of challenges, such as: planning for right investments, assessing transport services, evaluating land use distribution and transport system service, identifying inequities and suggesting interventions to yield improvement. Further more, Litman (2003) categorized transport performance measures under three perspectives: (1) Traffic-based measures (2) Mobility-based measures (3) Accessibility-based measures. He emphasized that the last approach is the most difficult but the best one to apply.

The definitions for accessibility suggest that transport system properties are important factors (see section 2.2). In addition to each single mode attributes, the ease of switching between modes also affects overall accessibility (Litman, 2008). According to this, accessibility can measure the impacts resulted from transport modes integrating. On the other hand, the quality and extent of using transport system is related to individuals' needs and abilities. This means that accessibility can be sensitive to socio economic properties of transport system users. Bocarejo S and Oviedo H

Table 1.1 Contrasting approaches to transport planning. Source: (Banister, 2008)

The Conventional Transport Planning and Engineering	**The Sustainable Mobility Paradigm**
Mobility	Accessibility
Physical dimensions	Social dimensions
Traffic focus, particularly on the car	People focus, either in (or on) a vehicle or on foot
Large in scale	Local in scale
Street as a road	Street as a space
Motorized transport	All transport modes (a hierarchy walking and cycling at the top and car at the bottom)
Forecasting traffic	Visioning on cities
Modeling approaches	Scenario development and modeling
Economic evaluation	Multicriteria analysis to take account of environmental and social concerns
Travel as a derived demand	Travel as a valued activity as well as a derived demand
Demand based	Management based
Speeding up traffic	Slowing movement down
Travel time minimisation	Reasonable travel times and travel time reliability
Segregation of people and traffic	Integration of people and traffic

(2012) applied accessibility measures to investigate how changes in the fare structure of the public transport system affect different socioeconomic groups in the city of Bogotá.

Connecting inhabitants and economic and social activities is one of the most important tasks of a transportation system (Cheng & Bertolini, 2013). In general, work is the main motive for commuters, and the trips to work places represent large part of transport system service. The quality of this trips is an indicator for transport system performance and effectiveness. Accordingly many accessibility measures developed to investigate job accessibility for urban inhabitants. These measures can be used to estimate the impact of a wide range of transport policies. Recently, there has been a growing list of countries which attempted to establish sustainable policies. Accessibility measures were proposed to evaluate these policies, and develop optimum alternative.

1.2 PROBLEM STATEMENT

Bogotá is the capital of Colombia, and the sixth largest city in Latin America. In recent decades, this city has been facing a range of issues related to unplanned urban developments, inefficient transportation, urban poverty and social segregation (Skinner, 2004). Decision makers in Bogotá aimed to address some of these problem through more sustainable transport policies. In 1998, a set of important interventions started, including implementation of Transmileno (TM), CicloRuta (the bicycle path network), and promoting Ciclovia (a program for restricting cars in the city during weekends and holidays). All the three projects intended to transform the expensive car-dependant transportation into a people oriented and affordable system (Ardila & Menckhoff, 2002).

TransMilenio as a bus rapid transit (BRT) and feeder bus service are part of the massive public transport system in Bogotá. This was developed to provide affordable and reliable transport in the city. Currently, TM consists of 11 main corridors which are constructed along major highways and avenues. A study conducted by Hidalgo (2008) shows that the implementation of this system not only reduced private car use and traffic congestion in the city, but also increased the use of NMT modes (specially walking). TM system operates with dedicated bus lanes, facilitated stations, advanced fair collection system and centralized control system. In addition, feeder buses cover local roads and provide access to main TM stations (Hidalgo et al., 2013).

CicloRuta is an initiative to promote a clean transport mode, in Bogotá. This network consists of 340 kilometers bicycle path, and it was designed to connect TM routes, parks and major urban centers. Provision of this infrastructure have accomplished significant achievements for the city. According to a traffic report by IDU (the department of local government in charge of planning and building infrastructure), the use of bicycle increased from 0.58% in the 1996 to 2.2% in 2002 (Pardo, 2013). UN-Habitat (2013) also reported that as an effect of this project the proportion of bike users doubled between 2000 and 2007.

TransMilenio and CicloRuta projects have produced significant positive effects for the city. However, there is no evidence on the impact of interaction and integration of these transportation initiatives. The results of Bogotá mobility survey (2011) reveal that only 0.01% of TM users use bicycle to reach TM stations (see chapter 4). This suggest that the potentials of combination of public transport and bicycle is not well recognized in this city. It is important to investigate the local factors which affect this potential.

Use of bicycles as an alternative to access TransMilenio can improve performance and sustainability of transportation systems. Currently, TransMilenio covers only 11 corridors across the city and direct access to this system by walking mode is limited to small areas around the stations. As a result, a great number of users who live farther access TM system through feeder buses or other local bus routes. These bus services which are mostly distributed in poor and middle income neighborhoods, allow larger number of citizen reach the TM system. But they also as motorized modes produce negative impacts such as traffic congestion and pollution. Sustainable transport practices around the world suggest use of bicycles as an alternative can reduce this share and expand direct access to TM. Then the main questions are how and to what extent bicycle can improve the system performance? What potentials and barriers exist in the city of Bogotá? And is this scenario worthy of implementation?

Accessibility measures can address those questions and demonstrate the impact of bicycle integration policies in Bogota. In addition to accessibility measures, exploring the current travel behavior (in relation to use of bicycle and TM), can also shed light on the questions. Indeed, citizen travel choice is also a function of accessibility and it can describe the influential local factors. The current research focuses in the case of Bogota and seeks, first to gain insight about potentials and barriers for use of bicycle to access TM system, and then, to quantify the effect of bicycle integration to the system. Due to the problem of social segregation in the city, it is more informative to compare the effect across different socioeconomic group. Results aim‘ to support more effective policies in future expansion of TransMilenio or Cicloruta networks.

1.3 RESEARCH OBJECTIVES

General Objective

The main objective of this study is to investigate the potential for integration of bicycle and TM subsystems in city of Bogotá, and to quantify the impacts through accessibility measure.

Specific Objectives

- To explore current intermodal behavior of TransMilenio users in relation to their socio economic status.
- To apply GIS-based techniques to model a multimodal transportation network of Bogotá with combination TransMileni and NMT modes.

- To assess the city wide level of accessibility to jobs through combination of bicycle and TransMilenio system across socio-economic groups.
- To recommend intervention strategies for an optimum integration of bicycle and TM sub-systems.

1.4 RESEARCH QUESTIONS

In order to achieve the research objectives, the following questions were framed.

Understanding current intermodal behavior in the city of Bogotá

1. How do people with different socio economic status access TM system?
2. What are the local factors influencing the use of bicycle as an access mode to TM system?
3. Which characteristics of TM system affect bicycle usage?

Modeling the multimodal transportation network of Bogotá

1. What existing modes should be modeled and how they can be included in model?
2. What characteristics of the network and of the system operation should be considered for setting up the multimodal network?
3. How and where are different modes connected?

Measuring the existing level of accessibility through Combination of TransMilenio and NMT modes

1. Which type of accessibility measure is appropriate to calculate job accessibility for this research? How should it be operationalized?
2. How many social classes can be defined and where are they located?
3. How many jobs are attainable for each social group and how are they distributed across the city?

Scenario development to integrate TransMilenio and bicycle, and to examine the impacts on level of accessibility.

1. What are the alternatives for bicycle and TM integration?
2. How different socio economic group benefit from integrating bicycle in transport system?
3. Which locations have the potential for the integration?

1.5 RESEARCH DESIGN

1.5.1 Conceptual Framework

Transportation systems can be evaluated with different measures and with different perspectives. Litman (2003) emphasizes that accessibility measures are more useful for multimodal systems, because these measures can take NMT modes into account actively. In the current research, accessibility is considered as a results of spatial and non spatial interactions between three concepts and components: transport system, land use, and socio-economic groups (see figure 1.1).

transport system provides mobility between different urban activity locations. Quality of Transport service influence costs of trips that people make to reach work in terms of money, time, comfort and etc. In case of multimodal system, the overall cost of trip is defined by available networks attribute individually as well as ease of access or switching between different modes. In other words, estimated accessibility through public transport varies by using different modes to access the system. More specifically, access by walking modes is limited walking speed and distance threshold, which are relatively smaller than bicycle modes. This suggests that providing access to public transport system by means of bicycle improves overall accessibility of a multi modal system.

land use is the second influential factor, which represents extent and spatial distribution of activities and job opportunities in urban area. Therefore, demand for travel and spatial pattern of trips would follow land use pattern (Geurs, 2006).

The third component is related to activity of workers in this study). This is because the *socio economic* characteristics of individuals define their transport mode choice, destination or even job selection. For instance, low income groups have limited options as transport mode and they can not travel far to reach more opportunities.

Accessibility has a feedback effect on each of the components as well. Kockelman (1997) proved that travel behavior is a function of accessibility. Likewise, land use type and urban activities in a certain location form in relation to the level accessibility that they are associated with. Besides, improving access broaden the range of available opportunities for inhabitants.

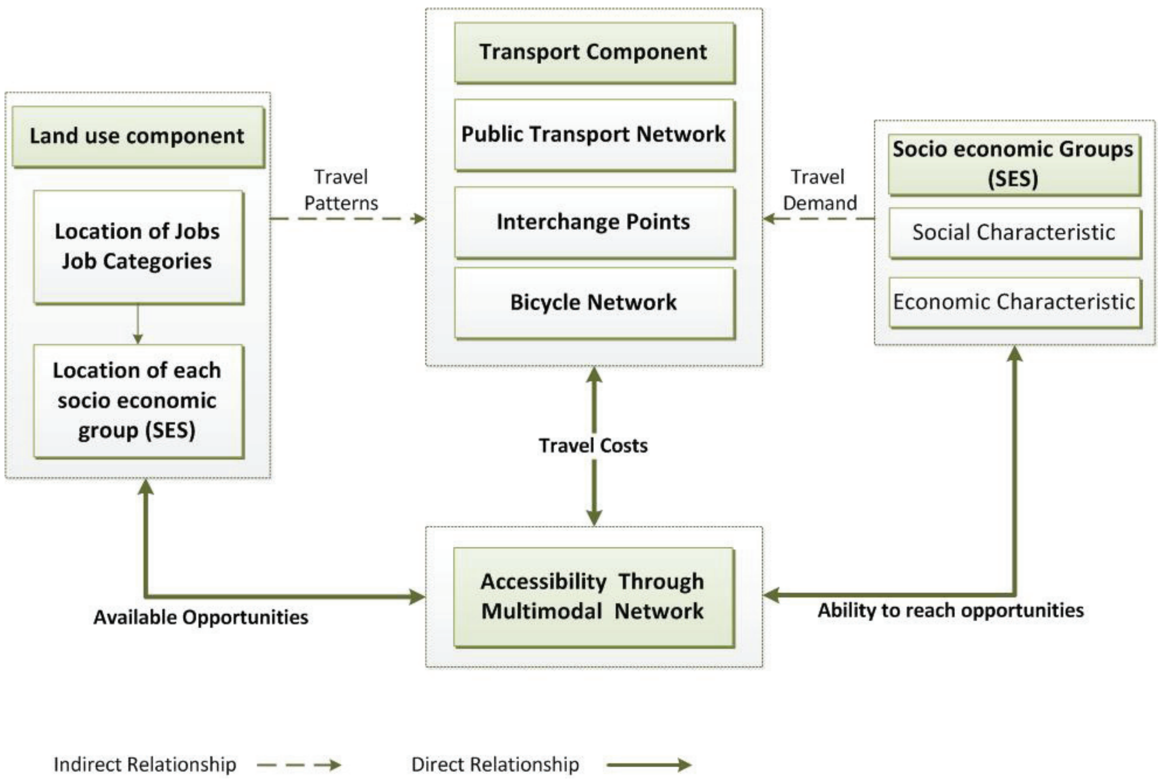


Figure 1.1: Conceptual Framework of Research

1.5.2 Research General Approach

Research started by reviewing literature on underlying related concepts such as; intermodal transport system, transport modeling and evaluations, accessibility measures. The second phase of research focused on the city of Bogotá as the study area. In this stage, field surveys were conducted to get more insight about existing integration and the potential for involving bicycle in daily trips. The results related to this survey are described in chapter 4. Afterwards, the third phase of this research employed accessibility measure to evaluate current level of integration as well as possible improvement scenarios. Table 1.2 summarizes the main tasks involved in this analysis and the required data.

There are two main sets of the data used for several processes in this research. The first source was Bogotá mobility survey database from (2011). The database consists of trips made by the households with inclusion of data on socio economic properties of trip makers. General descriptions of household size, income, trip origin, trip destination, trip length, trip purpose and trip mode are included. A total of 122362 records of trips were collected in the database. The data were analyzed to understand citizen travel behavior and extract necessary assumption for modeling processes. This research also applied GIS based techniques to achieve the last three objectives. So, the required geodata retrieved from IDECA geoportal (governmental organization in charge of planning and cadastral in Bogotá) and a recent study conducted by Braake (2013).

Table 1.2 Research Tasks and Required Data

Task	Method	Required Data	
Modeling Transportation Network	Multimodal Network Data set	TransMilenio and Feeder Buses	Location of bus lines Location of TM stations Operating schedule/frequency/waiting time Average speed
		Cicloruta	Bicycle path network location Average Speed Segments categories & intersections
		Transfer points	Parking locations(integrated/outside system) Parking Facility Capacity Parking Usage
		Streets/ Sidewalks	Location and Road type Average speed
Modeling Current Job Accessibility and Evaluating Integration Scenario	GIS tools Network Analyst Statistical Analysis Visualization	Origins	Location of Social strata across city
		Destinations	Location of jobs for each strata
		Decay functions	Mobility survey Field Surveys results Report

1.5.3 Thesis Structure

The thesis is structured under six chapters. This being the first chapter, the second chapter summarizes relevant existing literature related to the main subjects. It highlights intermodality options for bicycle and public transport under multimodal transport perspective. Moreover, the accessibility concept and the measures which were developed using this concept are discussed in the chapter. In Chapter 3, the city of Bogotá as the research study area is introduced. It highlights characteristics of the city in terms of socio economic, transport system and land use. Chapter 4 gives an insight to the current intermodal behavior in the city of Bogotá. This chapter reports the results from field surveys and summarizes the existing potentials and barriers to integrate bicycle and TM in the city. In Chapter 5, the technique which were used to implement the accessibility measure in GIS environment are described in details. After clarifying the steps taken for modeling the network, the calculation process for accessibility values are included. Additionally, the final output as mapped accessibility across social groups is presented in this chapter. Th final Chapter 6 consists of the main conclusions from field surveys together with accessibility results. It also provides recommendations for bicycle and TM system integration policies. In additions, the limitations of this research are described in this chapter. At the last, appendices documents the designed questionnaires and the steps related to calculation of decay functions.

Chapter 2
Literature Review

2.1 MULTIMODAL TRANSPORT SYSTEM

2.1.1 Multimodality Definition and Components

Nobis (2007) introduced *Multimodality* as an alternative travel behavior to *Monomodality* in transport planning. He defined Monomodlity as the exclusive use of one transport mode for entire urban trips within a certain time period. This is a very common pattern in highly automobile oriented urban areas. On the other hand, Multimodality refers to the use of at least two different transport modes in one week. If the change of transport mode occurs during the course of one trip, it is known as *Intermodality* or mixed-mode commuting. In comparison with car monomodality, multimodality and intermodality are more in favor of the sustainable transport objectives. Opposite to private car users, the groups who use NMT modes are more likely to combine different transport modes. According to Nobis (2007), frequency of using alternative transport network or mixing modes is related to travel distance, which is a function of city size. He noted that the socioeconomic attributes of users (e.g. age, gender, employment status) are also influential factors.

Multimodal transport planning combines various modes in one transport system. Litman (2011) explained that this is a more complex process, because it should consider that each mode have different characteristics such as availability, usability, speed, density, costs and constraints. Furthermore, providing possibility for chaining trips is another major concern in multimodal transport planning. Modal integration is possible with the coordination of different transport systems in terms of *infrastructure*, *services*, *facilities* and *spatial configuration*. These all aim to create seamless links between at least two different modes. Many cities around the world started connecting the transport modes through different integration policies such as: spatial, network, fare, information and institutional integration.

Parking facilities in the train stations are good examples of network integration policies: parkings for the cars or bicycles connect road network to the train network. Multimodal journey planners also other examples of integration policies, providing necessary information for the integration. They inform users about different modes of urban transport on one site: in Belgium "Scotty" webpage is able to advice users with reliable information, directly from various partners such as railway system, public transport and bus operators, bike sharing schemes, car sharing companies, airport and parking companies (Christiaens, 2012). In the UK , train system offers discount tickets for bus network, i.e. implementation of fare integration practice (UN-Habitat, 2013).

2.1.2 Intermodality of Bicycle and Public Transport

According to UN-Habitat (2013), intermodality is a key factor of attractiveness for public transportation. Pucher and Buehler (2008) proposed that integrating bicycle networks and public transport considerably expands the service area of public transport stops beyond walking distance, it also attracts cyclists as a new group of users to public transport system. Hegger (2007) emphasized that good transportation policy understands intermodality between bicycle and public transport as a potential synergy rather than a competition between them.

In general, factors affecting cycling are: history, culture, topography, climate and urban policies (Pucher & Buehler, 2008). To be more specific, for a single trip, the purpose of trip, transport infrastructure and trip makers characteristics are also determining factors (Hegger, 2007). In addition to these factors, for a multimodal trip, it is particularly important to facilitate easy transfers between bicycle and modes. Hegger (2007) stated that the first requirement for bicycle intermodlity is provision of the related facilities. The most basic facilities are parkings or any form of bicycle storage spaces. In addition to parkings, public bike renting systems help to involve bicycle in trips from public transport to final destinations. Also, allowing bicycle on buses or other public transport vehicles encourage the users to access and ride by their own bicycle.

Current intermodal practices which integrate bicycle and public transport system involve three forms:

- Bike and Ride (B&R) : When public transport access points are facilitated by bicycle storage spaces.
- Bike, Ride and Bike (B&R&B) : When public transport vehicle are equipped to carry bicycles, allowing to travel with a bicycle through the system.
- Ride and Bike (R&B) : When public transport offers bicycle rental services for users, then users complete their trip using a public bicycle.

European cities have taken the lead in bicycle integration practices. In Germany, train stations have been equipped with 70 bicycle storage facilities. In Berlin, 24,000 bike parking spaces have been provided(UN-Habitat, 2013). Hegger (2007) reported that, in Netherlands 35% of access trips to train system are made through bicycle mode. The main incentive is that all train station are offering guarded bicycle parkings as well as complementary facilities (e.g. bicycle maintenance and repair services). Moreover, train compartment provide special space for bikers to travel with their bicycles.

In recent years, many cities have established public bike sharing systems. Amsterdam in 1965, with the White Bikes was the first city that provided bicycles for public use in the city (DeMaio, 2009). Later, to improve integration between bicycle and train system in the Netherlands, another project as "OV-fiets" started operating. By this project, 100 train stations offered bicycle renting service with low price. Denmark also have developed a similar project where bicycles are provided for employees in a coordination with companies Hegger (2007). In Barcelona, a bike sharing service called "Bicing" was implemented in 2007. This service provided 6,000 bicycles in about 400 bike stations across the entire city. The main objective of Bicing is to cover small and medium daily routes in the city (Kaltenbrunner et al., 2010). Considering this trend, DeMaio (2009) stated that the new generations of bike sharing system are featured with: improved distribution, ease of installation, powering stations, tracking and pedal assistance.

2.1.3 Modeling Multimodal Transport Systems

Modeling the transportation network is prerequisite for most of the transport analysis and simulations. GIS provides a suitable platform and useful tools to storage, integrate and analyze spatial data. As a result, GIS network models have been widely used for modeling and analyzing transport networks. With the underlying graph theory, network modeling started as a network of interconnected nodes and links (physical or functional). Although traditional arc and node model has been applied practically for many modeling tasks, it has limitations to deal with the complex reality of non-planar and three-dimensional (3D) nature of the network (Mandloi & Thill, 2010). In order to deal with more complex networks, "Table Turn" function was added. This approach allows to model turning restriction and connectivity rules similar to the real world networks. The resulting vector data model along with the ability to store topological relationship of connectivity is called a network data model. After setting up the network data model, it is possible to run simple and complex network analysis such as vehicle routing, location-allocation modeling, and accessibility analysis (Mahrous, 2012).

Main challenge in this area includes the complexity of multimodal systems that combines several transport modes, for instance, in the case of public transport and NMT modes. Turn tables makes GIS a practical environment for management of coincident features of a multimodal network consisting of different subnetworks, such as streets and bus routes. Mahrous (2012) states that multimodal network modeling methods can follow three main approaches:

1. Using basic network data models, each route line needs to be digitized separately.
2. Using external tables (dynamic segmentation).
3. 3D models.

3D network modeling is a concept specially important in urban areas with high density. This model had been investigated by Mandloi and Thill (2010) and Thill, Dao, and Zhou (2011). They have applied the concept in central business districts (CBD) with multistory buildings, where activities take place on different floors, and major number of the trips occurs inside buildings. Thill et al. (2011) showed that 3D network models are capable of running analysis such as route planning, spatial accessibility assessment, and facility location planning.

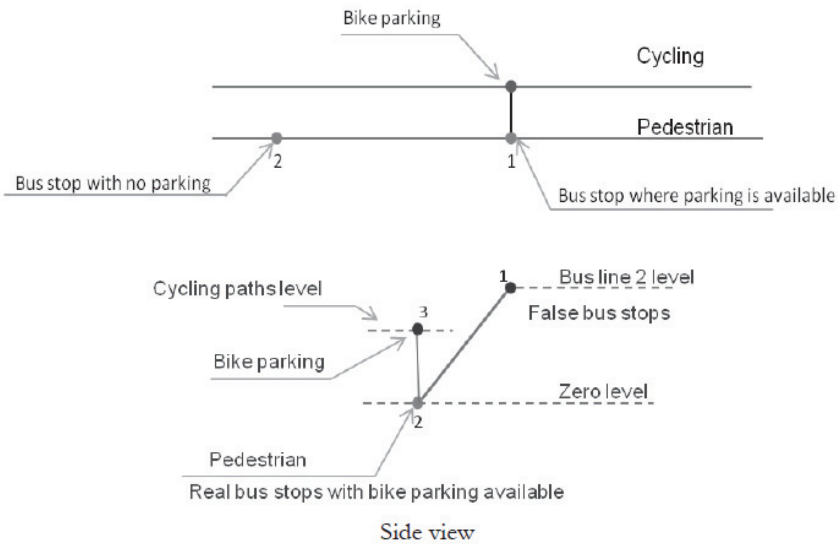


Figure 2.1: Conceptual design for transfers from bicycle mode to bus system in a multimodal network. source:(Mahrous, 2012)

2.1.4 Performance Measures for Multimodal Transport Systems

Performance evaluation is a process that measures effectiveness of implemented transportation policies. This process involves analyzing performance indicators and comparing the results to what was expected according to policy objectives. In general, transport policies objectives are related to concepts such as: motility, accessibility, safety and environment. Performance evaluation for a transport systems can be done from different perspectives such as users, modes and land use. The indicators could be analyzed under different conditions including: before-and-after, over a certain period of time, with-and-without (Litman, 2012). Traditional transport performance indicators were mostly based on motorized modes. Litman (2008) describes:

> "Such planning practices can result in decisions that increase mobility but reduce overall accessibility (for example, by reducing travel options and stimulating sprawl), and tend to undervalue other accessibility improvement options (such as more accessible land use development, and mobility substitutes such as telework). More comprehensive analysis can help decision-makers identify more optimal solutions... A paradigm shift (a fundamental change in how problems are defined and solutions evaluated) is occurring in transportation planning. This can be described as a shift from mobility-oriented analysis (which evaluates transport system performance based on quantity and quality of physical travel) to accessibility-based analysis (which considers a broader range of impacts and options)."

Accordingly, transport studies, have defined more sophisticated performance measures by operationalizing accessibility concept.

2.2 ACCESSIBILITY

Accessibility has become a well-known concept in the transportation planning field since the 1950. There is no single definition for this concept and, different studies have defined accessibility with different perspectives. Litman (2008) defined this concept as the ease of reaching desirable destinations or opportunities. Accessibility is also described as the overall benefits provided by transport system Dong et al. (2006). Other studies referred to it as the potentials for reaching spatially distributed opportunities (Páez et al., 2012). In the present study the definition by Páez et al. (2012) is adopted. This definition introduces the component which form accessibility. These components are further discussed in the following section.

2.2.1 Accessibility Components

Geurs (2006) recognized four major components when defining accessibility: land use, transportation, individual and temporal.

- *Land use* reflects the amount, quality and spatial distribution of opportunities supplied at each destination and the demand for these opportunities at origin locations. Also it shows the relation of supply of and demand for opportunities (competition for activities).
- *Transportation* determines the disutility of meeting supply and demand movement through space in different forms such as time, costs and effort. This would be a function of spatial and non spatial properties of transport system which are decisive factors for selection of travel cost and impedance functions.
- *Individuals* component expresses the needs, abilities and opportunities based on socio economic characteristics such as: age, gender, employment status, income, travel budget, educational level of individuals.
- *Temporal* component identifies availability of opportunities at different times, as well as time constraints.

Every component and the interaction among them affects the level or accessibility. Land use and distribution of activities influence travel demand and trips pattern. Time and operating schedule determines the exploited opportunities. Additionally, the individual component defines the perceived value of time, cost and effort, types of activities and the times in which a person would be involved. While interaction among components affect accessibility, any change of accessibility level creates feedback affecting each component itself. For instance, accessibility influences attractiveness of activities and as a result, travel demand, individuals economic and social opportunities, and the available time for using specific services (see Figure 2.2).

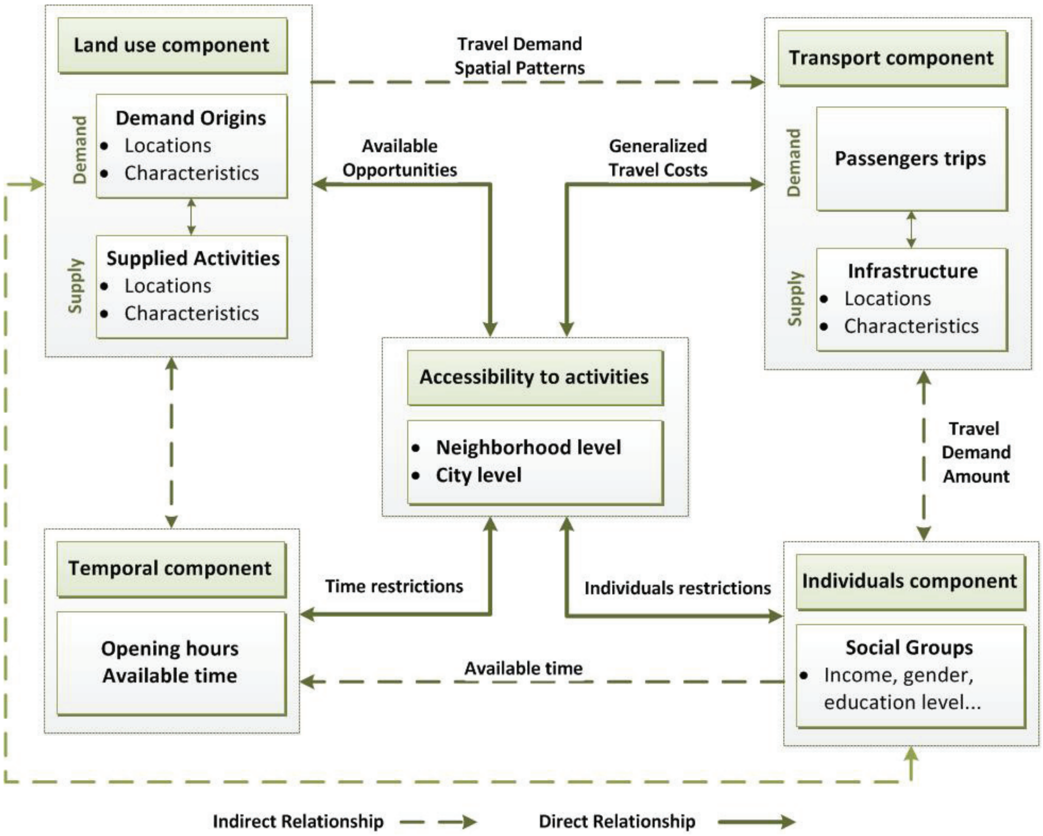


Figure 2.2: Relationships between components of accessibility. Source: (Geurs, 2006)

2.2.2 Overview of Accessibility Measures

In recent decades, many accessibility measures have been adopted to study a wide range of urban problems. Focusing on each of the accessibility components and applying different operationalization methods have resulted in various types of accessibility measures. Geurs (2006) categorized these measures under four perspectives: *Infrastructure-based, Activity-based, Individual based* and *Utility-based measures*. Table 2.1 summarizes some of the measures of common use.

Infrastructure-based measures are considered trip based and only incorporate transport component. They are not useful to investigate the effect of social status and land use patterns. Location based also know as Activity-based category takes into account both land use and transport systems which make them more realistic. Several studies including Dong et al. (2006) noted that activity-based are the most applied measures among four categories, this is because they require relatively less data and the quality of results is promising. This type of measures analyses the accessibility of

Table 2.1 Developed measures according to different perspectives on accessibility components. source: (Geurs, 2006)

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

locations and evaluates the spatial distribution of services or activities. Person-based measures investigate accessibility in individuals level. According to this perspective, accessibility varies across individuals' properties such as: income level, gender, age, occupation, trip purposes, modes of transport. These measures are very data demanding and they need high level of disaggregation (Bocarejo S & Oviedo H, 2012). The utility-based measures were developed under principle of random utility theory. They are considered more advanced compare to conventional measures because they are more sensitive to individual activity patterns and accessibility in space and time (Miller, 2005). Kumar (2011) after reviewing various application of accessibility measures concluded that activity based and utility based measures are the most appropriate types to deal with multimodal transport networks.

Different studies have operationalized each accessibility measures with different approaches. The simplest approach is cumulative methods which count reached opportunities by a certain threshold (travel time of distance), also known as contour measures or isochrone measures (Handy & Niemeier, 1997). Potential measures have been implemented broadly, with this approach opportunities in destination are discounted in relation to the travel distance, or generated cost by traveling (Van Wee et al., 2001). This is done by quantifying distance decay concept though decay functions. Decay function differs according to economy, travel behavior and perception of the opportunity values in each context. This function is discussed with more details in section 5.2.3. Gravity measures are more complex functions, and include travel distance and attraction effect in their calculations.

Recently, several studies attempted to improve potential measures and created competition based accessibility indicators. Approaches focus on including competition factors on demand and supply sides. Van Wee et al. (2001) measured job accessibility in Netherlands by considering competition on the employment market and Cheng and Bertolini (2013) included spatial factors (e.g. distance decay, spatial competition and spatial job diversity), and non spatial factors (social match) to calculate job accessibility in Amsterdam region. Although competition based measures are sophisticated, they are difficult to interpret and communicate. In addition, by including variant factors the resulted accessibility is not directly a function of transport policies.

Van Wee et al. (2001) emphasizes that the accessibility measures should be carefully selected according to the research purpose. Due to the definition and application of accessibility can consideraly affect the estimated results. Baradaran and Ramjerdi (2001), reviewed accessibility measures in relation to their theoretical foundation, complexity of construction, and demand on data. According to this review, even though simpler measures are less data demanding, theoretically they are less solid. On the other hand, more sophisticated measures provide more accurate results, but issues related to availability of required data and difficulties in interpretation and communication of outputs are the main drawbacks for their application (Handy & Clifton, 2001).

Accessibility measures have been widely implemented in GIS environment. A study conducted by the British government planning policy guidance, developed two GIS based models to measure accessibility at local and city scales. One of the models was used to investigate the accessibility of a particular residential location to public transport stops (local accessibility). This was estimated as the total time required to access the service, which consisted of walking time to the stop and the average waiting time before boarding. The model also measured the accessibility of locations to certain destinations through public transit (network accessibility). Network accessibility was calculated by defining the trip routes from residential origins to a set of destinations (e.g., schools or shopping centers). Then the total travel time to those destinations was calculated by integrating the results from local accessibility process (Handy & Clifton, 2001).

Another study by Iacono et al. (2010) developed an accessibility measure to calculate accessibility through walking and bicycle modes. The research attempted to develop a measure which was sensitive to spatial scale of NMT modes. Also, it was important that measure can compared across the neighborhoods and could be easily interpreted. The accessibility levels were analyzed for work, shopping, restaurant and entertainment centers for 1600 residential blocks. In principle, to estimate accessibility values, impedance functions were applied to discount the activities in each destination. Household travel survey was used in order to calibrate the impedance functions according to each mode and the trip purpose. The final accessibility values were calculated as the total number of activities in for each destination normalized by the total activities in the study area.

Accessibility measures are also used to investigate inequality and social exclusion issues in urban areas. Bocarejo S and Oviedo H (2012) evaluated the impact of increasing public transport fares for different social groups in the city of Bogotá. Accessibility was calculated as the number of jobs that can be reached considering time and budget. The study introduced a composite impedance function by combining travel time, travel budget and the percentage of income spent on transportation. This function was calibrated for different areas of the city, which they correspond with different socioeconomic groups in the city.

Chapter 3

Study Area: An Overview of the City of Bogotá

This chapter introduces the city of Bogotá as the research study area. It aims to provide some insight about the city in terms of socioeconomic, transport, and land use characteristics.

3.1 SOCIO-ECONOMIC PROFILE OF BOGOTÁ

Bogotá as the capital of Colombia is the sixth largest city in Latin America. The boundaries of the city district surround an area of 1732 km2, but less than a quarter of this area is the urban area, which are concentrated in the city of Bogotá. It is inhabited by 7.3 million people (2010) and one of the most densely populated cities in the world. The population density was about 20,500 person per square kilometer (Bocarejo, Portilla, & Pérez, 2013) at that time. Industrialization was an important factor for a dramatic population growth which turned the city into the major industrial, commercial, educational, and service center. However, there are complex political and social reasons, like poverty and violence, which increased migration from rural areas to urban centers during the 20th century and beyond.

Table 3.1 demonstrates some demographic aspects of city population in 2011. This table suggests that active population represent a large share in population structure at Bogotá.

Table 3.1 Bogotá Population Structure in 2011. source: (SDP, 2011)

	Age			Gender	
Population Struacture	0-14	15-64	above 65	Male	Female
Percentage of Total	24.30%	69.20%	6.50%	48.23%	51.77%

The city authorities have categorized households according to their average income into six ascending social strata (1-6) abbreviated as SES. This was done for financial, planning and management purposes, so the residents' service tariffs could be levied accordingly. The highest strata has a SES of 6 and needs to pay the most per unit of service. As table 3.2 presents, only 5% of the population belong to rich groups (SES 5 & 6), wheras 51% of citizens are associated with the low income groups (SES 1 & 2). This shows that there is a considerable disparity between the rich and poor groups which has resulted in problems related to inequity and social segregation.

This social segregation is manifested in spatial segregation as well. As figure 3.1 presents, the northern parts of the city contains the high income groups, namely the neighborhoods of Chico and Santa Barbara. The poorest groups inhibit the southern informal settlements like Ciudad Bolivar and Bosa neighborhoods. Bocarejo et al. (2013) reported that these areas have the highest population densities, and in terms of formal employment they have the lowest densities. The middle classes are mostly residents of the central, western and northwestern city sections. Due to this social segregation, policy makers focus their development objectives on the reduction of poverty, the promotion of employment and equity. The underlying concept of these policies is defined as "A Community State: Development for All". Accordingly, the local government started programs as targeted assistance policies such as subsidies and support for job creation.

Table 3.2 The average income of each household stratum in Bogotá (SDM, 2011)

SES	1	2	3	4	5	6
Average Income (USD $)	4.2	5.9	11.4	24.1	39.2	62.3
Population Percentage	9%	42%	35%	9%	3%	2%

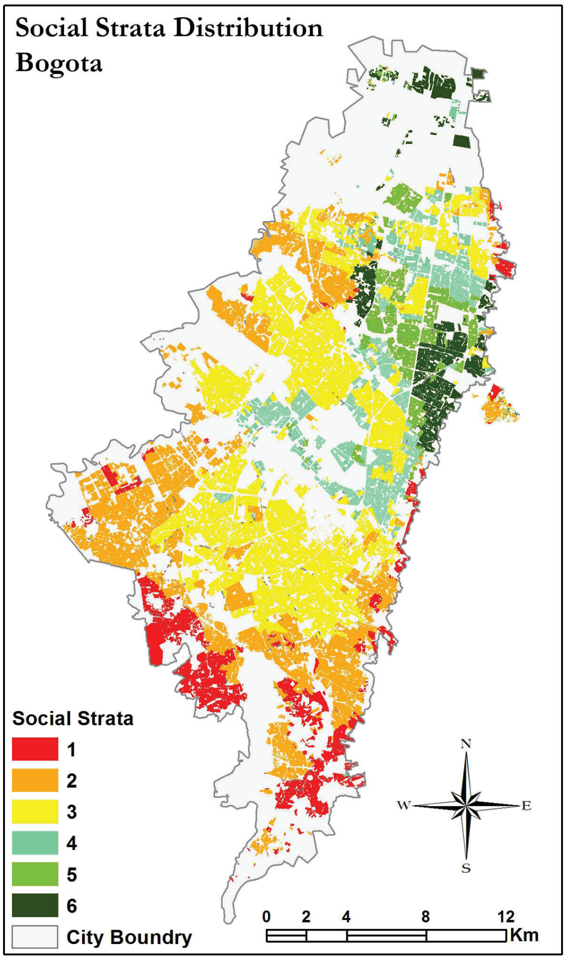


Figure 3.1: Distribution of different social strata across the city of Bogotá

In this study, employment in the city was explored using the mobility survey data. Figure 3.2 summarizes the pattern of jobs which were extracted from Bogotá mobility survey database. Notice that the total number of jobs for each zone was estimated based on the number of work trips entering the zone. The resulted pattern indicates that employment are concentrated in the eastern part around the old city center.

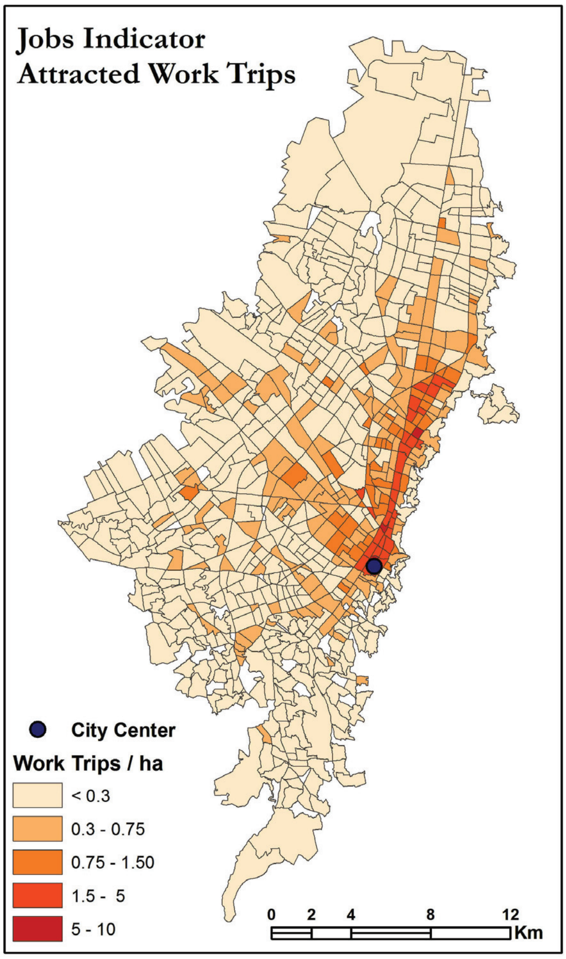


Figure 3.2: Distribution of jobs. Source: Bogotá mobility survey.

3.2 URBAN TRANSPORT SYSTEMS IN BOGOTÁ

In 1998, the development of TransMilenio started as a fast and reliable public transportation system. Nowadays, over 1.7 million citizen commute daily through the TransMilenio network. The first two phases were completed by 2006, and recently phase III has expanded the system to its current extent (figure 3.3). Before that system, public transportion in Bogotá meant old buses operated by a large number of different operators (Ardila & Menckhoff, 2002). The implementation of this system has reduced travel time by 34%, and traffic fatalities by 88% UN-Habitat (2013).

TransMilenio system is designed with 11 corridors along major city roads. The average commuting speed along corridors was 27 km/hour in 2011. Although overall system planning, management and oversight is performed by a new public agency, bus and fare collection services are managed privately (Hidalgo, 2008). System coverage is maximized by feeder bus services linking the peripheral areas, and provide access to TransMilenio portals. Considering the location of SES strata, feeder routes are mostly covering the low income areas.

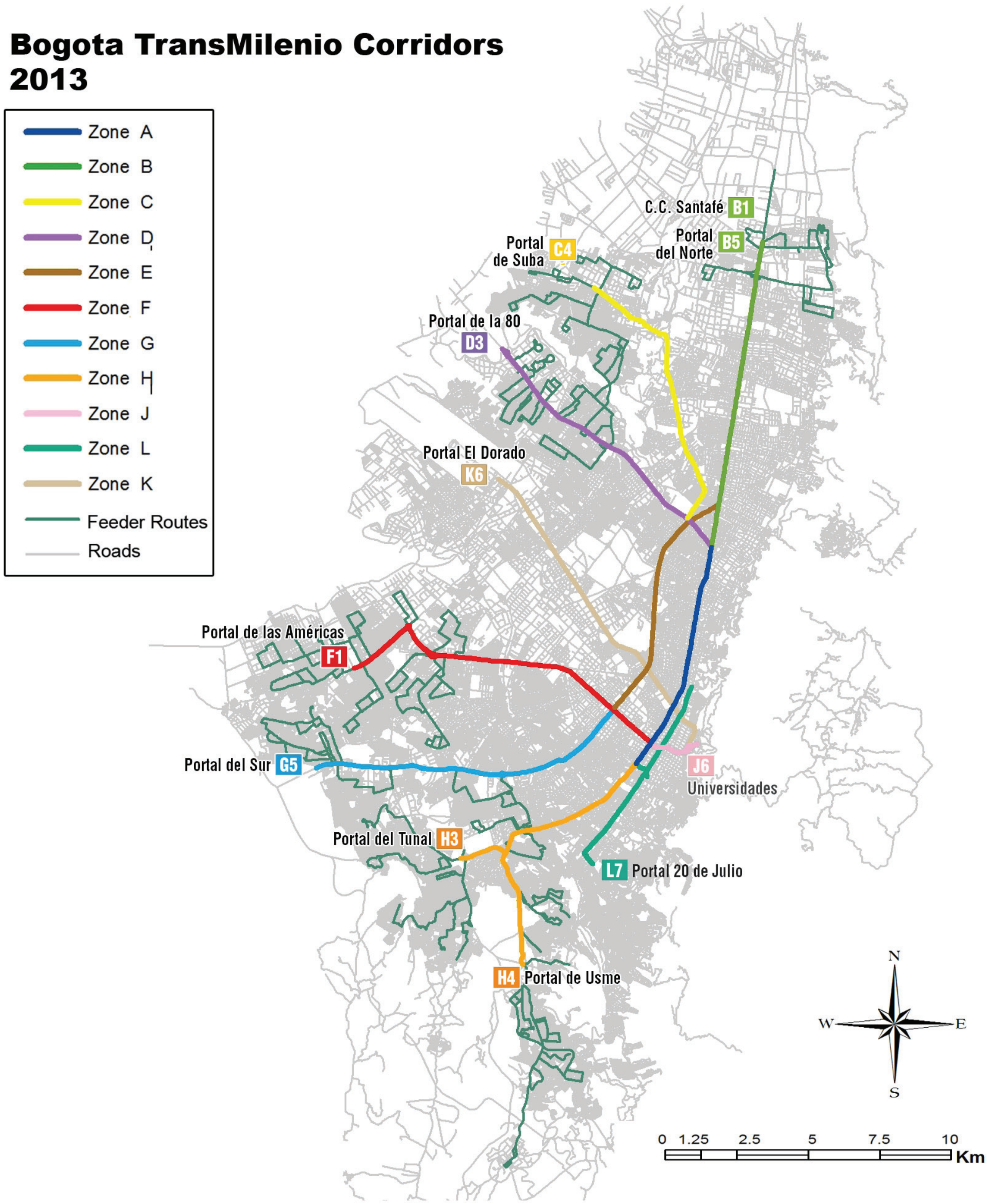


Figure 3.3: Transmilenio corridors and associated feeder routes in 2013.

Hidalgo et al. (2013) reported following attributes for phases II and III of the TransMilenio:

- "Dedicated Bus Lanes: 84 km
- Feeder Buses Routes: 663 km
- Total Number of Stations: 114
- Trunk Vehicles: 1262 articulated buses 10 bi-articulated buses

- Feeder Vehicles: 519 conventional buses (12 m)
- Feeder Routes: 83
- Payment System: Contact-less smart card
- Control Center: On-line and real-time supervision
- User information: Fixed sign and dynamic display panels
- Total passengers: Average of 1.7 million on weekdays
- Users of feeder routes: 48% of the total users
- Fare: Flat-rate COL$1700 per trip (USD 0.94), including transfer”

In overall, TransMilenio has improved general mobility conditions, and most of the social groups benefit from it. However, Bocarejo et al. (2013) described that low income SES benefit the most. They contribute almost 40% of TransMilenio passengers (SDM, 2011). In terms of travel cost, these groups seems to be at a disadvantage because the TransMilenio is more expensive than traditional buses. This could be the reason for lower daily travel rates. In average, the lower income groups make 1.13 while the higher income groups make 2.05 trips per day (Bocarejo et al., 2013).

The focal point of TransMilenio corridors is the city center with its high job concentration. Although these lines are operating at their maximum capacity during peak hours, they do not yet provide enough capcity to deal with the high travel demand towards central areas.

CicloRuta is another major transport infrastructure in Bogotá. This network covers over 340 km of bicycle routes, and it was designed to connect citizens to major TransMilenio corridors, parks, and community centers. This investment had a great impact on reducing car dependency and promoting bicycle based trips. In 2002, a traffic count developed by IDU showed that bicycle use had increased from 0.58% in the 1996 to 2.2% (almost 4 fold increase from the previous decade). Currently, the integration of TransMilenio with Cicloruta is limited by the avaliable bicycle parking facilities. This topic is discussed in more depth in section 4.1.

In addition to infrastructure, individuals’ attributes and environmental conditions are influential factors on bicycle usage. Sarmiento et al. (2004) conducted a study to explore cycling as a transport mode among middle and low income populations of young adults in Bogotá. The results revealed that 20% of adults use a bicycle at least 10 minutes per week. According to a report by Bogotá’s Chamber of Commerce in (2009), 86% of cyclists were male. In general, cycling is more likely among those who live in neighborhoods with good quality bike paths. Although not all bicycle trips are made through CicloRuta, it was influential in promoting a safe biking image in the city. Between years 2003 and 2008, the number of injured cyclists in traffic accident decreased by 70.7%. The same report proposed that there is substantial need for a bike sharing system. Along this study, a survey conducted at two TransMilenio stations investigated whether users would use their own bike or a public bike to complete their trip. The results showed that nearly 50% of respondents favour the bike sharing plans (Camara, 2009).

It is important to note that social programs such as Ciclovia play an important role in promoting bicycle usage. There is a bike sharing pilot project (see figure 3.5) along some segments of Septima (7th) avenue which is one of the main commercial axis in Bogotá. The main objective of this program is to promote cycling. Note that it is not connected to the TransMilenio system.

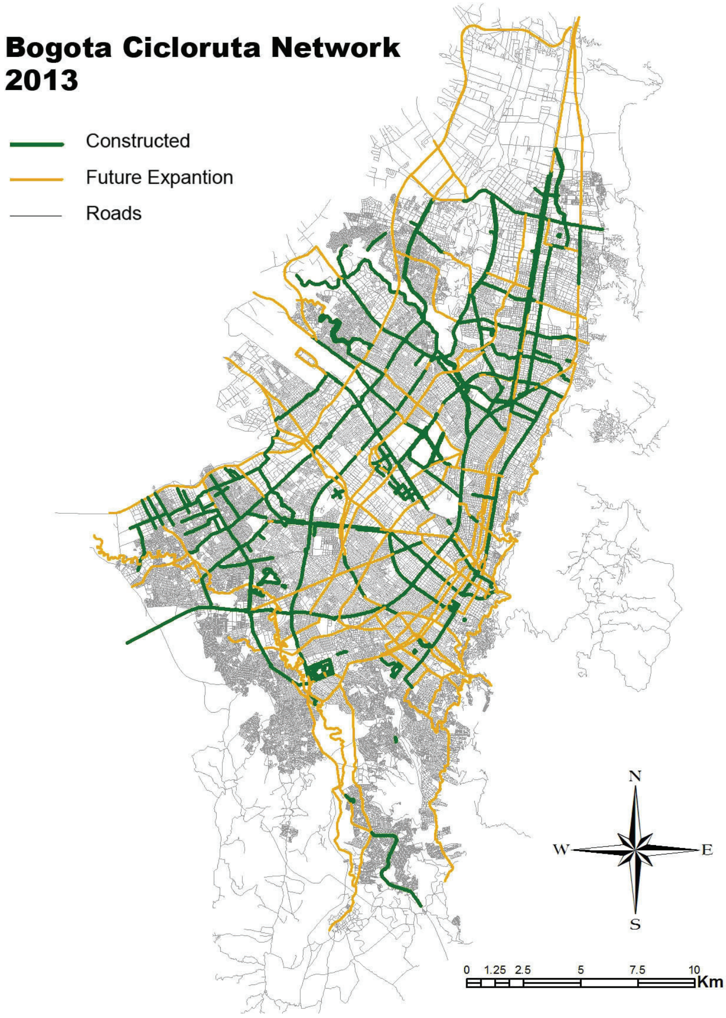


Figure 3.4: The spatial extent of Cicloruta network in 2013

Figure 3.5: Current bike sharing system in 7th avenue.

In terms of modal share, public transport represents 30% of citizen trips, according to Bogotá mobility survey in 2011. As illustrated in figure 3.6 this share includes 20% traditional buses, 9% TransMilenio, and 1% intermunicipal transportation. It can be seen that other buses have a greater share compare to TransMilenio. The reasons may be the limited number of corridors and the highly occupied buses. Hidalgo et al. (2013) noted that in recent years, user satisfaction rate for TransMilenio has been declining. Issues such as: overcrowded buses, insecurity, and feeders' low frequency are among the users complaints. In relation to NMT modes share, walking is the dominant mode, and only 3% of total urban trips are made with a bicycle (as the main mode of trips). Private car share is around 10%, which even larger than Transmilenio's share. Currently, private car share is less than public transport, but Hidalgo and Huizenga (2013) pointed out that the annual growth for car and motorcycle ownerships is high. Thus, this share is predicted to increase.

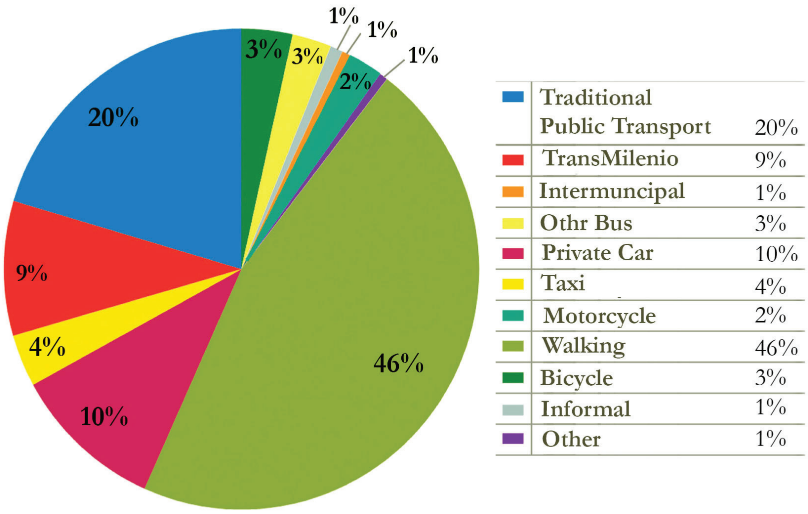


Figure 3.6: Modal share for urban trips in the city of Bogotá. Source: (SDM, 2011)

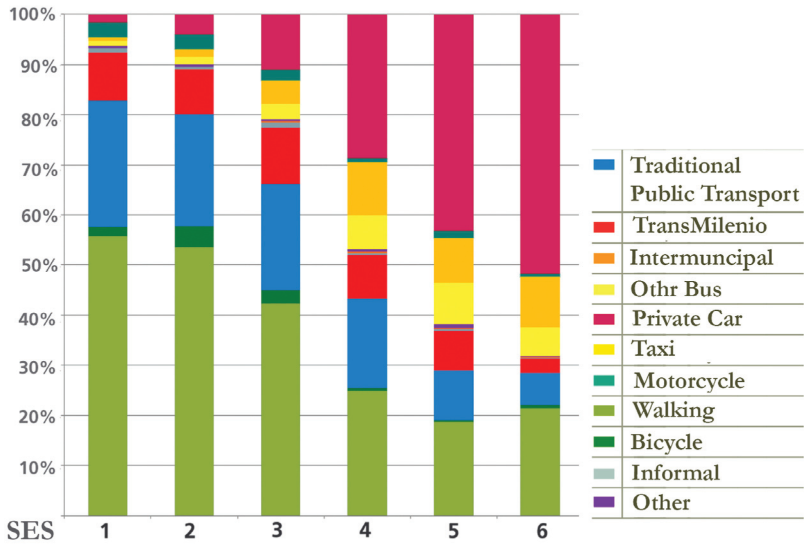


Figure 3.7: Modal share for urban trips per social stratum. source: (SDM, 2011)

Figure 3.7 compares the modal share for each social stratum in the city of Bogotá. It can be seen that as income increases, people tend to use private cars more than public transportation. For the highest stratum the usage of a private car is the dominant mode while for the lowest stratum the largest share is composed of walking and public transport. A similar relation is recognizable between the income level and bicycle use. The lower strata tend to use bicycles more, however the lowest stratum (SES 1) does not follow this trend. This could be due to environment conditions, because it is located in informal settlements with steep topography.

3.3 LAND USE CHARACTERISTICS

As noted earlier, Bogotá is one of the densest cities in the world. Currently, Bogotá habitats around 85% of the regional population, and acts as an attractor of both population and employment. This resulted in a mono centric urban form in macro scale. The arrived population from rural areas have developed large and unplanned urban structures especially at marginal parts of city. There are natural restrictions such as Bogotá's river defining boundaries for city sprawl (Wessels et al., 2012) at its western and northern borders.

Bocarejo et al. (2013) stated that in recent years the city grew through densification process rather than sprawl. The results of his study confirmed that the areas where TransMilenio and feeder buses had been provided, experienced an increase in population density . Furthermore, he noted that TransMilenio development resulted in land use changes, especially around portal and along the TM corridors. Commercial centers were build around the TM portals even in the peripheral and economically stagnant zones. Kernel density maps in figure 3.8 illustrates how commercial and industrial activities have been reformed following the TM system structure. Figure 3.9 also shows the similar effect for educational and health facilities. In overall, concentration of economic and activities close to the old city center resulted in formation of the central business district (CBD). Moreover, this area is also the center point for TM corridors.

Munoz-Raskin (2010) investigated the impacts of TransMilenio development on residential property values. He concluded that proximity to the TM system was valued more by middle strata residents. On the other hand, the lowest income group were not willing to pay more to live close to TM stations or corridors. For higher income groups the access to TM was also not a preference.

Distribution of urban employment also shows that most of work related activities are located in and around the CBD. This concentration of jobs in one single area resulted in a mono centric destination of work related trips and high levels of congestion at and around the this center. Hence, Wessels et al. (2012) vision and policies are defined to create a polycentric metropolis with a decentralization of population and employment. To achieve this goal there is a need for integrated planning between land use and transport features and effective economic, political, and social interventions.

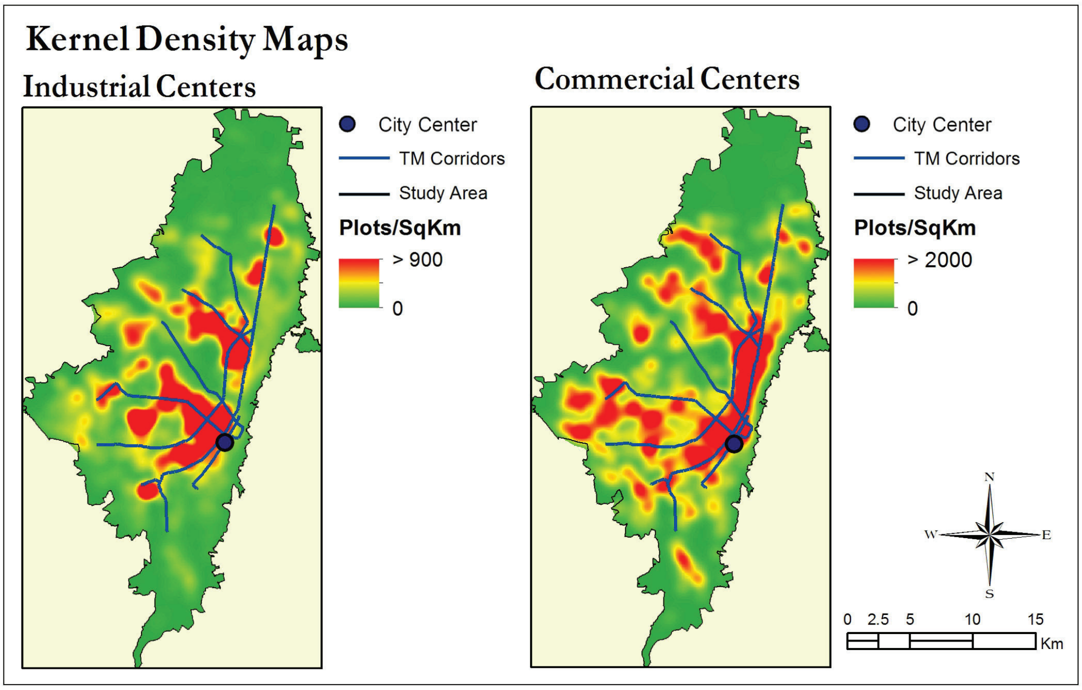


Figure 3.8: Kernel density maps corrosponding with commercial and industrial landuses in the city of Bogotá

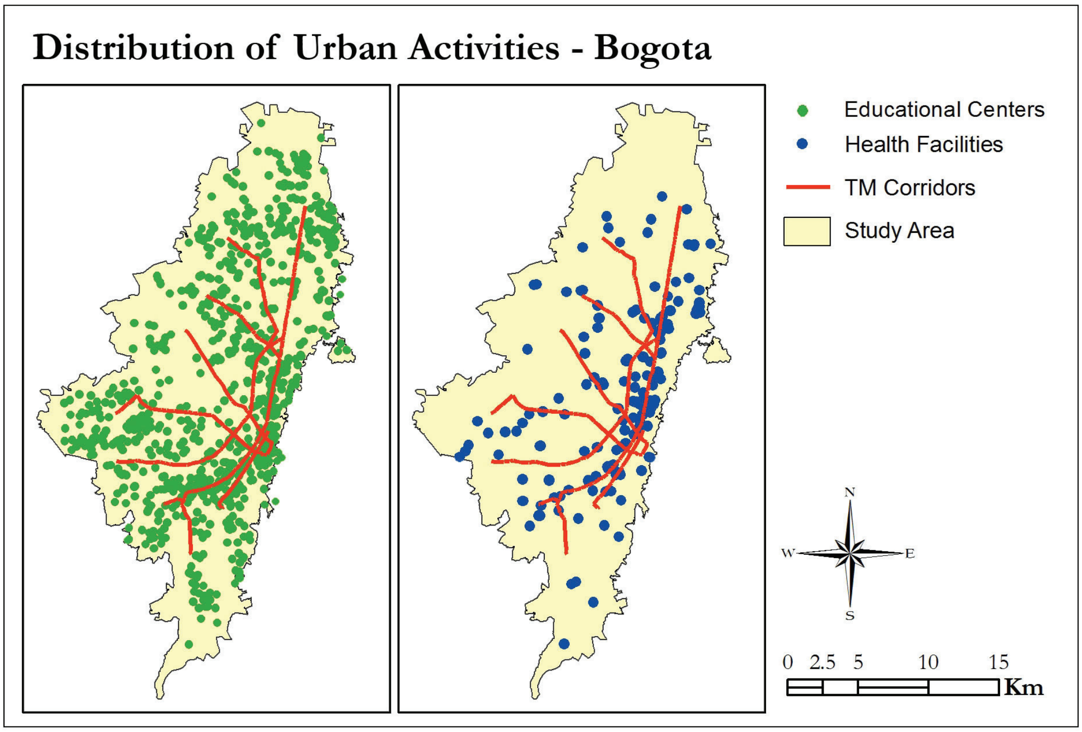


Figure 3.9: Distribution of educational and health facilities across the city of Bogotá

Chapter 4

Current Bicycle - TransMilenio Integration in Bogotá

This chapter is devoted to provide some insight about the current state of this city in terms of intermdality. The first section documents the existing infrastructure that create connections between TransMilenio and Cicloruta networks. The second section describes current intermodal behavior of citizens by including the finding from field surveys.

4.1 EXISTING FACILITIES FOR BICYCLE AND TM INTEGRATION

Bogotá city owns two massive transport infrastructures: TM system and Cicloruta bicycle network. The recent expansion plans and transport policies started giving more attention to integration of these two transport subsystems. Although the first phase of TransMilenio was completed without any relation to bicycle network, the next two phases included bicycle parking facilities at portals and some of the major stations. Figure 4.2 presents the distribution of these facilities across the city. This service is managed by TransMilenio organization, and it provides users with guarded parking spaces for free. However, users are required to register their bicycle in the system database. In the most of the portals, monitoring the entering/leaving bicycles, is fully computerized and it does not add considerable time to TM access time. These parkings are built inside the stations, so it is possible to pay the TM fare at their entrances, which are less busy compare to walking entrances. Currently, only nine stations have been facilitated which are mostly located in low and middle income areas. IDU reported that plans for further expansion of this system are in process.

In addition to the parking inside TM stations, there are four more parking facilities managed by IPES organization. IPES is a governmental organization which initiates economic activities for low income groups. These bicycle parkings belong to a set of urban structures which provide other public services for citizen, (e.g. food stands, market stalls and public washrooms). These activities are located in major intersections of Cicloruta and TM corridors. They are mainly designed to service citizen during Ciclovia program and weekdays from 6 a.m to 7 p.m. Each of these parkings accommodates up to 40 bicycles.

(a) Bicycle parking at Portal Americas (b) IPES Bicycle parking

Figure 4.1: Bicycle parking facilities related to TransMilenio Stations

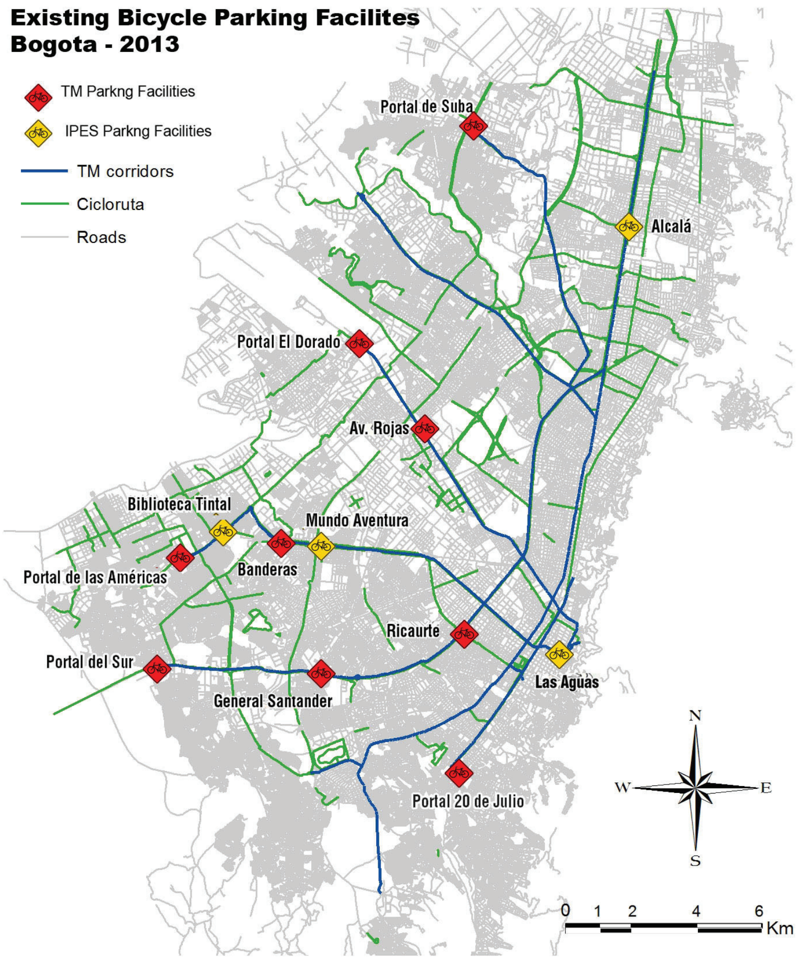


Figure 4.2: Map of CicloRuta and TransMilenio Interchang Points

Table 4.1 presents the percentage of usage for the nine operating bicycle parkings that are manged by TransMilenio organization. It is evident that in overall these parkings have low usage.

The highest usage is related to Portal Americas (figure 4.1a), which is surrounded with low income and highly populated area. On the contrary, the bicycle parking associated with Ricaurte station has the lowest usage rate. One possible reason is that the station is located close to industrial activities. Also, the nearest residential areas are corresponding with middle income strata. These field observation suggested that the location may affect the parking usage, or in other words, the number of TM users who actually use bicycle to reach the station. Especially the distance from housing centers and socioeconomic properties of those centers seemed to be an influential factors.

Table 4.1 Operating integrated bicycle parkings at TM stations. Source:IDU 2013

TM Station	Capacity	Usage Percentage in 2011
Portal Americas	785	46%
Banderas	101	12%
Portal Del Sur	220	26%
Portal De Suba	324	27%
General Santander	48	31%
Ricaurte	165	4%
Portal 20 De Julio	216	-
Portal Eldorado	184	-
Avenida Rojas	28	-
Total	2071	

4.2 INTERMODALITY SURVEYS

Citizen travel behavior is an indication of how they use transport systems. Understanding the travel behavior that users of each transportation mode exhibit, and exploring the underlying reasons for that behavior, can lead to more effective policies. Several studies have found a significant relationship between travel behavior and socio economic properties of trip makers. Syam (2012) stated that income level is an influential factor which results in different travel behaviors. Recognizing these difference across a city helps to develop optimum policies to meet all citizens travel need. In the case of this study it was important to understand the intermodal behavior between TM and bicycle mode. As discussed in previous section, there have been developments of infrastructures to ease the transfer from bicycle to TM mode. However, there are more local factors which can encourage or discourage intermodality. To investigate these factors and the users' behavior, two sets of field survey were conducted across three groups of low, middle and high income respectively. Additionally, these provided information could assist the further analysis in addressing the research questions.

The first survey aimed to capture the use of bicycle by TM users at three TM stations namely: Portal Americas, Portal Suba and Ave. All these stations have parking facilities and each of them can be associated with one of the income groups. The survey were conducted during morning peak hours (6:15-7:15) on weekdays. Table 4.2 summarizes the survey attributes for each station. It is notable that Las Aguas station, which is close to the city center, was selected to run the test survey prior to portals. In general, TM passengers were interviewed on the stations platforms as well as parking spaces. There were very small percentage of TM user who would arrive by bicycle to station, and there was less or no possibility of finding these groups on the platform. To account those rare cases, part of the survey was conducted in parking spaces rather than TM platforms. This way it was possible to interview cyclists, however the result would not reflect the travel behavior from a random sample of TM passengers. During interview, open questions were used, but the questionnaire was designed with semi closed structure to ease the process for the interviewer. The questionnaire is provided in appendix B.

Table 4.2 Summary of survey conducted in sampled TM stations

TM station	Facility	Socio-economic level	Completed surveys
Las Aguas	IPES Parking	The City Center	31
Portal Americas	TM Parking	Low Income	51
Portal Suba	TM Parking	Middle Income	40
Rojas	TM Parking	High Income	31
		Total	153

Accepting and using bicycle as a mode of transport is fundamental to bicycle intermodality. Therefore, the second survey attempted to determine factors that affect the use of bicycle as a main mode of transport. This survey was conducted in three universities including: National University, Piloto University and Polytechnice University of Javeriana. Universities were selected based on the socio economic profile of students, and their locations. Since Javeriana is a private university with high tuition fee, it was associated with high income groups. Piloto University is also a private university where students are mostly from middle income groups. National University as the largest public higher education institution in Colombia, students were accounted as low income group. As presented in figure 4.3, all three universities are located around TM corridors. In terms of parking facility, both National and Javeriana provide bicycle parking spaces for students. Table 4.3 presents an overview on sampled universities. The survey was designed in form of written questionnaire with semi closes questions. In addition to written forms, questionnaire became available in form of an on line survey. Structure of the questionnaire is provided in appendix ??.

Table 4.3 Summary of survey conducted in sampled universities

Universities	Facility	Socio-economic level	Completed surveys
National University	With Bicycle Parking	Low/Middle Income	97
Javeriana University	With Bicycle Parking	High Income	82
Piloto University	Without Bicycle Parking	Middle Income	27
		Toal	206

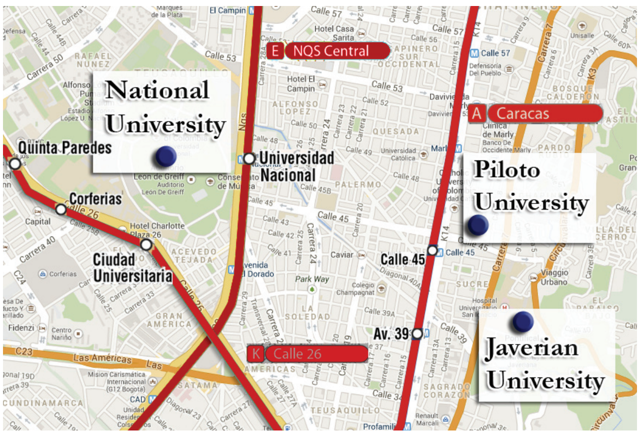


Figure 4.3: Location of sampled universities in relation to TM lines

(a) National University (b) Javriana University

Figure 4.4: Bicycle parking facilities in sampled university campus

Sample Profile

In total, 122 interviews were completed with TM users in three sampled stations. Also, 206 written questionnaires filled out in the selected universities. In case of station-survey, respondents' age were between 17 and 60 years old. Age range for universities was between 16 and 32 years old. In terms of gender, for the survey in stations the majority of interviewees were male, while in the case of universities more female students completed the questionnaires. In overall more than 76% of respondents in universities confirmed that they are able to ride bicycle, and from this share 60% own a bicycle or have access to a bicycle. In case of TM station, only 56% of respondents could ride a bicycle, while more than 60% of them stated that they have no access to bicycle.

4.3 SURVEYS FINDINGS

This section presents findings and results of interviews and written surveys. Additionally, it was possible to use mobility survey records to complement the discussion about intermodal behavior in Bogotá.

Mode Choice

How people use the bicycle as a transport mode can indicate whether they would use it in a multimodal trip or not. Results from university survey suggest that choosing bicycle to travel to a destination is related to bicycle facilities in that destination. Especially, availability of bicycle parking is important. Table 4.4 and figure 4.5 summarize the modal share of trips to sampled universities. It is evident that in Piloto University, where there is no bicycle parking, cycling was not an access option. On contrary, in National university with considerably large parking availability, bicycle was a more common mode of transport. In overall, the main mode used by students to reach universities was TransMilenio. Almost 47% of students used TransMilenio. This share was followed by buses and bicycle. It is important to note that relatively high bicycle usage in case of National university is the result of specific characteristics of this university. The university is located in a very large campus, surrounded with residential areas. A large number of students live in the housing around the campus which are highly accessible by bicycle. This factor in addition to parking facilities may encourage the students to cycle more than average citizen.

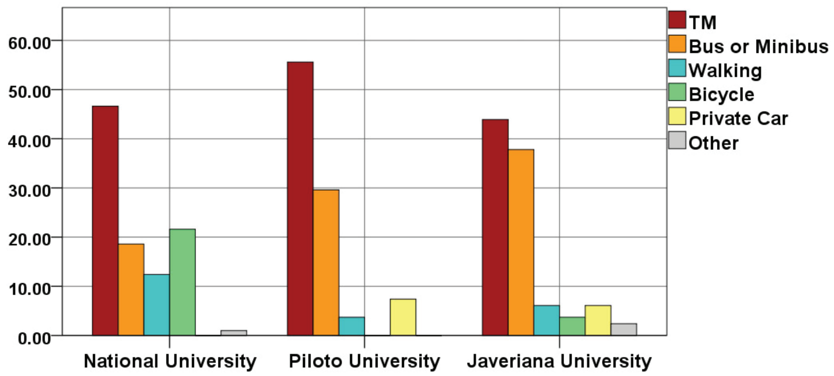


Figure 4.5: Percentage of stated modes within sampled universities

Table 4.4 Modal Share for trips to sampled universities

Mode to university		National	Piloto	Javeriana	Total
Walking	% within University	12.40%	3.70%	6.10%	8.70%
Bicycle	% within University	21.60%	0.00%	3.70%	11.70%
Bus	% within University	18.60%	29.60%	37.80%	27.70%
TM	% within University	46.40%	55.60%	43.90%	46.60%
Car	% within University	0.00%	7.40%	6.10%	3.40%
Taxi	% within University	0.00%	3.70%	0.00%	0.50%
Other	% within University	1.00%	0.00%	2.40%	1.50%
Total	% within University	100.00%	100.00%	100.00%	100.00%

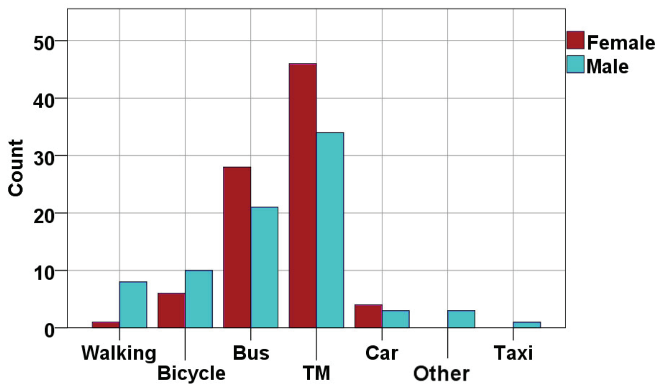


Figure 4.6: Stated transport modes to sampled universities by gender

Although, Javeriana University provided bicycle parking in the campus, there was only 3 records of cycling to this university. One offered reason is the effect of income level on students mode choice. In universities related to high and middle income groups, students tend to use private cars, while for the ones with relatively lower income profile, walking and are more frequent (see table 4.4). Other influential factor is the location of this university in relation to CicloRuta. Currently, Cicloruta network has less coverage at this area. In addition to this, physical conditions and steep topography may be a discouraging factor. This can be confirmed by the percentage of bicycle user who cycle through Cicloruta. In case of portals, more that 66% of bike users stated that they choose routes through Cicloruta, because of less accident risks. This share for case of university was lower. This could be due to the longer distances that students need to travel.

In terms of gender, walking and cycling were used more by male students, see figure 4.6. On the other hand, more female students traveled by collective modes and private cars. This could be related with the level of safety experienced with each mode. A study by Krizek et al. (2005) showed that safety preferences for cycling differs by gender.

In general, the modal share for Javeriana university suggested that in northern parts of Bogotá, buses are more effective than TM. It was discussed in section 3.2 that the majority of TM users are from low and middle strata. Table 4.6 also shows that the great percentage of TM users belong to social strata 2 and 3. The highest and the lowest strata make less number of trips through this system. This can be explained by the population of these two strata, which is a small share compare to entire city population. In case of the very poor, afford-ability may be another influential factor, because TM is more costly compare to other local buses. Furthermore, this stratum is mostly concentrated in the informal settlements at city boundaries. Distance could affect their demand to travel to city center areas. In case of the highest stratum, one reason for less number of TM trips is that, they easily afford private cars.

In addition, the quality of TM service can affects the choice. TM buses are overcrowded during peak hours, and users experience longer waiting time and less comfort. For higher income groups comfort is valued more than monetary costs, as a consequence, TM seems to be a less attractive mode for them. On the other hand, lower income students use TM more and even travel longer distances through this system. This is reflected in table 4.5 as well; where average travel time for this groups is longer. The same behavior was observed in case of walking and bicycle modes. The average travel time by walking for students in National university was around 18 minutes, while for students from Javeriana University (high income group) was 13 minutes.

Table 4.5 Average Travel Time for different modes of trips to selected universities

	National		**Javeriana**		**Piloto**		Total	
Main Mode to University	Minutes	σ	Minutes	σ	Minutes	σ	Minutes	σ
Walking	17.33	11.904	13	7.583	20	.	16.28	10.487
Bicycle	27.52	13.325	40	0			29.08	13.121
Bus	42.33	17.241	42.1	14.01	46.88	19.809	42.87	15.63
TM	50.18	17.618	46.25	13.855	41.4	14.101	47.33	15.925
Car			30	17.795	37.5	10.607	32.5	15.083
Taxi					25	.	25	.
Other	12	.	20	7.071			17.33	6.807
Total	39.27	20.171	40.93	15.873	41.33	15.981	40.21	17.954

TransMilenio Access Mode Choice

Through field surveys, access to TransMilenio system was investigated in terms of *where* and *how* people access the system. Data collected from both surveys suggests that distance is the most determining factor for selection of a TM station. When TM users and students were asked how they choose the TM station to start their trip, more than 70% of interviewed TM users stated that they entered the system at the closest station to their home. This is consistent with the great share of walking as most common access mode in trips recorded in the mobility survey database. By extracting only TM based trips from mobility survey (2011), it was observed that very few number of TM riders use bicycle to access this system. Table 4.6 summarized different access modes to TM stations per social strata. It is evident that only 0.1% of system users chose cycling for the first part of their TM trips. This could be the result of developed bicycle parking facilities in the portals. After walking, feeders and other local buses had the largest share for access trips. According to this results, TM users only choose motorized modes beyond walking distance. The small share of others is related to the use of motorcycle or bicitaxi in some cases.

Table 4.6 Modal share for access trips per social strata. source: Bogotá mobility survey

		SES						
		1	2	3	4	5	6	Total
Walking	% within SES	10.4%	39.0%	66.9%	75.4%	85.0%	71.9%	55.7%
Feeders	% within SES	71.1%	38.0%	20.0%	10.5%	1.5%	3.5%	27.2%
Other Bus	% within SES	16.4%	21.1%	11.8%	10.3%	9.3%	17.5%	14.9%
Car	% within SES	0.4%	0.6%	0.6%	1.1%	2.1%	7.0%	0.8%
Taxi	% within SES	0.2%	0.6%	0.5%	2.1%	1.8%	0.0%	0.8%
Other	% within SES	1.0%	0.6%	0.3%	0.6%	0.3%	0.0%	0.5%
Bicycle	% within SES	0.4%	0.1%	0.0%	0.0%	0.0%	0.0%	0.1%
Total	% within SES	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Percentage of trips per Strata		6.9%	33.1%	41.4%	12.9%	4.8%	0.8%	100.0%

In total, 6962 number of TM based trips summarized

Comparison of access modal shares across different social strata, suggested that stratum 1 has the lowest walking access to TM. This group can access TM mostly through feeder buses. It was interesting to see that the rare cases of combining bicycle and TM also belong strata 1 and 2. This again highlighted the relation between bicycle usage and income level. In other words, lower income groups consider bicycle for daily transport, rather than only for recreational or sport activities. The results from field surveys also reflected similar pattern to mobility survey sample trips. Students in National university needed to travel more and longer through feeders buses to reach TM stations. As figure 4.7 shows, the larger percentage of middle and high income students could access TM stations by walking distance. Figure 4.8 presents the average access time for each modes, which resulted from surveys records. It can be seen that, the groups with lower income group needed to bike or take feeder buses to reach the TM portals. Travel times for walking mode also followed the same pattern. However, interviewed TM passengers in the Portal Americas reflected shorter walking access trips. Indeed, this station is located in a high density residential area, and because of this more people can reach the station within walking distances.

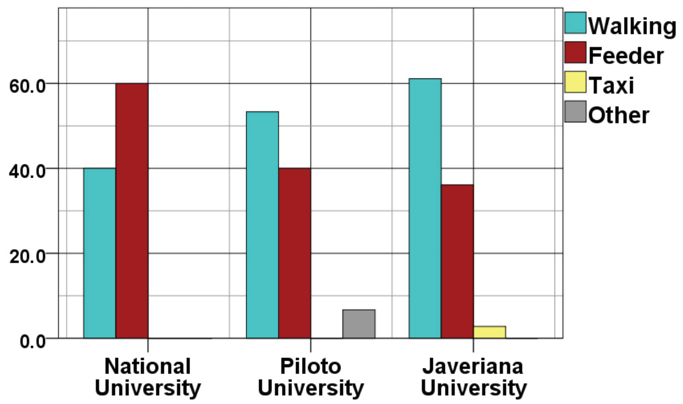


Figure 4.7: Share of each access modes to stations by universities

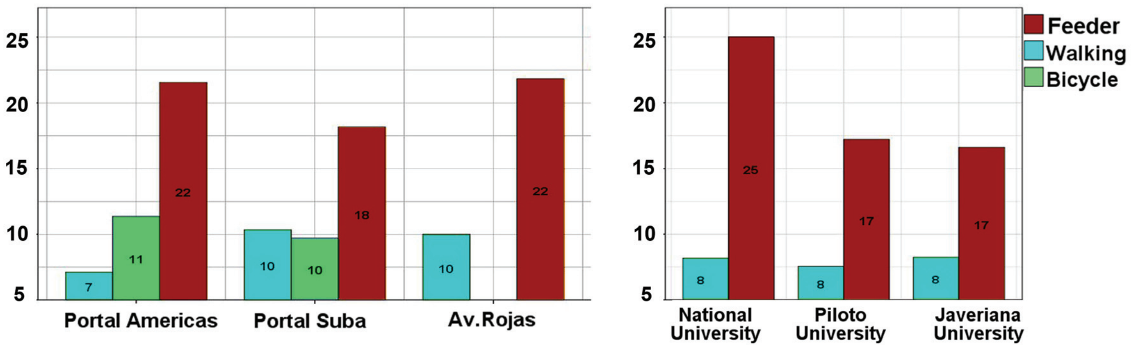


Figure 4.8: Average minutes traveled to access TM stations per mode

Barriers to the Use of Bicycle as Access Mode

For any effective integration policy, it is important to understand the local factors which encourage or discourage the use of bicycle. Accordingly the designed surveys attempted to explore issues that affects this intermodal behavior in the city of Bogotá. In general, the results implied that other than physical infrastructure, users' perspective towards cycling is influential. In the case of these surveys, although the majority of respondents confirmed that they are able to ride a bicycle, only 30% of them actually considered it as an option to make daily trips. This suggests that respondents don't see cycling as a transport mode. Also, in the both surveys, TM users were asked about the reasons why they do not use bicycles to reach stations. This question was structured with relevant choices and an option to include any other possible reasons. The related questions coded as NB4 and NB 5 are included in appendices A and B. Figures 4.9 and 4.10 summarized the responses as the barriers to the use of bicycles for each sampled group.

The most important reasons to not use bicycles, are related to safety and security. Indeed, Bogotá had the highest homicide rate among capital cities in Latin America in 1994, and it was considered to be in the list of the most violent cities in the world (Tella et al., 2010). However the city has been successful to lower its crime rate and change the violent image. Yet, survey results indicted that being exposed to violence was still an important discouraging factor for . In addition to this, exposure to accidents was mentioned frequently. This could be due to fact that, there is no well defined rights and regulation for cyclists in the city. Additionally, the physical infrastructure does not provide a continuous and safe bicycle path across the entire city.

It was suggested that the trip purpose could affect the extent of barriers. In two of the universities weather condition was noted as a constraint for cycling. However, this was not a major problem from TM users perspective. Another observed problem was related to awareness and information policies. Results showed that even in stations with bicycle parking, users listed lack of these facilities as a barrier. This suggests that, although policies could include this opportunities physically into the system, users are not well informed about the provision of them.

Additional reported problems that discourage the use of bicycles differ across income groups. The higher income strata reported issues more related to comfort. A considerable number indicated that bicycle is not comfortable for daily trips to their work place. They stated that due office clothing, cycling is difficult for them. This suggests that potential of bicycle as a transport mode is not well known and accepted among this group. On the other hand, not affording a bicycle had a greater effect on the lower income groups. Figure 4.10 reflects this difference clearly.

It is important to note that the original question included a choice as distance barriers. Users who live very far to station could select this option as a barrier to use of bicycle to access TM station. However, a large number of students and users answered this question in relation to the entire trip rather than only access trip. Due to this, the option was excluded from the analysis. However, this is an indication that combining bicycle and other modes was not a recognizable option.

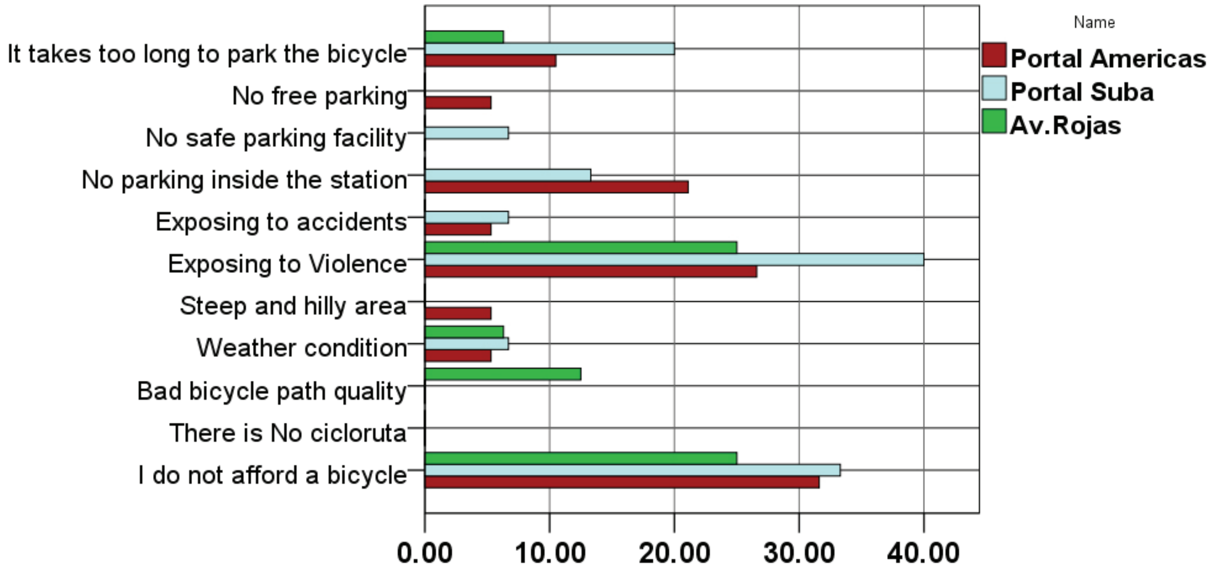


Figure 4.9: Stated barriers to use of bicycle as an access mode to stations by TM users

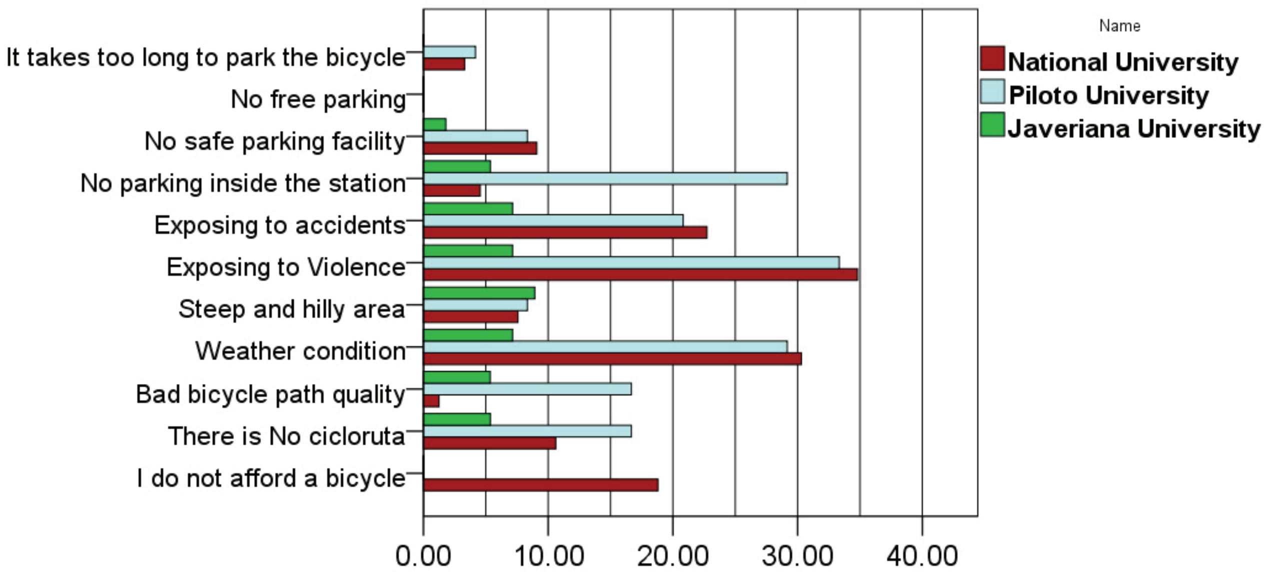


Figure 4.10: Stated barriers to use of bicycle as an access mode to stations by students

Synthesis of Findings On Bicycle Intermodality

From what was discussed earlier, in relation to integration of bicycle and TransMilenio in the city of Bogota, the following remarks summarize the main results of this chapter:

- Overall, the use of bicycle as a transport mode was low. It was observed that cycling was more common within the lower income groups. The higher strata tend to use bicycle less and within shorter trips.
- In most trips involving bicycle mode, this mode was the only and the main mode of transport. It was less likely that citizens combine bicycle with other modes of transport. Again, this intermodal behavior was limited to the poor income groups.
- Provision of bicycle parking facility was recognized as a prerequisite to combination of bicycle and TransMielnio.
- The better off groups considered cycling as a recreational or sport related activity, rather than a mode for transport. As citizen did not consider cycling as a common mode of transport, provision of infrastructure is not enough for actual bicycle - TM integration to occur.
- Security was identified as an important barrier to use of bicycle in the city. Most women, which constitute half of the population, did not see cycling as a safe transport mode.
- Safety and accident risk also discouraged the use of bicycle. Network interventions to improove continuity for cycling trips as well as increased enforcement of cyclists rights are needed to improve cycling experience in the city.

Chapter 5

Accessibility Analysis

This study employed job accessibility measures to investigate the impact of bicycle integrating and TransMilenio in the city of Bogotá. As an indicator for policy effectiveness, job accessibility through TransMilenio and NMT modes was calculated under three scenarios (No integration (base scenario) to full integration).

The main tasks involved in this process are: modeling the transport network of Bogotá, identifying the origins and destinations, modeling the trips, estimating the cost functions and calculating the final accessibility values. This chapter describes in detail the methodology and applied techniques to measure job accessibility in details. It also includes the final results corresponding to each section.

5.1 MULTIMODAL TRANSPORT NETWORK DATASET

In order to estimate accessibility, it is essential to measure travel cost through the set of transport modes. This can be done by simulating trips with GIS based transport network models. Considering the objectives of this study, two multimodal network models were required to integrate TranMilenio and Walking or Bicycle modes under the desired scenarios. It was important to create a network model which was consistent with real world dynamics, and that can produce correct and reliable routing results. Therefore, networks were designed to support door-to-door navigations (see section 5.1.2).

Overall, datasets of base features including roads, bicycle routes and TM corridors were prepared to represent the transport network. Then, a 3D modeling approach was applied to design the GIS model of the integrated network based on existing transport infrastructure in the city (specially for major streets and highways structures which are depicted in figure 5.1). Accordingly, connection features were added to provide proper transfers between the separate modes (see figure 5.2).

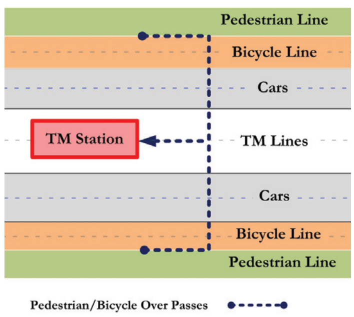


Figure 5.1: Main roads structure details

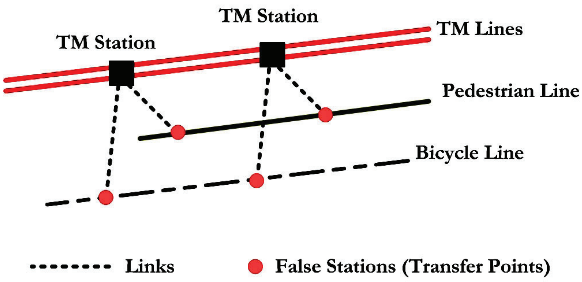


Figure 5.2: Transfer between modes through links and false stations

5.1.1 Data Preparation

Firstly, features associated with TransMilenio system including the corridors and stations were updated to the current network extent. Then, the streets layer was edited to adopt it as a base for walking trips. Highways lanes, which were not walkable, were excluded form the layer. In order to allow crossing, existing pedestrian over passes were identified using to Google Earth and added to the pedestrian network. Afterwards, a new point feature of false stations corresponding to real TM stations was created. These points located at the endpoint of road segments and represent the entrance of TM stations. Also, false links were digitized as the connection between these two sets points (including false walking stations and the TM stations). They represent boarding or exit of TM lines in the real world.

The next step was preparing the bicycle network features. Currently, Cicloruta consists of the exclusive bicycle lanes in the city. But it is not a continuous network. For this reason, cyclists ride on street lanes as well as sidewalks. Thus, the pedestrian network was adapted for bicycle trips. This was done by assigning a new attribute to identify the Cicloruta segments on the street layer. As a result, it was possible to differentiate the Cicloruta trips from the rest. Afterwards, false stations and links were added to this group as the bicycle network features.

5.1.2 Travel Impedance Measures

One essential part of accessibility analysis is estimating travel costs. The ease or cost to travel through a network can be measured in various forms such as travel time, fare, distance, risks, comfort or other qualities for trips. These measures can be used in disaggregated or aggregated manner. Generalized cost functions enable the combination of different measures and include more sophisticated factors. Travel time was selected to measure trip impedance (cost). This was because, walking and cycling have no direct monetary costs and generally, work related trips are more sensitive to time factor. Furthermore, data availability was another determining factor.

Recent transport studies take into account every stage of a multimodal trip to estimate travel times. (Salonen & Toivonen, 2013) defined this as "door-to-door approach".This approach accounts travel impedance from the origin to final destination including the time needed to access, switch and egress the transport systems. This is crucial in this case, because multimodal trips were modeled by combining TM and NMT modes, therefore waiting time can be taken into account.

Basic stages for 2 options of possible modal combination for a TM based trip are illustrated in figure 5.3. They include: (1) walking from the origin to the closest TM station, (2) waiting for the TM bus to arrive and to board, (3) TM ride between initial station and final TM station, and (4) walking from the last TM station to the final destination. It is possible to Transfer from one

TM line to another inside the stations and there is no need to exit the system. For the case of using bicycles, there are additional time costs to park the bicycle at the initial TM station or access public bike at final stations.

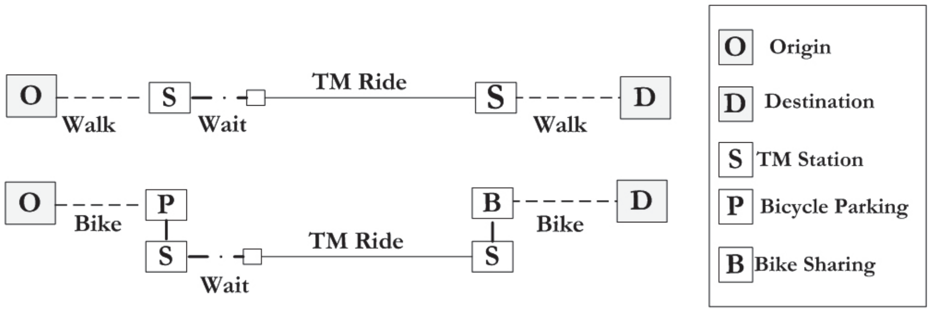


Figure 5.3: Two door-to-door options for a TM trip. Source: adapted from (Salonen & Toivonen, 2013)

In order to measure travel time in the modeled network, each mode average speed was assigned to related segments in a GIS environment. Travel time along routes was calculated based on the speed and length of each segment. Assigned values are summarized below:

- 4.5km/h as walking speed for pedestrians, measured in a study conducted by Knoblauch et al. (1996).
- 27 km/h for average speed of TM buses, according to Hidalgo et al. (2013).
- 10km/h for cycling along Cicloruta and 8km/h for off Cicloruta routes.
- 6 minutes as the average waiting time assigned to walking and bicycle links, according to Braake (2013).
- 2 minutes additional time to park or access bicycle assigned to bicycle links, based on field survey.

Although Jensen, Rouquier, Ovtracht, and Robardet (2010) showed that in normal conditions and for average users cycling speed is 13.5 km/h, lower speeds were selected for this network. This is due to Cicloruta connectivity and continuity issues. In fact, bicycle ride is interrupted at every road intersection which slows down the movement considerably.

The final step after defining impedance attributes was building a network data set. The above mentioned layers were grouped and each mode formed its own connectivity group in the network dataset. Integration of modes was verified by calculating the shortest routes between different stops and making use of direction tool from Network Analyst.

5.2 IMPLEMENTATION OF THE ACCESSIBILITY MEASURE

Based on the reviewed literature and available data, the potential activity based measure was found to be suitable to achieve the objective of this research. The main focus of this study was to investigate the impact of transport policies across different social strata. These policies consisted of interventions in TM system infrastructure which could involve bicycle in the trips to/or from

TM stations. For this reason, it was important to select a measure which could reflect the transport network effect as well as variation due to the location of origins and destinations for different SES groups. Although gravity and competition based measures seem more sophisticated, they are more suitable to study interactions between different activities. In other words, they include complex factors from land use side which affects the transport network contribution. Van Wee et al. (2001) also described that potential measures are useful for comparing between transport modes, because the time impedance can have a great impact on calculated values and results can linked to existing travel behaviors.

According to a review of accessibility measures conducted by Kumar (2011), potential accessibility measures were used for the first time by Hansen (1959). In his study, accessibility was conceptualize as the potential of opportunities for interaction. He advocated that these measures are useful to examine the effect of different factors such as income, zoning, taxes and land costs on urban developments. Many studies adapted the potential concept to measure accessibility to certain destinations or from certain origins. Geurs and Van Wee (2004) described that these measures estimate the accessibility of opportunities in zone i to opportunities in all other zones n, by considering negative effect of travel cost. This is achieved by using distance decay functions (see section 5.2.3). In principle, the measure has been adapted in different studies using equation 5.1.

$$A_i = \sum_{j=1}^{n} D_j f\left(c_{ij}\right) \tag{5.1}$$

where A_i is accessibility level for zone i to all opportunities D in zone j, c_{ij} is the costs of travel between i and j and $f(c_{ij})$ is the distance decay function.

Equation 5.1 was adapted for this study to estimate potential job opportunities for residential locations, across five social strata (1, 2, 3, 4 and a group of 5 and 6). Final result is stored as an attribute for residential areas, indicating the spatial and social accessibility that transport network provides for each origin. This estimation was repeated with three transport network conditions. The first network simulated trips with combination of walking and TM. This was considered as the base scenario. New accessibility levels were calculated with integrating bicycle in the access trips to TM as well as trips from TM to final destinations.

5.2.1 Origins and Destinations

The current study used the Bogotá transportation analysis zones (TAZ), to identify spatial locations of origins and destinations for accessibility analysis. According to this structure, the city of Bogotá is divided into 999 zones. The spatial extent of zones varies across the city and the area of the zones range from small urban blocks around the the city center to larger areas at the city fringe. A mobility survey database also provide socio economic data within the zones, which helped to specify the modeling process across different social strata.

Strata Locations

A large number of daily urban trips start from residential areas and end in work centers. It was important to identify the spatial pattern of residential locations as the origins of urban trips. These locations were extracted for each social strata separately and assigned to the corresponding TAZ.

As mentioned in section 3.1, the spatial and social segregation is very evident in the city of Bogotá. Each social strata tends to concentrate in different parts of the city. This also can be seen in figure 5.4, where social stratum 1 is settled in marginal zones an mostly towards the south. On the other hand, by moving toward the city center and northern parts of the city, zones exhibit a predominance of high income groups. It is notable that the zones which are located at the north east and associated with social stratum 1 are informal developments with steep topography.

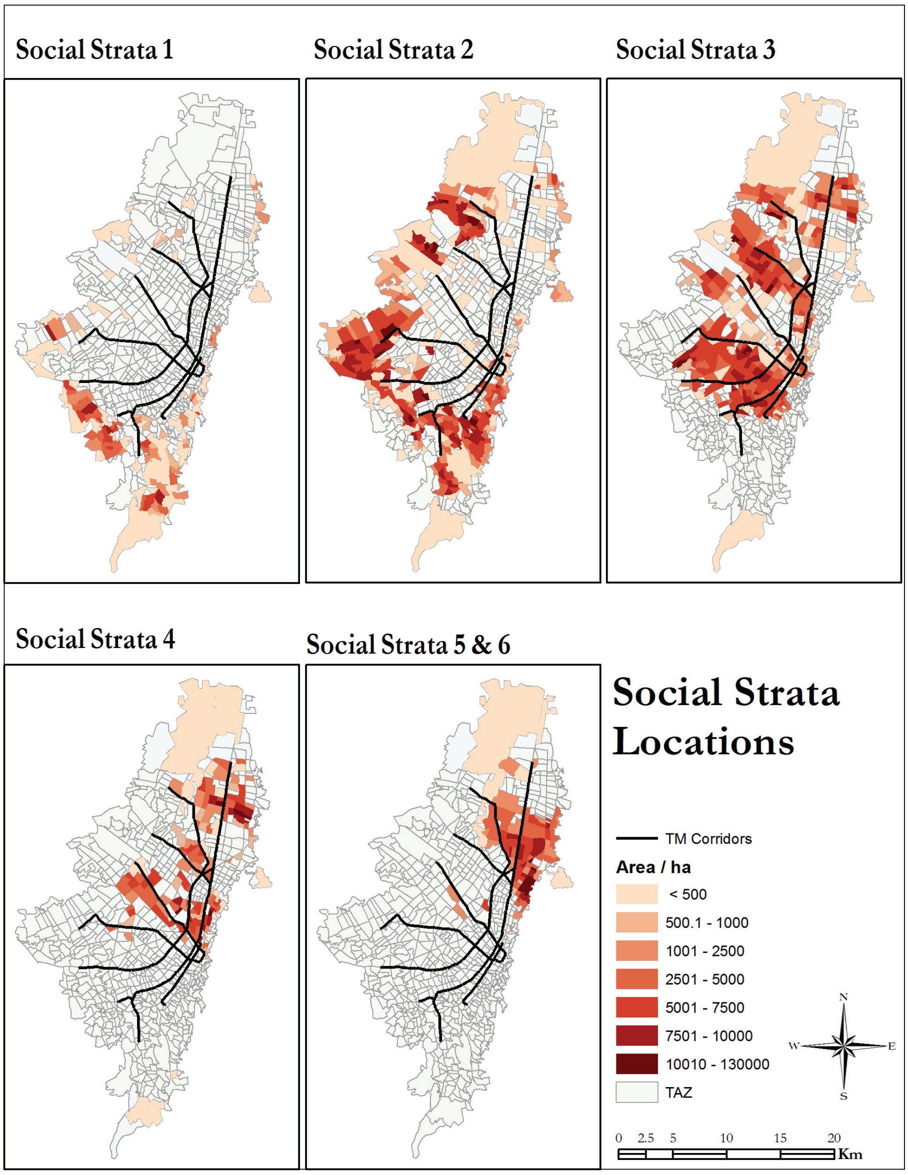


Figure 5.4: Residential locations for each social strata

Job Locations

As this study focused on work related trips, job centers were selected as the destinations for the accessibility analysis. Similarly to residential locations, jobs were identified according to TAZ zones structure. Another reason for this selection was that the data related to jobs was derived from mobility survey. The total number of trips attracted to each zone for work purposes was taken as the jobs indicator in each zone. This does not represent the absolute number of jobs in the city, however the estimated indicators are relatively true in the sense that they can reflect the actual pattern of job distribution across the city. Furthermore, this way, it was possible to match the destinations for each social strata. Table 5.1 summarizes the total number work trips per social strata. In overall jobs indicator is the highest for SES 2 and 3.

Figure 5.5 presents the resulting spatial pattern of jobs indicator per social strata. It can be seen that for the majority of social groups, most opportunities are concentrated in the north east part of the city. It is notable that jobs for the lowest social strata show a markedly different spatial pattern, because the type of jobs are likely informal as opposed to the economic activity of the higher social strata. Although, the spatial distribution of jobs indicator for SES 1 shows a more disperse pattern, overall, as the income increases, the related jobs locations concentrate in northern parts of the city. Since the residential lotions of the higher strata are also clustered close to this centers, this suggests that the origins and destinations are located closer to each other, leading to shorter trips.

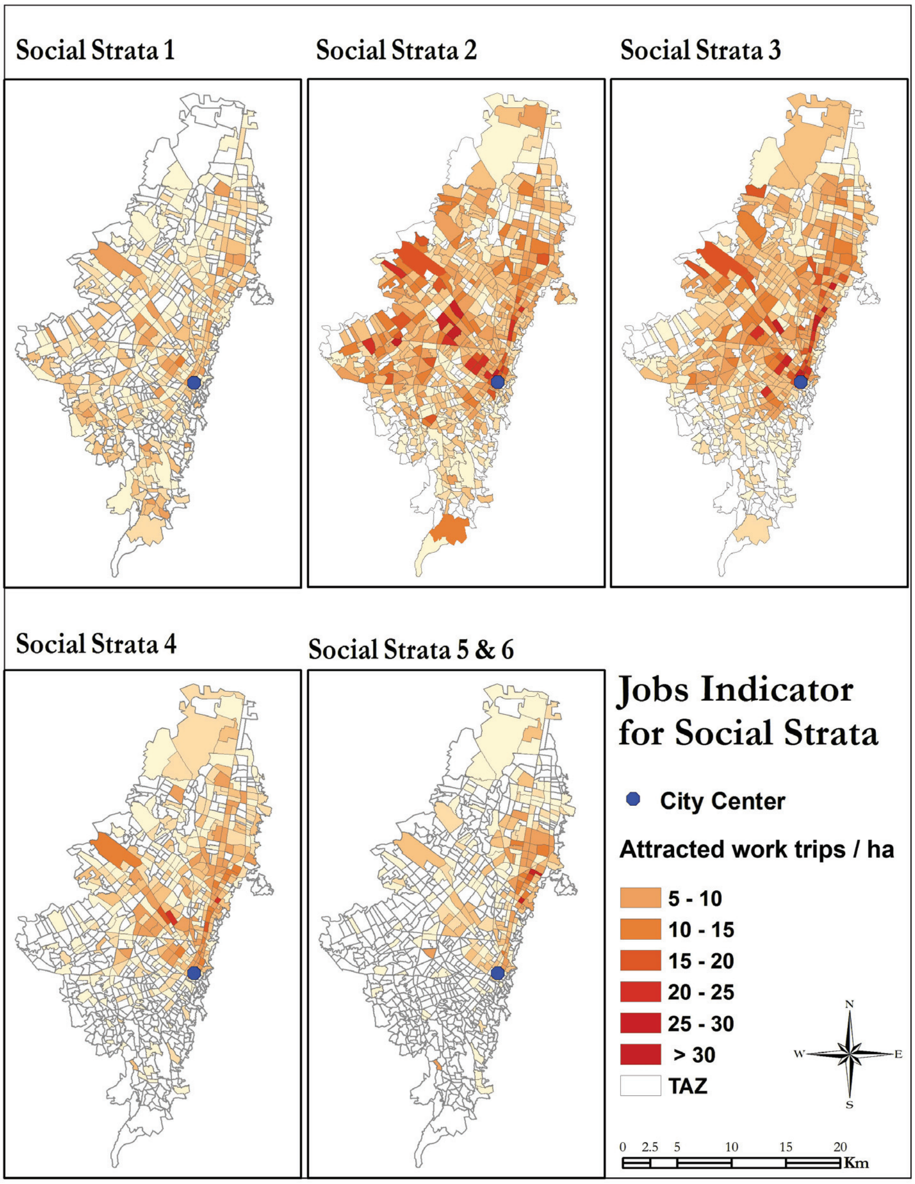


Figure 5.5: Distribution of corresponding jobs indicator for each social strata

Table 5.1 Total number of job trips per strata according to mobility survey respondents

SES	Total Number of Jobs
1	989
2	3386
3	3198
4	1240
5 & 6	789
Total	9602

5.2.2 Modeling Multimodal Trips

Accessibility analysis requires to estimate travel time between origins and destinations. The main aim of this stage was generating an OD matrix for each set of origin destinations through the networks which were constructed beforehand. The OD matrix was the input for the cost calculation process in the next stage of analysis. The main transport modes included in the networks were: walking, bicycle and TM. As discussed in chapter 4, bicycle has a very small modal share for access trips to TransMilenio system which means very low or no bicycle integration. The majority of TM users walk to the closest station, or in case of longer distances, they use feeder buses or other motorized modes. Therefore, combination of walking and TM could represent the current situation in Bogotá in terms of bicycle integration. In consequence, different OD matrices were required for the following conditions and combination of modes:

1. No Integration :
   - Walking
   - Walking + TM + Walking
2. Bike and Ride condition:
   - Bicycle
   - Bicycle + TM + Walking
3. Full integration conditions (Ride and Bike in addition to previous condition):
   - Bicycle
   - Bicycle + TM + Bicycle

ArcGIS Network Analyst was successful in creating two OD matrices for the first and the third conditions. However, practice showed that this tool faced limitations to combine three travel modes for to the second condition (see 6.3). Therefore, a different approach was applied to model these trips and estimate the corresponding optimum travel time.

An alternative approach was developed based on the reported travel behavior of citizens in Bogotá. As discussed in chapter 4, intermodality survey results show that in Bogotá people enter TransMilenio system at the nearest station to their home. According to this finding, the closest station was known as an important point in every multimodal trip which can be identified for each origin. This point was used to divide the multi modal trip into sub trips which were made by use of one single mode (or two modes at the most). These sub trips could be easily simulated with available network data sets and algorithms.

For each pair of origin destination, travel time was calculated by adding the optimum travel time of two stages. See Figure 5.6. Stage 1 provided the optimum time to reach the closest TM station, and stage 2 the optimum time to reach the final destination from the TM station. In order to generate an OD matrix for multimodal trips, two OD matrices corresponding to each stage were generated separately and joined using the common TM station ID (see 5.8). Also, it was important to consider the very short trips that could completed faster by using a single NMT mode which in this case was bicycle. Consequently, for each pair of locations, travel time by bicycle was calculated and compared with the time that resulted through TM combination to select the optimum (less costly) option.

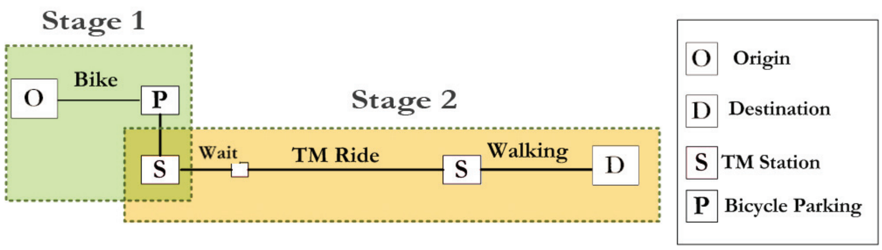


Figure 5.6: Sub trips of a TM trip with different modes at ends

In general, the main steps taken to implement the alternative approach are as below.

1. Creating an OD matrix between residential areas as origins and job locations as destinations with use of bicycle single mode network. This table captured interzonal trips which could be faster with only bicycle mode.

2. Assigning the closest station to each origin center with the bicycle network (see figure 5.7). The output was the second OD matrix with residential zones as origins and TM stations as destinations. This step assumes that the access trip to TM is made by bicycle.

3. Taking the closest TM stations as new set of origins and calculating optimum travel time to job destinations. These trips are modeled in the network with combination of TM and walking mode. The output was the third OD matrix.

4. Combining the last two OD matrices and calculating accumulated travel time for travels between each pair of origins and destinations. Waiting time for TM was added to the results.

5. Comparing calculated travel time with first OD matrix result and taking the shortest value. This generates a single OD matrix with optimum travel time which could be used to apply the decay functions in the next stage of accessibility analysis

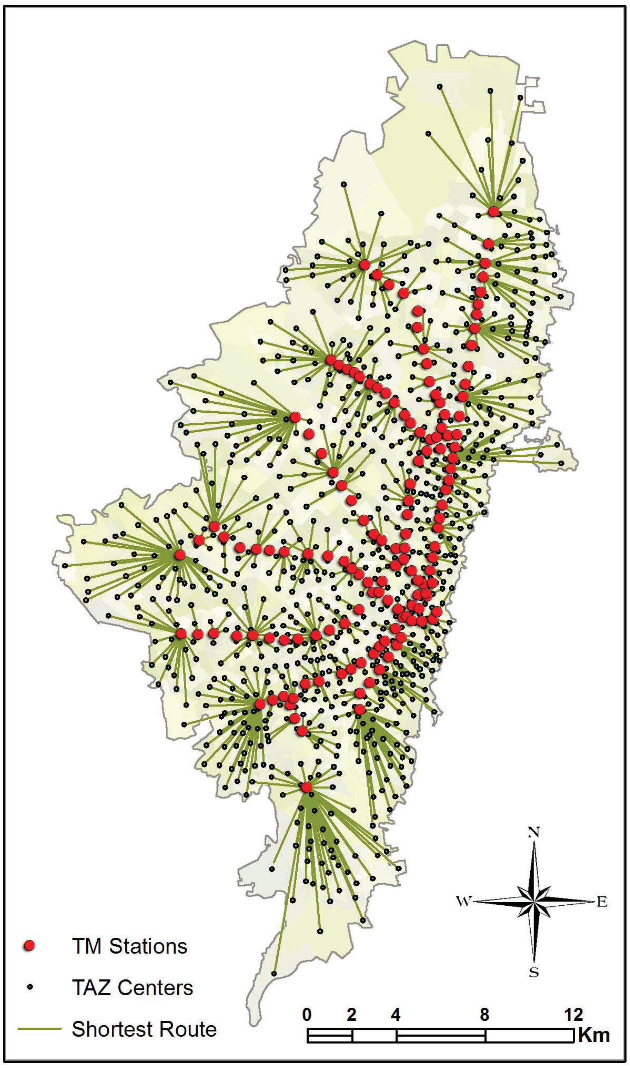


Figure 5.7: Assigned closest TM station to TAZ centers

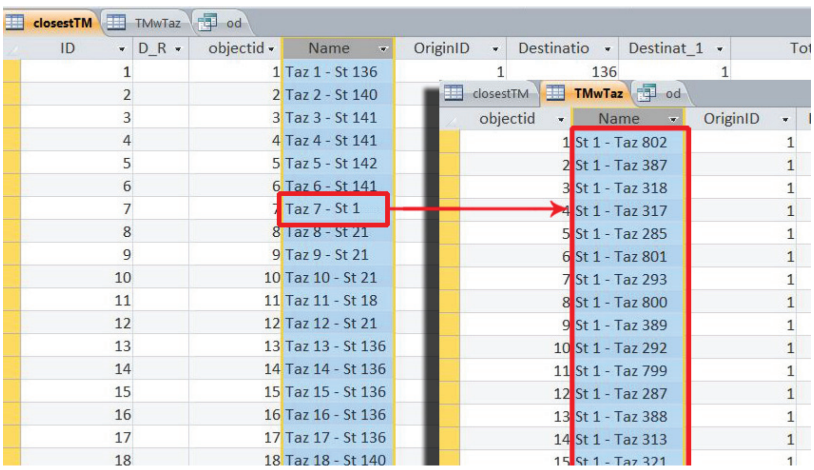


Figure 5.8: Joining the two OD matrix to generated multimodal OD matrix

5.2.3 Decay Functions

Tobler (1970) cited by (Skov-Petersen, 2001) formulated the first law of geography:

"Everything is related to everything else, but near things are more related than distant things."

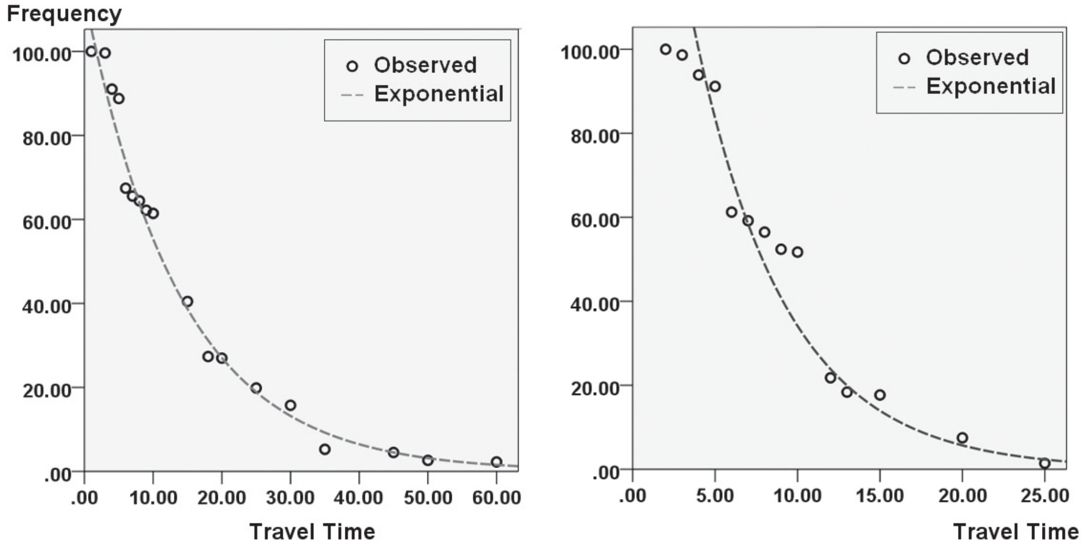
According to this law, increasing the distance or travel cost has an inverse effect on the interactions between origins and destinations. Consequently, the potential of reaching opportunities in destinations is related to the cost of the trip to that location. This negative influence of travel costs on human behavior was formalized as a "Distance Decay", and it is one of the fundamental assumptions for measuring accessibility of the users to a certain location. Distance decay is a quantitative conception of this phenomena. It has been operationalized through decay functions (Skov-Petersen, 2001). Accessibility studies applied impedance functions from spatial interaction models and calibrated the parameters according to empirical data. The most commonly adopted functions are exponential and power functions. Also, some other studies used different approach such as threshold functions and Gaussian functions.

In principle, travel behavior differs by trip maker characteristics, transport mode properties, location of origin and destination. Geurs (2006) emphasizes that decay function should be selected according to each transport modes, trip purposes and trip makers characteristics (e.g. gender, age, income and educational level). Decay function should be the best-fit to the existing trip behavior in the study area. From chapter 4, it was concluded that the extent and the quality of urban trips is different for each social strata in the city of Bogotá. As a result, it became important to estimate distance decay for each group and each mode separately.

Therefor, cost functions were defined by using the database from Bogotá Mobility Survey of 2011. Work trips for each social strata were extracted separately, and accumulated frequency of travel time was calculated for the three modes (walking, bicycle and TransMilenio).

To simulate the relation between travel time and the respective frequency, different functions were tested. It was observed that the negative exponential was the optimal curve to fit the pattern, so the cost function was defined as equation 5.2, where $f(c_{ij})$ is the generated cost of trips, and t_{ij} is the travel time between zones i and j. Afterwards, the β parameter was calibrated for each transport mode and each social strata (see table 5.2). Calculations excluded outliers from the data, to avoid bias in the results. This process is described in appendix C. In some cases, a limited number of records (mostly in higher social strata) resulted in functions that are not statistically significant, but they are consistent with the generally expected results from the theory. Following figures compare the resulting functions for low and high income social strata and the details of functions are provided in table 5.2 and appendix D.

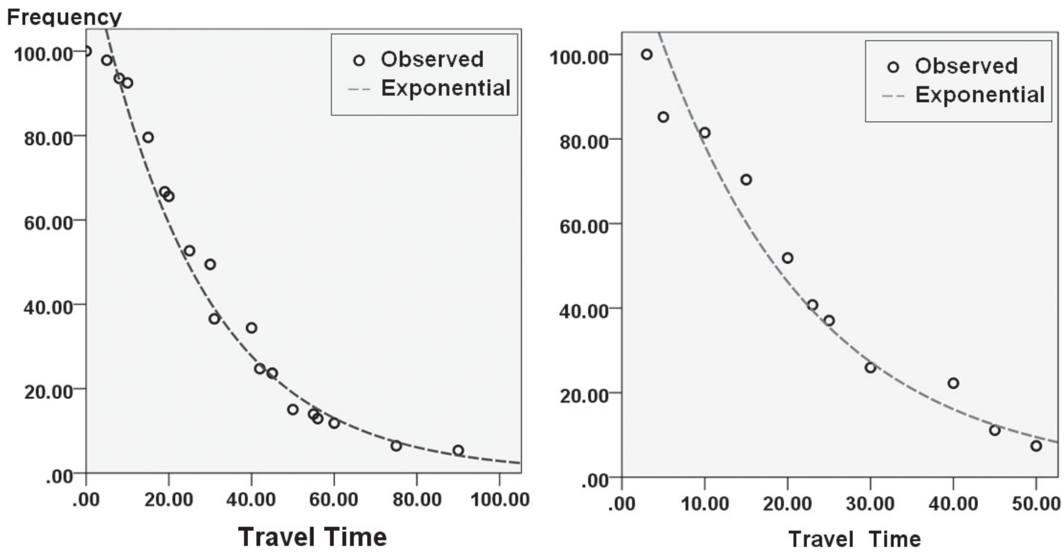
$$f(c_{ij}) = \exp^{-\beta * t_{ij}} \tag{5.2}$$



(a) SES 1 - $\beta = 0.072$ (b) SES 4 - $\beta = 0.179$

Figure 5.9: Estimated decay functions for walking mode per social strata

Figure 5.9a and 5.9b presents the estimated walking cost functions for social strata 1 and 4. It can be seen that the lowest strata are wiling to walk longer distance to reach their job. The higher income groups do not walk more than 25 minutes and they tend to use other modes beyond this threshold. More than 40% of walking trips for social strata 1 is up to 15 minutes while for social strata 4, this is less than 10 minutes.

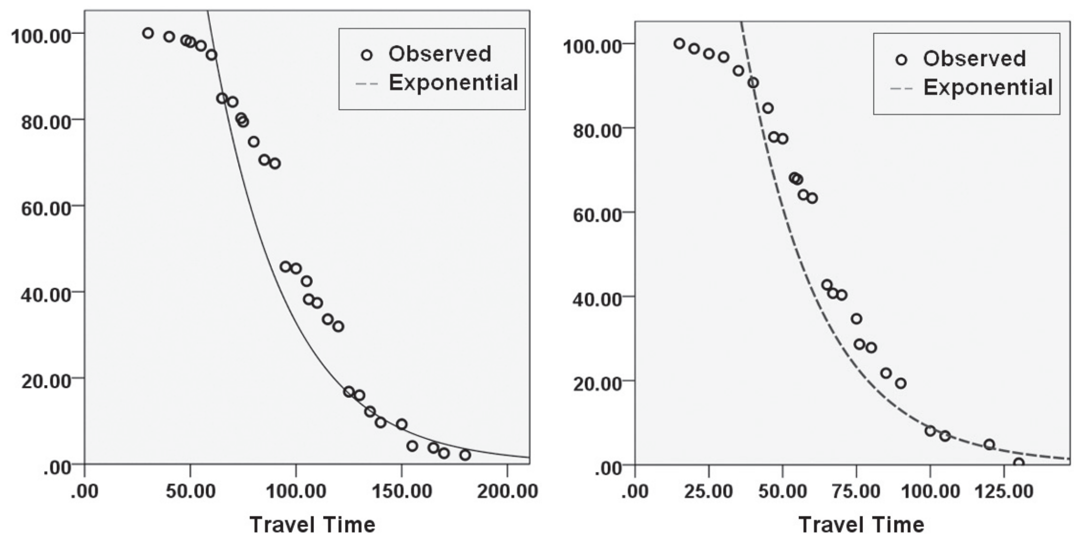


(a) SES 1 - $\beta = 0.038$ (b) SES 4 - $\beta = 0.053$

Figure 5.10: Estimated decay functions for bicycle mode per social strata

The calibrated cost function of bicycle trips for social strata 4 (figure 5.10b) shows that this group is willing to use bicycle for trips shorter than 50 minutes. This threshold is significantly larger for the poorest strata, where they travel up to 90 minutes (see figure 5.10a). Only 10% of these groups travel longer than 60 minutes. More than 80% of bicycle trips are made by higher income groups within 10 minutes, while the same share of trips related to social strata 1 cover more than 15 minutes.

Decay curve for travel time in TM revealed that only 10% of trips made by social stratum 4 are within 90 minutes, where up to 50% of trips related to social stratum 1 are more than 90 minutes. By increasing the travel time, the percentage of people who are willing to travel by TM, sharply declines. In the case of the poor group, only 20% are willing to travel for 120 minutes and no one is willing to travel beyond 180 minutes. Also for the rich stratum, acceptable travel time by TM is 130 minutes. It is notable that both TM functions for trips less than 50 minutes show different behavior. It seems that TM is not a very attractive mode for trips within this threshold and people prefer to use other modes (e.g. TCP and local buses). Indeed, waiting times and lines for boarding TM and overcrowded buses have reduced the TM users' satisfaction. On the other hand, there are no defined stations for local buses and people can get on the buses everywhere along the routes.



(a) SES 1 - $\beta = 0.028$ (b) SES 4 - $\beta = 0.039$

Figure 5.11: Estimated decay functions for TM mode per social strata

Table 5.2 summarizes the estimated cost functions for this study. It appears that, as the income increases, it is less likely to use TM or NMT modes. Because the rich groups value time and comfort more, so they mostly prefer private car to public transport modes. This is consistent with the modal share for social strata which was discussed in section 3.2. Also, for this group, by increasing the experienced cost, the incentive to reduce trip length is strong. This means that the higher strata tend to use faster modes for shorter trips.

Another possible reason may be the spatial distribution of social strata and jobs in the city. Since higher income groups are located closer to employment centers, they do not need to travel far to reach job opportunities. This also explains why the β for social strata 5 & 6 does not follow the pattern: because these groups are the closest to job centers and the corresponding travel distances are very short, possibly within NMT thresholds. This can be confirmed with the walking modal share discussed in 3.2, where this share for social stratum 6 is larger than social strata 5.

Table 5.2 Calibrated β parameters per transport mode and social strata

	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

5.2.4 Estimates of Accessibility

Estimation of final accessibility values proceed after generating cost functions and the desired OD matrices for each pair of residential location and related jobs location. Average speed for each trip was calculated using the accumulated time and length of the trip. This was done to identify intermodal trips from single mode trips and apply the appropriate cost function for each category. In general, if the average speed was more than the assigned speed for NMT mode, it was a clear indication for intermodality (in which case, the TM decay function was applied). Other trips were dealt as a single NMT mode. According to these condition, the cost of trips were calculated using resulting functions.

Attractiveness and the ease of reaching jobs is a function of travel cost. In this study, for each social group, accessibility was estimated as the sum of the jobs indicator, discounted by the corresponding decay function. The summed jobs indicator only included those areas in which the corresponding stratum had access to jobs (refer to section 5.2.1). To ease the interpretation and communication of the results, the values were normalized by the total number of jobs indicators for each social strata.

5.3 ANALYSIS OF ACCESSIBILITY RESULTS

The accessibility results were calculated for three scenarios. Each scenario represents a different level of integration between bicycle and TM. The base scenario includes no integration (which is to say only walking and TM modes are part of the network). Two additional scenarios were developed to simulate bicycle integration. The first integration scenarios introduced bicycle in the first stage of TM trips (from origins, home to TM stations). In the second integration scenario, bicycle was involved in both ends of the TM trips (from origin to TM stations and from TM system to final destination).

The following sections discuss the resulted accessibility levels across social groups under these three scenarios.

5.3.1 Base Scenario

Since currently there is no meaningful bicycle integration in the city, the base scenario reflects the existing level of integration. Figure 5.12 combines the resulting accessibility for five social strata across the city. It can be seen that, moving from the fringe of the city towards the center, the accessibility level increases. This is the consequence of the spatial arrangement of activities across the city, especially the high concentration of jobs.

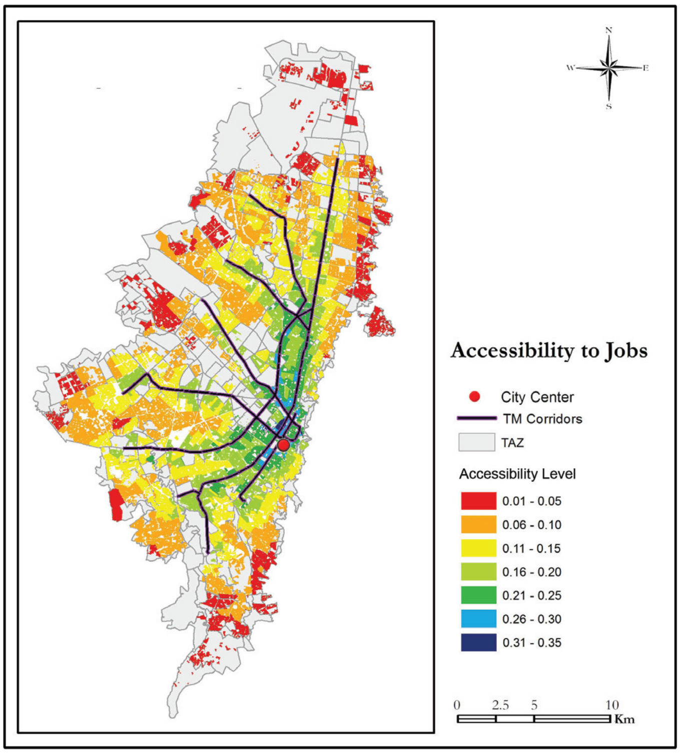


Figure 5.12: Accessibility to jobs through combination of walking and TM

Moreover, the resulting accessibility shows variation across the social strata groups. Table 5.3 summarizes the calculated average accessibility per social strata. In general, as the income increases, so does the accessibility. The exception for this pattern is SES 5&6, which also present the higher coefficient of variation.

Table 5.3 Summary of resulted average accessibility for base scenario per social strata

Walking - TM-Walking

	Average Accessibility	CV
SES 1	0.099	0.524
SES 2	0.119	0.541
SES 3	0.138	0.484
SES 4	0.139	0.528
SES 5&6	0.087	0.601

* CV is the coefficient of variation

SES 5 & 6 are associated with the lowest level of accessibility. This can be explained by the fact that, most of the origins and destination for these groups are located at the closest distance to each other (compare to other SES groups). Therefore a large proportion of work trips are very short. On the other hand, these zones can benefit from less number of TM corridors. Due to low access to TM and considering waiting time for TM trips, in the real world, the higher income groups complete the relatively short trips with other modes (mostly private cars). In the modeled scenario the only alternative mode to TM is walking. Since the trips in the model are assigned to the lowest cumulative travel time without considering the decay function, The model likely considers those trips as walking trips. The cost generated by these trips was estimated very high, because the discount of the walking decay function is much greater than the equivalent discount of TM decay function. As a consequence of this, the resulted accessibility for this groups is very low. Also, for this group there are few zones (in north fringe of the city), which are far from job centers and TM corridors. This is the reason for the highest variation in the accessibility results. The spatially disaggregated results per social are presented in figures 5.14 to 5.18.

Central zones which correspond with SES 4 and 3 have the highest level of accessibility. One possible explanation is that, the two social groups live relatively close to their job centers. Also, they are located along the TM corridors and they have better access to this system. They can reach TM with short walking distances. This is an indication of a spatial match between land use and transport system for these groups (under the defined conditions).

SES 1 and 2, which mostly reside in peripheral zones, experience very low accessibility. These groups are located within the largest distances to corresponding job centers (relatively to other SES groups), and they need longer trips to reach their workplaces. Additionally, TM has less to no coverage in these zone (especially SES 1). In consequence, the access to TM stations requires longer walking trips for SES 1 and 2 than any other strata. This increases the overall cost of the trips made by this groups. In the real world, some of these trips are made by other buses and the time saving would be compensated by the fare cost, which would be added to the generalized cost of the trips.

In general, within each strata, as the distance from the city center increases, the accessibility decreases. Moreover, the TM network is denser near the city center. This suggests that, proximity to TM corridors also can increase the accessibility of each zone. However, this variation differs across strata groups. As scatter plots 5.13 describes, the reduction of accessibility as the distance from the center increases, is larger for higher income zones than the other strata (e.g. the trend line for stratum 4 has sharper slope compared to that of stratum 2).

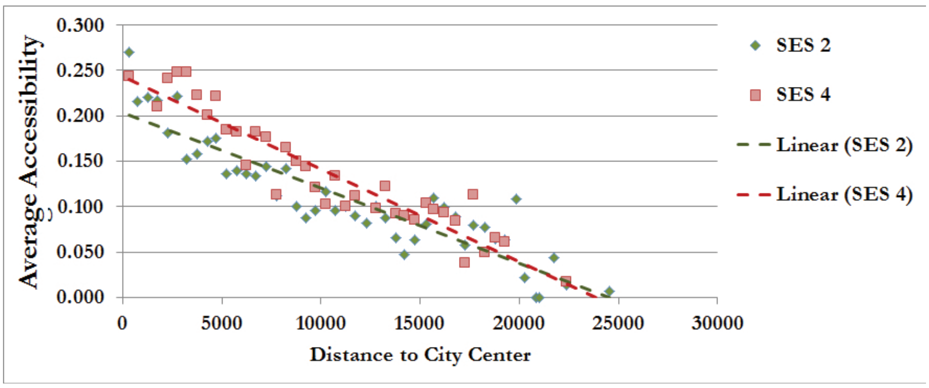


Figure 5.13: Average accessibility vs. average distance to the city center, comparison of TAZ corresponding to strata 2 and 4

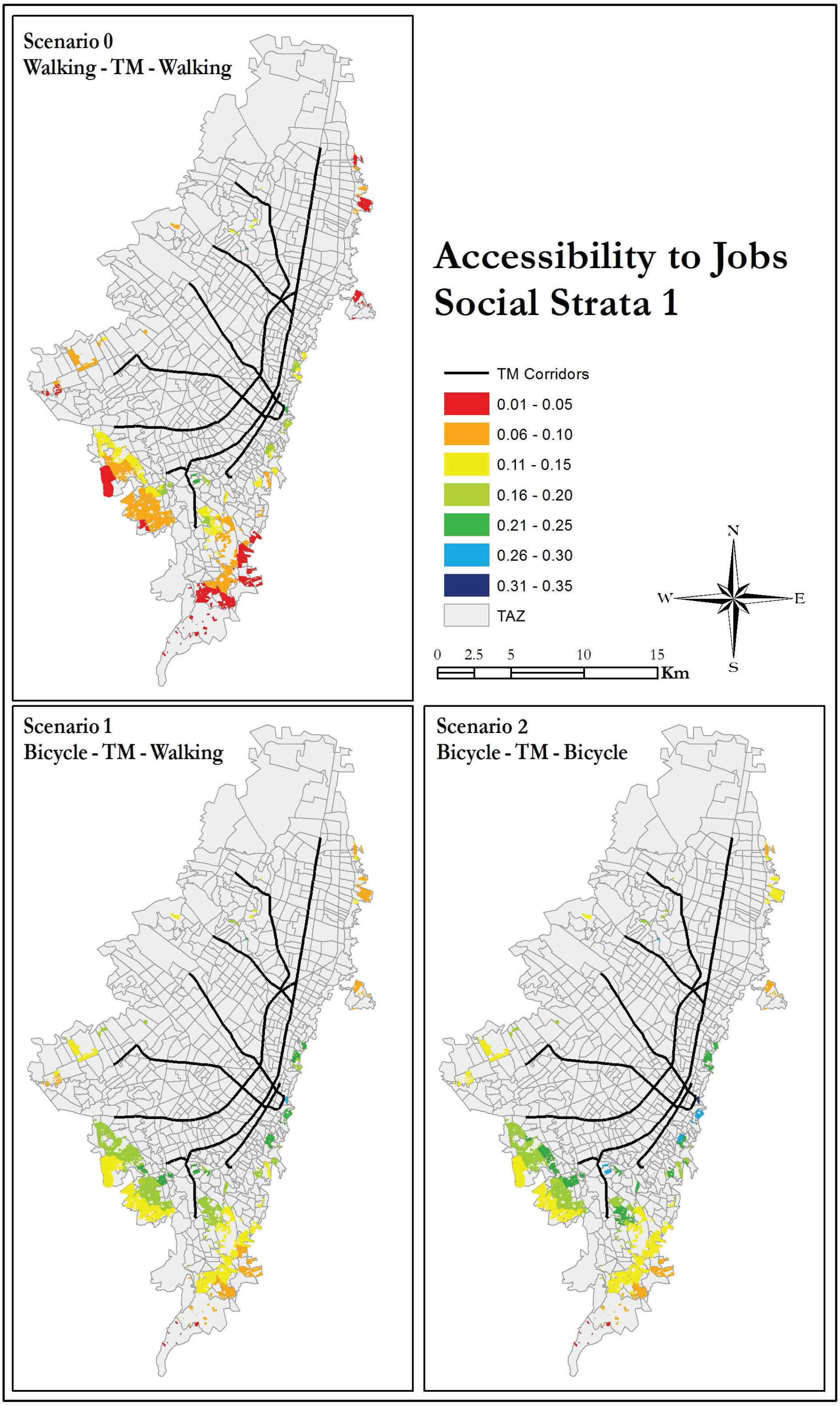


Figure 5.14: Accessibility to Jobs for social Strata 1 under 3 scenario.

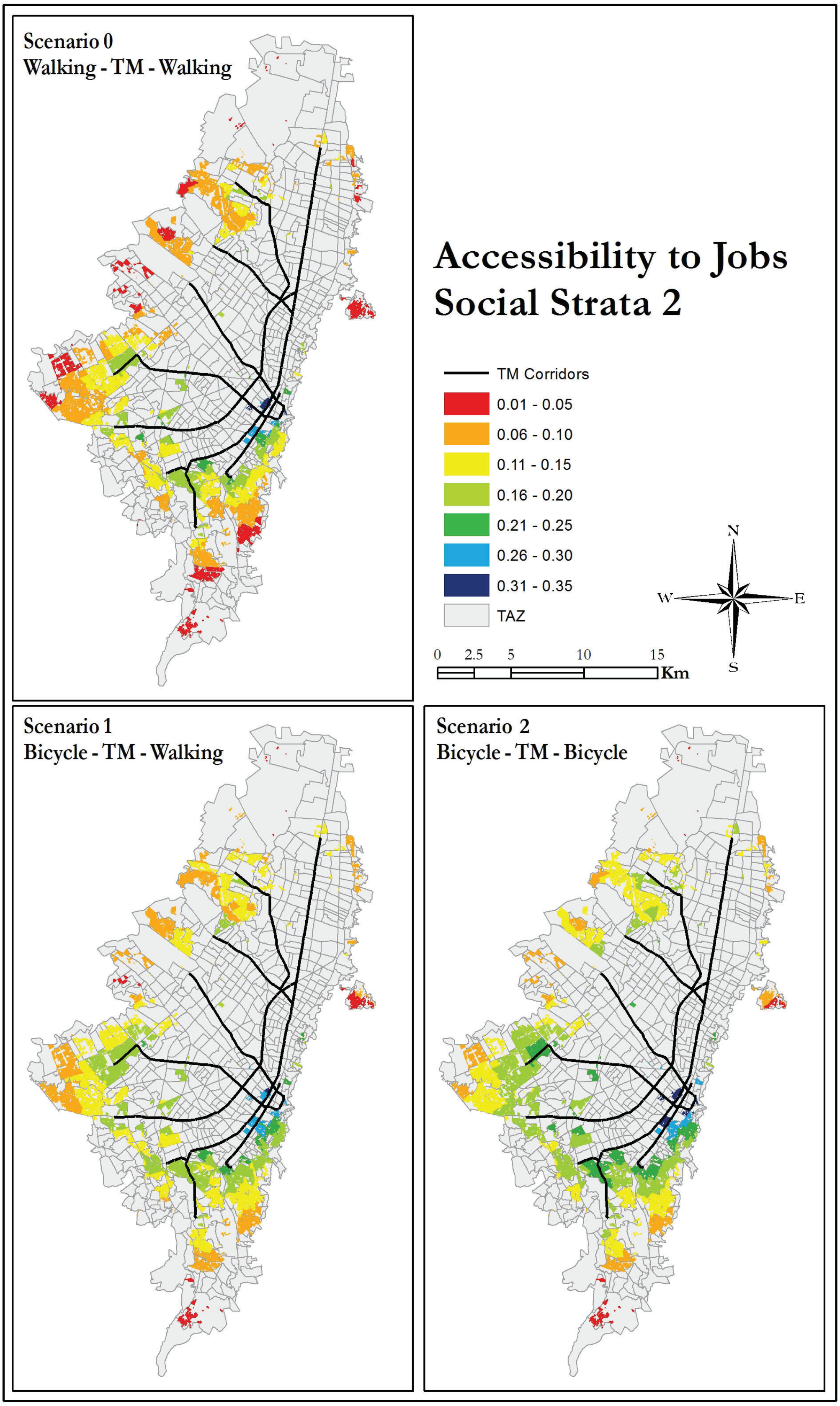


Figure 5.15: Accessibility to Jobs for social Strata 2 under 3 scenario.

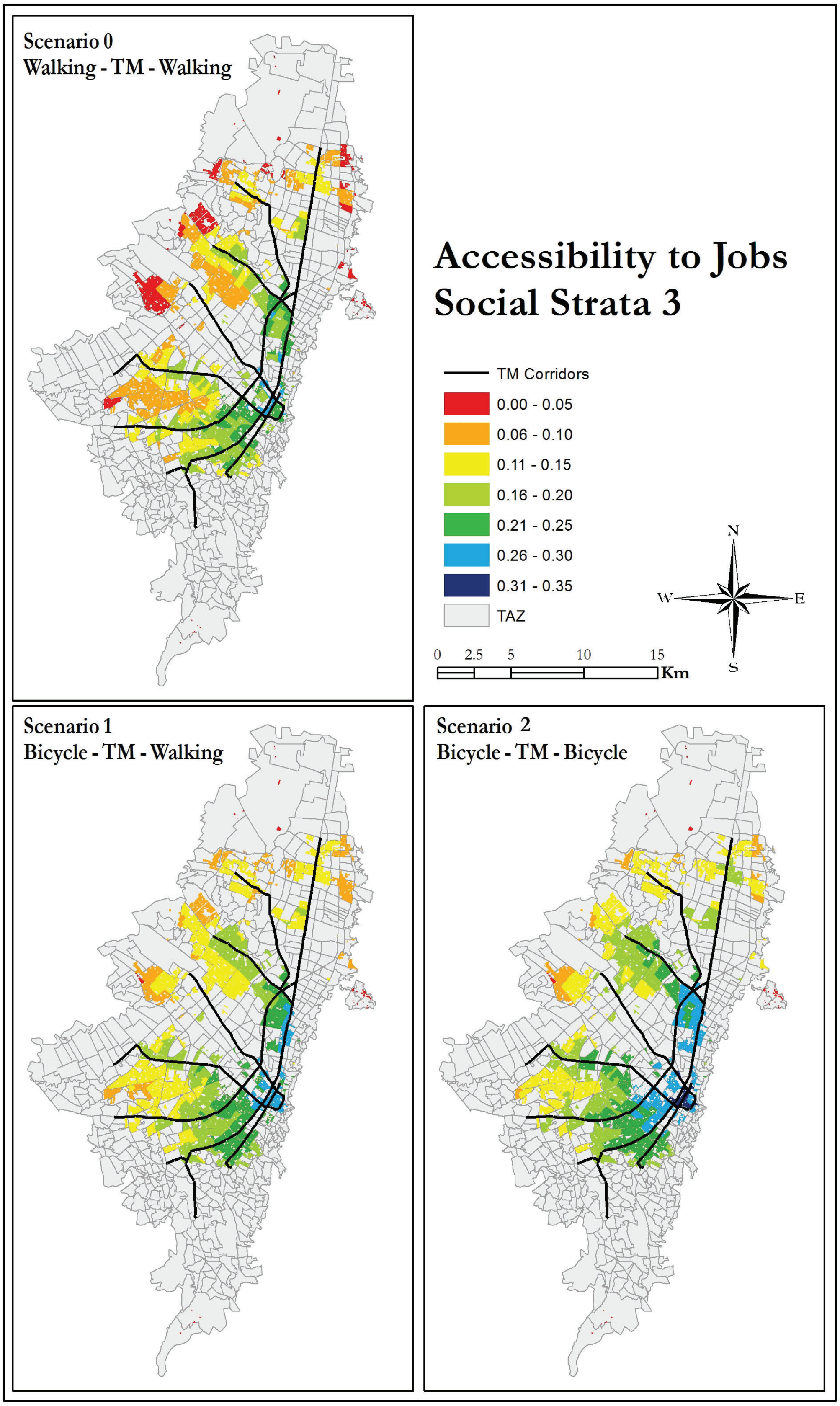


Figure 5.16: Accessibility to Jobs for social Strata 3 under 3 scenario.

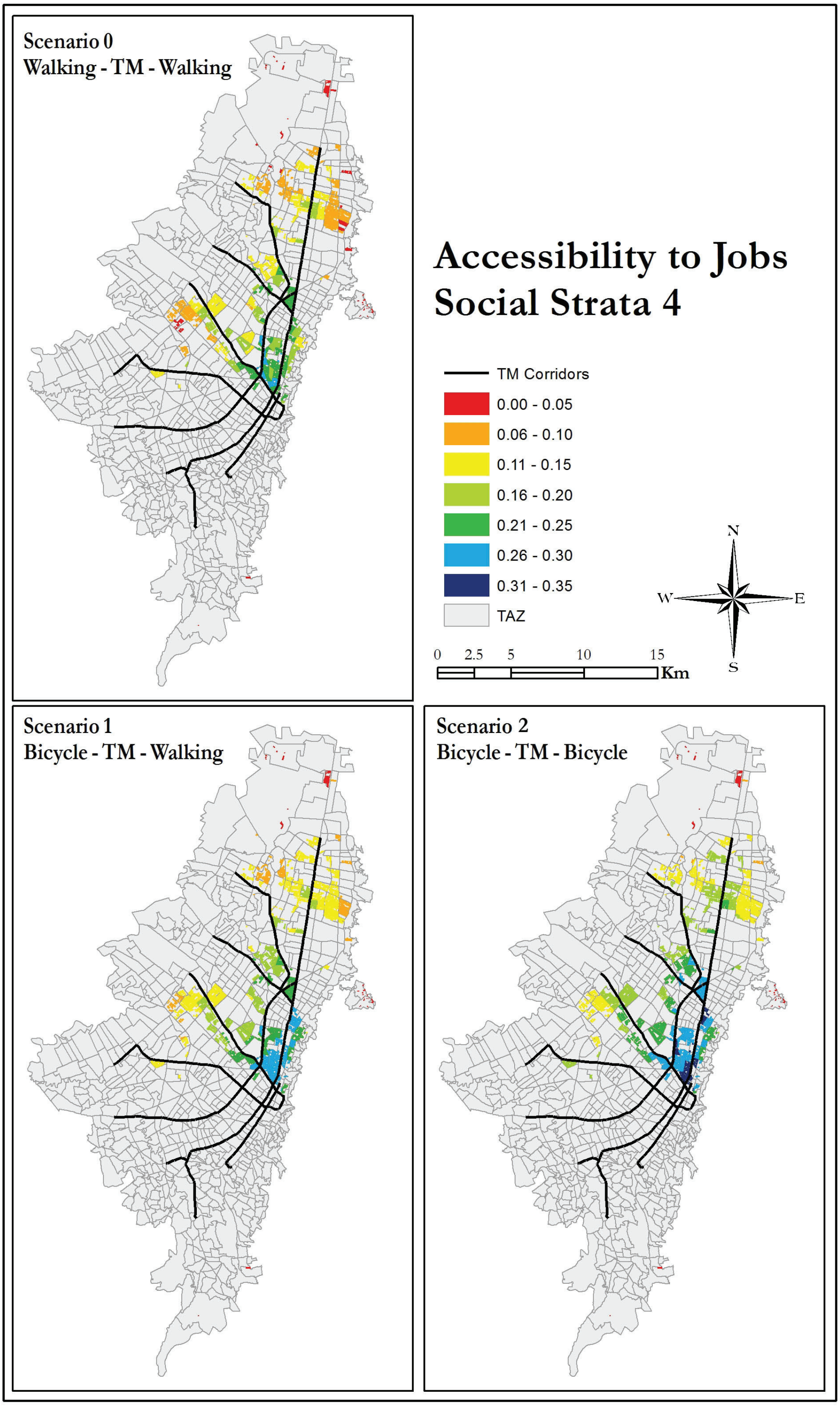


Figure 5.17: Accessibility to Jobs for social Strata 4 under 3 scenario.

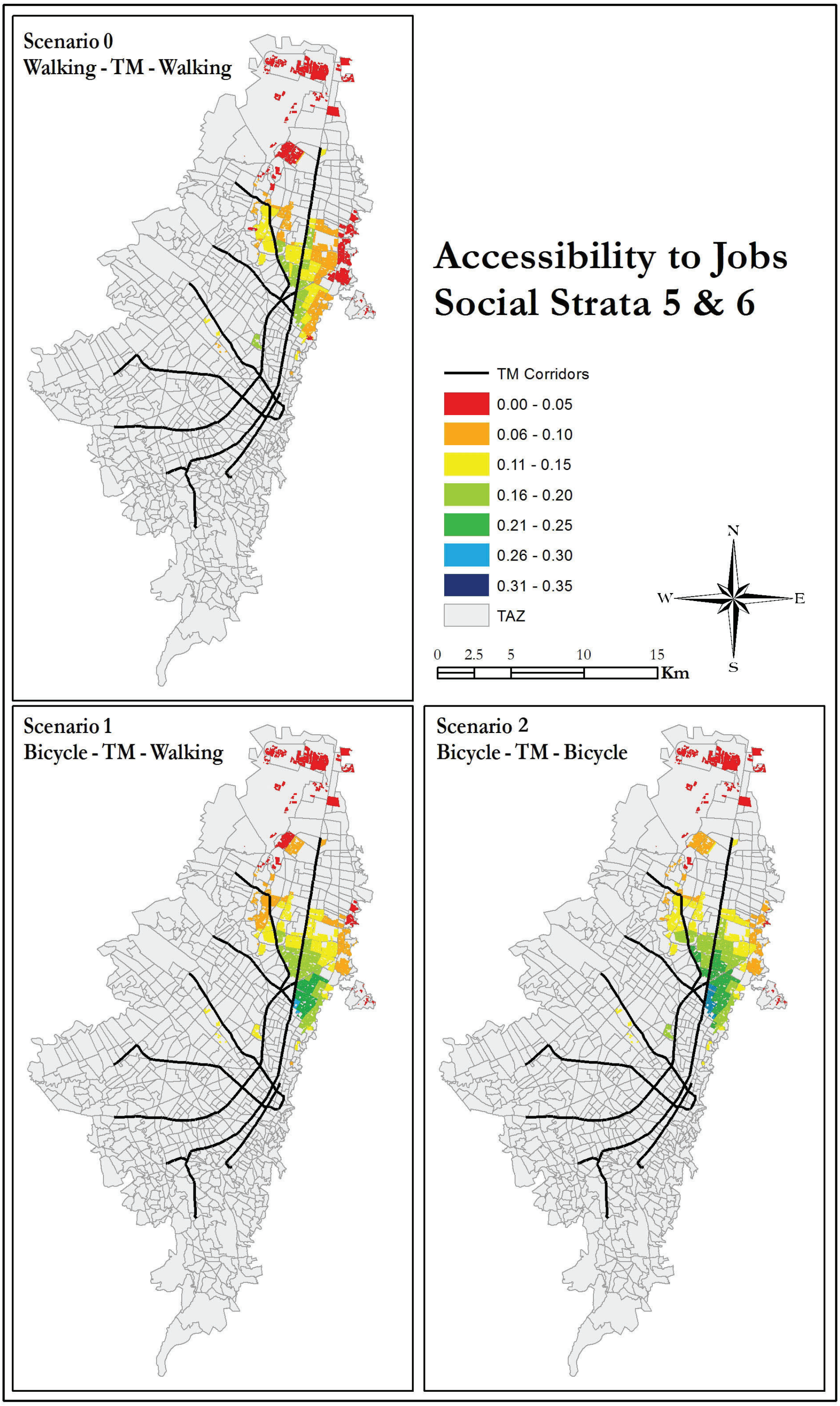


Figure 5.18: Accessibility to Jobs for social Strata 5 & 6 under 3 scenario.

5.3.2 Integration Scenarios

Accessibility results were calculated by integrating bicycle in TM trips under two scenarios. The first scenario included bicycle in the first stage of trips as the access mode to TM system. The second scenario simulated the full integration for bicycle, where it could be used in the first and the last stage of TM trips. The resulting accessibility for each social strata is presented in figures 5.14 to 5.18.

Overall, the results show that all social groups benefit from bicycle integration in the system. According to table 5.4, those groups which had the lowest accessibility level in the base scenario experience the greatest gain with both integration scenarios.

Table 5.4 Summary of resulting accessibility for 5 social strata, under 3 scenario

	Walking - TM - Walking		Bicycle - TM - Walking		Bicycle- TM- Bicycle	
	Average Accessibility	CV	Average Accessibility	CV	Average Accessibility	CV
SES 1	0.099	0.524	0.156	0.315	0.170	0.317
SES 2	0.119	0.541	0.143	0.377	0.165	0.373
SES 3	0.138	0.484	0.162	0.373	0.185	0.351
SES 4	0.139	0.528	0.169	0.435	0.193	0.393
SES 5&6	0.087	0.601	0.122	0.543	0.141	0.483

*CV is the coefficient of variation or normalized of dispersion for calculated average values

SES 1 presents the largest increase in accessibility. This is due to their location and jobs distribution pattern, which results in a large proportion of TM based trips. Additionally, they need to travel longer distances to reach the TM system. Therefore, bicycle as a faster mode (compare to walking) considerably reduces the cost of these trips and improves the accessibility for the associated zones.

The second largest gain of accessibility corresponds with SES 5 &6. As it was explained for this group the close proximity between origins and destinations implies a larger proportion of NMT trips (the share that do not involve TM), leading to a very low accessibility. Because the base scenario accessibility for SES 5 &6 is very low and bicycle NMT trips are much faster than walking NMT trips, the accessibility gain for this group is large. This can be confirmed by table 5.5, where the proportion of the bicycle based trips is the largest for this group.

Table 5.5 Summary of bicycle based and TM based trips under 2nd scenario

Trips	**Bicycle based**			**TM based**		
	% of total trip	Average Travel Time (min)	Average Length (m)	% of total trip	Average Trip Time (min)	Average Travel Trip Length (m)
SES 1	31.05%	56.40	8044.61	68.95%	82.00	20709.48
SES 2	31.89%	52.97	7716.93	68.11%	75.88	19664.39
SES 3	33.88%	45.31	6650.28	66.12%	65.56	16880.88
SES 4	37.19%	43.75	6493.59	62.81%	64.31	16057.81
SES 5&6	45.46%	44.30	6555.26	54.54%	64.05	15542.06

Figures 5.19 to 5.22 compare the resulting average accessibility for each strata in relation to corresponding average distance to the city center. This distance was estimated through the network. From these figures it can be seen that, in general, the difference between the base scenario

and integration scenario 1 is larger than the difference between integration scenario 1 and 2 (by the way in which they were specified, the base scenario has lower accessibility than integration scenario 1, and integration scenario 1 has less accessibility than integration scenario 2). The first scenario represents the gain from introducing bicycle in the first stage of the TM trips (from home to TM station). Most of the accessibility increase predicted by both scenarios occurs at this stage. This also suggests that for the majority of Bogotá citizens, the access trips to TM are longer than the trip from TM to their job destinations. In other words, TM system has better coverage in relation to jobs than residential locations. This could be explained by monocentric form of the city where, jobs are mostly concentrated around the city center, and the TM corridors also have the best coverage near to this center.

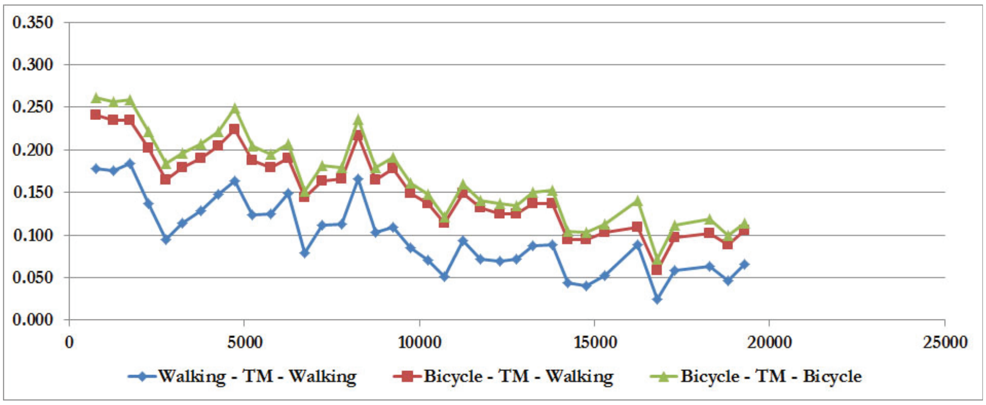


Figure 5.19: The resulting accessibility under 3 scenarios per SES 1

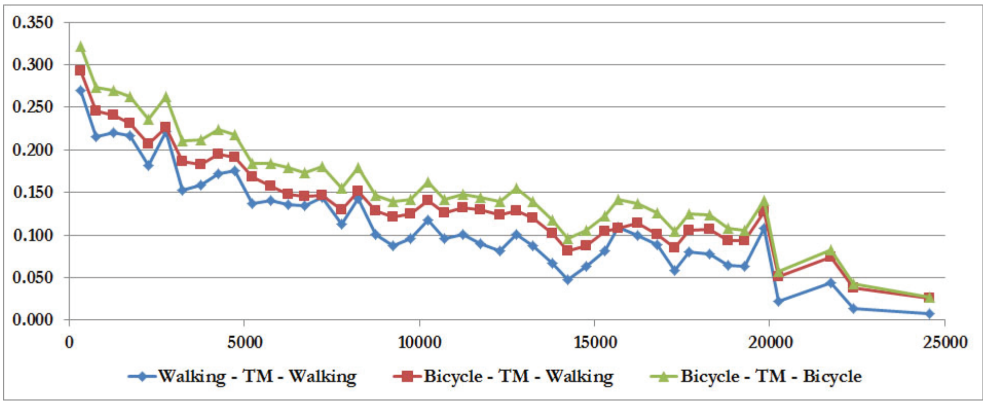


Figure 5.20: The resulting accessibility under 3 scenarios per SES 2

Moreover, comparing the two integration scenarios shows that the introduced increase in accessibility is related to spatial location of each strata. The first integration condition creates more positive impacts for the poor social strata groups. The second scenario benefits the higher income more. The zones closer to the city center show a larger difference with respect to integration scenario 1, than the zones which are located farther from the city center. Additionally, these groups live relatively close to TM corridors and have very short access trips. Therefore the last stage of trips would more determining in relation to overall cost ot the TM trips. In the case of poor social groups (especially SES 1), the access parts of the trips are dominant and the gain related to the last stage of trips is very less. On the other hand, this group live in peripheral zones and due to higher travel cost or type of available jobs in the center they are less likely to travel to the center.

It is interesting to see that, even within the higher income groups, the impact of this full integration markedly varies across the zones. From the presented patterns in the figures 5.20 to 5.22, by moving towards the central zones, the impact of bicycle use in the last stage of the trips become more significant.

It is notable that the fluctuation in the resulting average accessibility is due to network effect. The road structure or presence of TM portal could result in considerable difference in the accessibility of the zones within the same strata and distance from the city center.

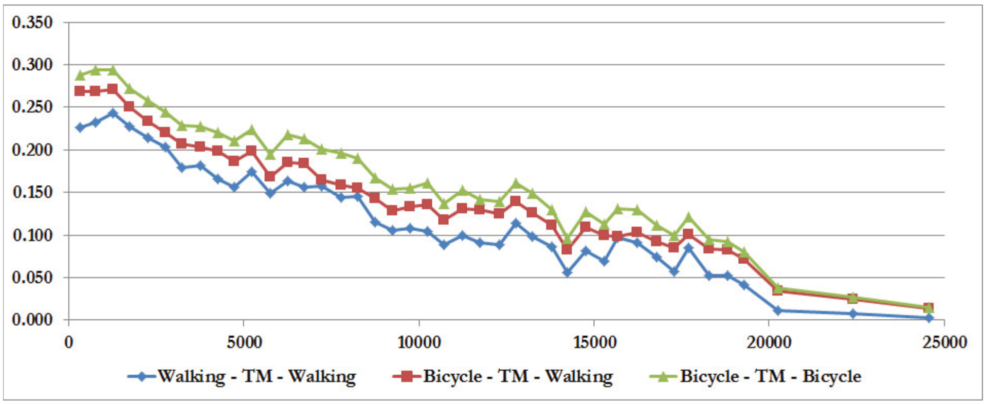


Figure 5.21: The resulting accessibility under 3 scenarios per SES 3

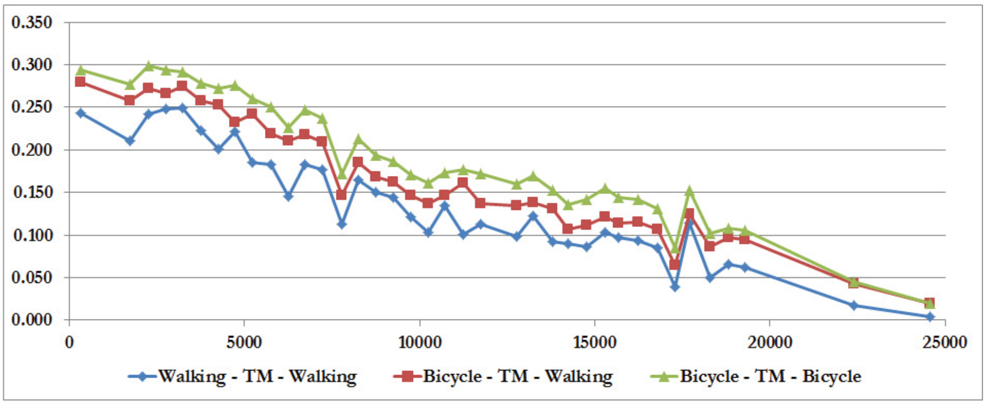


Figure 5.22: The resulting accessibility under 3 scenarios per SES 4

Chapter 6

Conclusions and Recommendations

6.1 REMARKS FOR BICYCLE INTEGRATION IN THE CITY OF BOGOTÁ

In this study, the potential for integration of bicycle and TransMilenio was investigated for the city of Bogotá. Accessibility to jobs was modeled under three bicycle integration scenarios and used to assess the impact of the integration across five social strata.

The resulting accessibility under base scenario, which assumes no bicycle integration and reflects the current operation of the system, was linked to the level of income as a social factor and distance from the city center as a spatial factor. The higher income groups experience better accessibility. However, the social strata 5 & 6 was an exception to this pattern. Moreover, within each strata proximity to the city center is associated with higher accessibility.

Overall, the results from accessibility analysis suggest that bicycle integration show a high potential for improvement in the city of Bogotá. In relation to each strata different policies are more effective. For the poor strata, which are clustered in the peripheral zones and far from TM portals, involving bicycle in the access part of trips to TM stations produces greater impact. Developing bicycle parking facilities is a more efficient policy choice for these groups. In relation to the higher income strata, since they are more centrally located, the stage of the trips from TransMilenio stations to the final destinations becomes more important. Thus, a bike sharing system may be an appropriate option.

Regarding the variation of accessibility gain with distance, within the same stratum, two general characteristics have been derived. The difference between the base scenario and the first integration scenario (which involves bicycle only in the first stage of the TM trips) is larger for the zones located farther from the city center. On the other hand, the accessibility increase of the second integration scenario (which involves bicycle in both ends of the TM trips) with respect to the first integration scenario is larger for the zones that are closer to the city center.

The desirability of different modes was found to differ between different strata. This was introduced into the accessibility analysis using different decay functions for each social group per modes of transport to discount the negative effect of longer travel time on job accessibility. The lower income groups tend to use NMT modes more frequently, they are also less sensitive to the negative effect of distance.

The current intermodal behavior in the city, in terms of physical(infrastructure) potential as well as user perspective, was explored through field surveys. These provided information that informed the network analysis. The main conclusions included: First, citizens perspective towards cycling is related to their income level. The lower income groups are more likely to use bicycle as a mode of transport, while the higher income groups consider cycling as a recreational activity. In the cases that bicycle was used as a transport mode, it was mostly not used in combination with other modes. The few cases of combining bicycle and TM only occurred in the stations with bicycle parking facility. Safety and security were perceived as discouraging factors for cycling. Improvements on the discontinuity of the Cicloruta network might address some of the safety concerns by reducing the risks of accidents.

6.2 DISCUSSIONS ON FIELD SURVEYS

Every survey can have its imperfections. In this study, due to the time constraints and limited resources, designed surveys in the field faced some shortcomings. What has been presented in the chapter 4 is the collected data and what could be analyzed only within the very limited period.

The initial objective of survey was to interview random TM passengers on the stations platform, which could capture the current proportion of TM users who use bicycle to reach TM stations. However, direct observations in the field and the test survey revealed this proportion can not be capture within available time and sources. In order to record responses from this proportion, an adjustment was made in administering the interviews. From the total time devoted to each TM station, one third was allocated to interview cyclists in bicycle parking area.

Another important barrier was the language. However, both questioners were translated into local Spanish and TM survey was conducted with local assistance. It was found out that, some questions were not clearly understood. When people were asked only about access part of their trip, many responses were about the entire trip. For instance, for questions NB4 and NB5 in both surveys (which are documented in appendices A and B), there were many records that the distance is too far to use bicycle. It was observed that some of these respondents were the group who had walk to the TM station. Moreover, this is an indication for people attitude towards bicycle use as a transport mode.

Also, the responses to the question regarding recommendation was very poor. Most of the answers repeated the choices from barriers sections. For the case of TM surveys, this could be due to the nature of short interviews. On the other hand, the survey needed to fit into the waiting time.

6.3 DISCUSSIONS ON NETWORK MODELING AND ACCESSIBILITY ANALYSIS

To model the network in ArcGIS environment each transport mode was associated with a separate set of features. The Network Analyst uses these feature as a source layer to identify the location of trips origins and destinations. However, the limitation of this tool is that the algorithm can locate origins and destination within only one source feature. The tool is able to generate an optimum route only when a trip starts and ends with the common source feature. This means that the trips should start and end with the same mode. These trips can be combination such as; walking-PT-walking or bicycle-PT-bicycle. This was recognized as a limitation to deal with s trips which involves different feature at two ends of a trip. This study used another approach to model the trips with combination of bicycle-PT-walking.

The generated OD matrix by ArcGIS Network Analyst tool only includes the length and the total time from each origin to each destination. The applied approach in this study could provide these details for each stage of a multimodal trip. This way it was possible to distinguish the NMT trips from TM and apply the appropriate decay function. In the case of base scenario and the second integration scenarios, the final OD matrix was generated by using the network analyst tool. Therefore, average speed of trips was used as a criteria to apply decay functions. Comparing the resulted accessibility under the three scenario suggest that average speed was not a perfect criteria. In fact, the waiting time in addition to required time for parking or removing the bicycle could result in a TM trips with very low speed. This is more likely when the access trips by bicycle are made through normal segment which associated with lower speed compare to Cicloruta segments.

As mentioned earlier, this research was based on the available data and within a limited time. Therefor, to complete the objectives making some assumptions was inevitable. Modeling the TM network was a process based by assuming that all the routes have the same speed. Future studies may include the TM lines with more details (separated express and normal lines).

In this study, mobility survey record were analyzed to estimate the decay functions. This sample is not very large and some of resulted function statistically are not significant (specially for SES 4, 5 &6). Yet, the estimated functions could represent the general pattern of trips.

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Appendix A

Designed questionnaire for university survey

	Intermodality Questionnaire -2	No.	**a**
	This survey is conducted as part of a M.Sc. research project. The aim of this research is to investigate use of bicycle to reach TransMilenio stations in the city of Bogota. We would appreciate your taking the time to complete the following questionnaire. The information you provide will be used to improve knowledge about transport system in the city. Your answers will be completely confidential and will be used only for statistical purposes.		
	University Name:	Age:	Sex:

A

How do you reach your university form your home? Please describe different stage of your trip to university by type of transport mode and duration.

Transport modes = Walking/cycling/Feeder buses/ Transmilenio

Stage	From (Origin) Street / station	To (Destination) Street / station	Transport Mode	Duration (minutes)

1. If your trip is done completely or partly by Transmilenio, How do you choose the origin /end station?
- ☐ It is the only possible option
- ☐ It has bicycle parking
- ☐ It is the closest to my home
- ☐ It is a portal, so and I can seat in the bus
- ☐ There are several options of routes to my destination from here
- ☐ Other ……………………………………………………………………………………………………….

2. How did you reach this Transmilenio station?
- ☐ Walking
- ☐ Bike Feeder
- ☐ Other ……………………………………………………………………………………………………….

If you use "Transmilenio and bike" at some stage of your journey to the college, please answer the following questions. Otherwise please continue with section C or D.

B

BT1. How long did it take to get to this station from the origin of your trip? ….min

BT2. Do you mostly bike through cicloruta? ☐ Yes ☐ No

BT3. Why do you choose this rout?
- ☐ No violence
- ☐ Shortest
- ☐ Fastest
- ☐ Less accidents
- ☐ Other ………………………………………………………………...……………………………

Figure A.1: Sample of designed questionnaire for university survey

	BT4. How Far do you bike from your home to reach cicloruta? ……. min
	BT5. Where do you park your bike? Station parking ☐ other................ BT6. How much is the parking fare? ☐ Free ☐ Parking fare ………………… BT7. Why do you park there? ....
	If you use ONLY bike to get to university, please continue with the following questions.
C	B1. How long does it take to get to the university from the beginning of your trip? ..... min B2. Do you mostly bike through cicloruta? ☐ Yes ☐ No B3. Why do you choose this rout? No violence ☐ Shortest ☐ Fastest ☐ Less accidents ☐ Other ………………………………………………………………………………………………………. B4. How Far do you bike from your home to reach cicloruta? ……. min B5. Where do you park your bike? ☐ Station parking ☐ other................ B6. How much is the parking fare? ☐ Free ☐ Parking fare ……………………………………… B7. Why do you park there? ....
	If you do Not use bike for any part of your trip, please answer following questions.
D	NB1. Do you have access to a bicycle? ☐ Yes ☐ No NB2. Can you ride a bike? ☐ Yes ☐ No NB3. Have you ever considered biking to reach station? ☐ Yes ☐ No NB4. What are the reasons for not biking to reach TransMilenio station? ☐ It is too far by bike ☐ I do not afford a bicycle There is No cicloruta ☐ Bad bicycle path quality Weather condition ☐ Steep and hilly area ☐ Other: ☐ Exposing to Violence ☐ Exposing to accidents ☐ No parking inside the station ☐ No safe parking facility ☐ No free parking ☐ It takes too long to park the bicycle ……………………………………………………………………………………………………...…… NB5. What could be done to use bicycle to reach this station? ……………………………………………………………………………………..………… No. | b

Figure A.2: Sample of designed questionnaire for university survey

Appendix B

Designed questionnaire for TM stations survey

	Intermodality Questionnaire - 1	No.	a

This survey is conducted as part of a M.Sc. research project. The aim of this research is to investigate use of bicycle to reach TransMilenio stations in the city of Bogota. We would appreciate your taking the time to complete the following questionnaire. The information you provide will be used to improve knowledge about transport system in the city. Your answers will be completely confidential and will be used only for statistical purposes.

TM Station Name:	Age:	Sex:

A

1. How did you reach this Transmilenio station?
☐ Walking
☐ Bike Feeder
☐ Other.................

2. What is your destination station? ....

3. How many times per week do you do this trip? ....

4. What is the motive for this trip? ....

5. Why did you select this station TM?
☐ It is the only possible option
☐ It has bicycle parking
☐ It is the closest to my home
☐ It is a portal, so and I can seat in the bus
☐ There are several options of routes to my destination from here
☐ Other ....

If the answer to question 1. was "Bike", Please continue with the following questions. Otherwise Please answer the questions in section C.

B

B1. How long did it take to get to this station from the origin of your trip? ….min

B2. Do you mostly bike through cicloruta? ☐ Yes ☐ No

B3. Why do you choose this rout?
☐ No violence
☐ Shortest
☐ Fastest
☐ Less accidents
☐ Other ....

B4. How Far do you bike from your home to reach cicloruta? ……. Min

B5. Where do you park your bike?
☐ Station parking
☐ other...............

Figure B.1: Sample of designed questionnaire for TM stations survey

B6. How much is the parking fare? ☐ Free ☐ Parking fare …………………

B7. Why do you park there? ……………………………………………………………………………

If the answer to question 1. was NOT "Bike", Please continue with the following questions.

C

NB1. How long does it take to reach this station per each of modes? ……… min

NB2. Do you have access to a bicycle? Yes No

NB3. Can you ride a bike? Yes No

NB4. Have you ever considered biking to reach station? ☐ Yes ☐ No

NB5. What are the reasons for not biking to reach this station?

☐ It is too far by bike
☐ I do not afford a bicycle
☐ There is No cicloruta
☐ Bad bicycle path quality
☐ Weather condition
☐ Steep and hilly area
☐ Other:
☐ Exposing to Violence
☐ Exposing to accidents
☐ No parking inside the station
☐ No safe parking facility
☐ No free parking
☐ It takes too long to park the bicycle

………

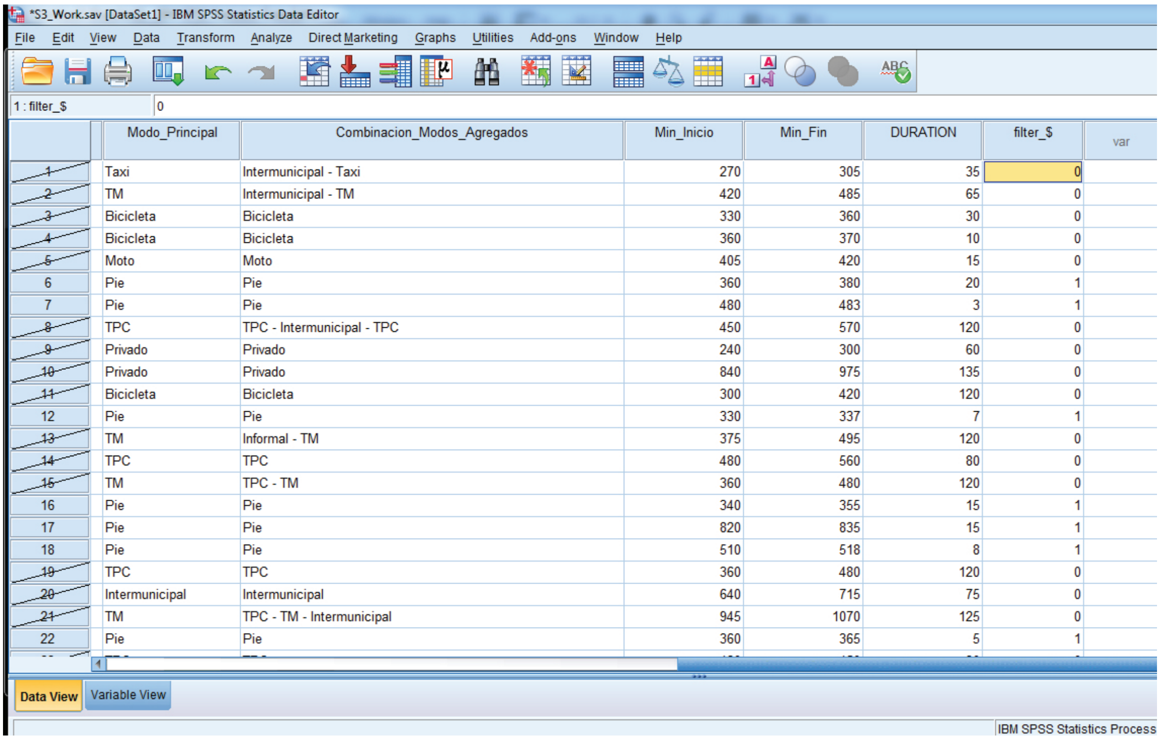
NB6. What could be done to use bicycle to reach this station?
………

No. **b**

Figure B.2: Sample of designed questionnaire for TM stations survey

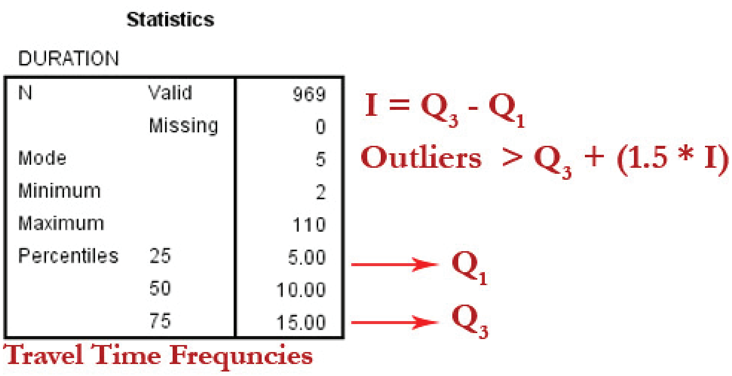
Appendix C

Decay Function Calculations



	Modo_Principal	Combinacion_Modos_Agregados	Min_Inicio	Min_Fin	DURATION	filter_$	var
1	Taxi	Intermunicipal - Taxi	270	305	35	0	
2	TM	Intermunicipal - TM	420	485	65	0	
3	Bicicleta	Bicicleta	330	360	30	0	
4	Bicicleta	Bicicleta	360	370	10	0	
5	Moto	Moto	405	420	15	0	
6	Pie	Pie	360	380	20	1	
7	Pie	Pie	480	483	3	1	
8	TPC	TPC - Intermunicipal - TPC	450	570	120	0	
9	Privado	Privado	240	300	60	0	
10	Privado	Privado	840	975	135	0	
11	Bicicleta	Bicicleta	300	420	120	0	
12	Pie	Pie	330	337	7	1	
13	TM	Informal - TM	375	495	120	0	
14	TPC	TPC	480	560	80	0	
15	TM	TPC - TM	360	480	120	0	
16	Pie	Pie	340	355	15	1	
17	Pie	Pie	820	835	15	1	
18	Pie	Pie	510	518	8	1	
19	TPC	TPC	360	480	120	0	
20	Intermunicipal	Intermunicipal	640	715	75	0	
21	TM	TPC - TM - Intermunicipal	945	1070	125	0	
22	Pie	Pie	360	365	5	1	

Figure C.1: Selection of work trips based on the transport mode and SES



Statistics

DURATION

N	Valid	969
	Missing	0
Mode		5
Minimum		2
Maximum		110
Percentiles	25	5.00
	50	10.00
	75	15.00

Figure C.2: Excluding outlires from the calculations

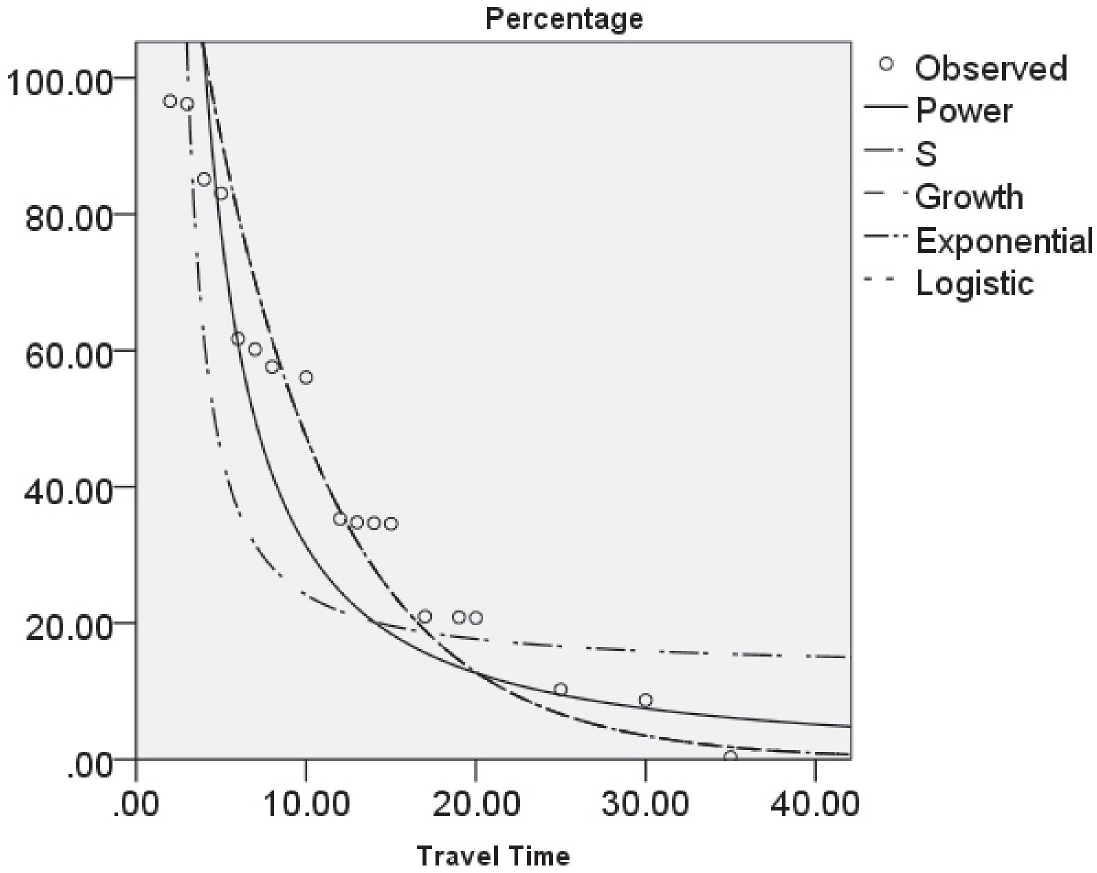


Figure C.3: Estimated different functions for the curve fit

Model Summary and Parameter Estimates

Dependent Variable: Percentage

Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Power	.606	24.641	1	16	.000	633.595	-1.306
S	.328	7.796	1	16	.013	2.558	6.257
Growth	.838	82.726	1	16	.000	5.168	-.131
Exponential	.838	82.726	1	16	.000	175.545	-.131
Logistic	.838	82.726	1	16	.000	.006	1.140

The independent variable is Travel Time.

Figure C.4: Model summeray of estimated functions

Appendix D

Details of Applied Decay Functions

Model Summary and Parameter Estimates

Dependent Variable: Frequency

Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Exponential	.866	291.312	1	45	.000	430.134	-.030

The independent variable is Travel Time.

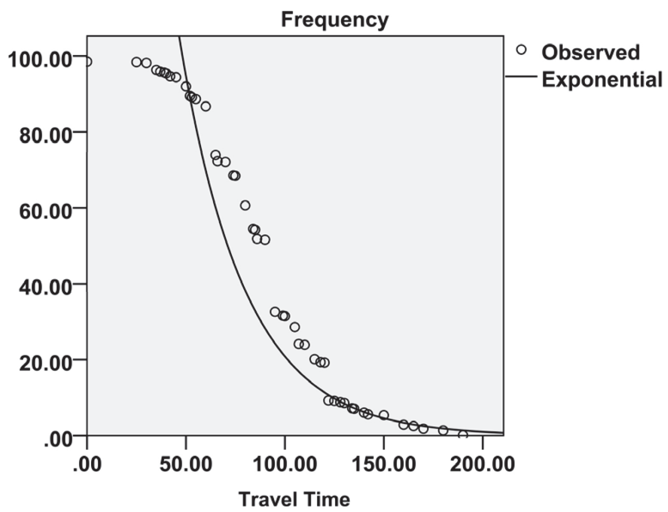


Figure D.1: Estimated decay function for TM mode per SES 2

Model Summary and Parameter Estimates

Dependent Variable: Frequency

Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Exponential	.941	493.566	1	31	.000	147.768	-.053

The independent variable is Travel Time.

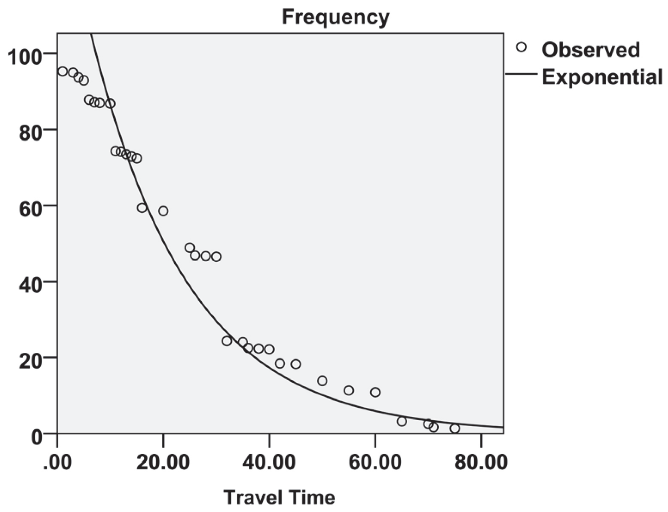


Figure D.2: Estimated decay function for bicycle mode per SES 2

Model Summary and Parameter Estimates

Dependent Variable: Frequency

Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Exponential	.974	813.750	1	22	.000	130.887	-.104

The independent variable is Travel Time.

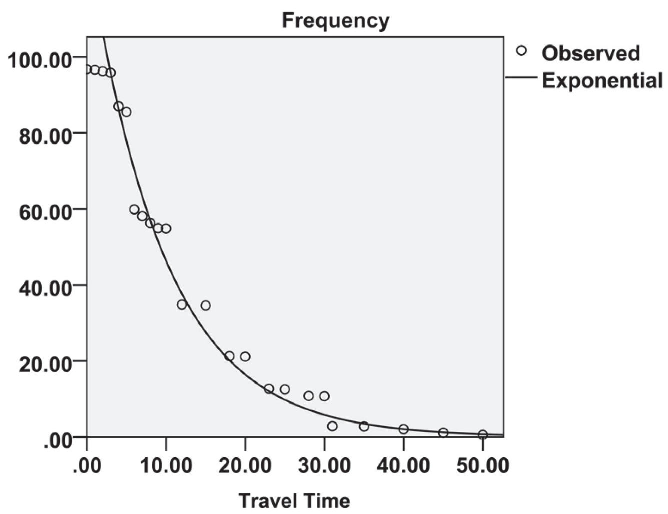


Figure D.3: Estimated decay function for Walking mode per SES 2

Model Summary and Parameter Estimates

Dependent Variable: Frequency

Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Exponential	.871	275.616	1	41	.000	429.052	-.037

The independent variable is Travel Time.

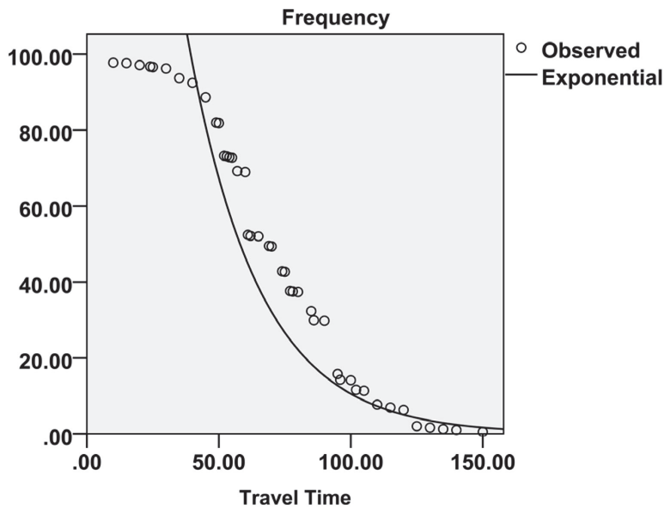


Figure D.4: Estimated decay function for TM mode per SES 3

Model Summary and Parameter Estimates

Dependent Variable: Frequency

Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Exponential	.873	123.491	1	18	.000	130.842	-.054

The independent variable is Travel Time.

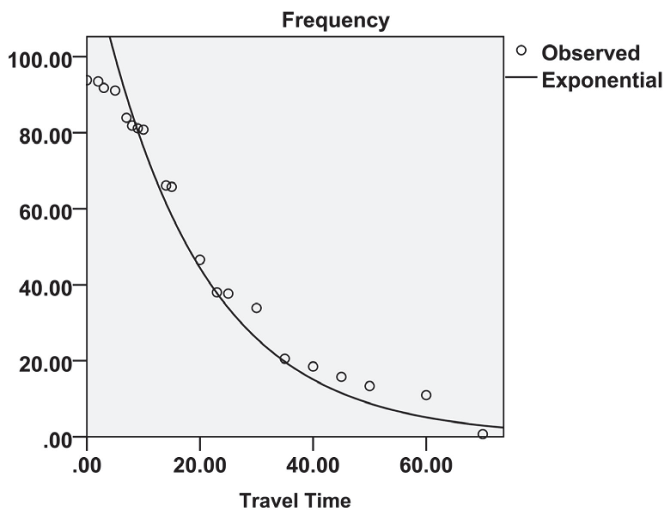


Figure D.5: Estimated decay function for bicycle mode per SES 3

Model Summary and Parameter Estimates

Dependent Variable: Frequency

Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Exponential	.838	82.726	1	16	.000	175.545	-.131

The independent variable is Travel Time.

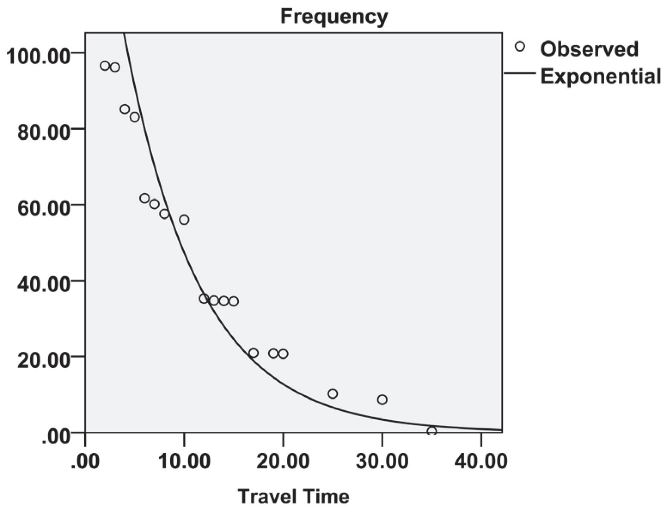


Figure D.6: Estimated decay function for walking mode per SES 3

Model Summary and Parameter Estimates

Dependent Variable: Frequency

Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Exponential	.896	86.607	1	10	.000	408.066	-.047

The independent variable is Travel Time.

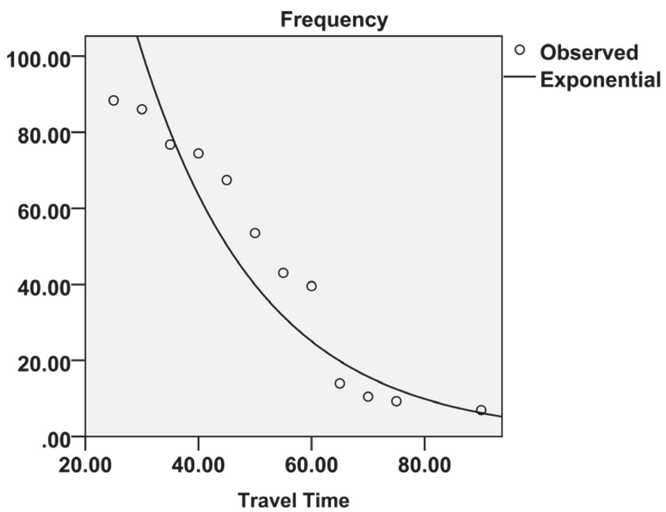


Figure D.7: Estimated decay function for TM mode per SES 5 & 6

Model Summary and Parameter Estimates

Dependent Variable: Frequency

Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Exponential	.916	32.546	1	3	.011	129.382	-.078

The independent variable is Travel Time.

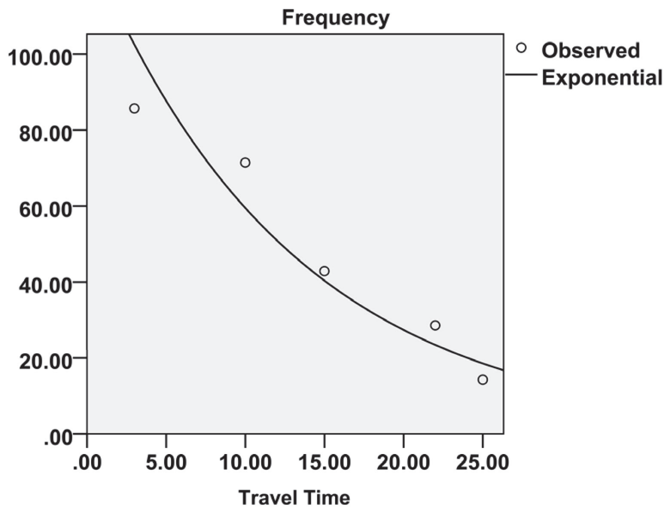


Figure D.8: Estimated decay function for bicycle mode per SES 5 & 6

Model Summary and Parameter Estimates

Dependent Variable: Frequency

Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Exponential	.957	201.699	1	9	.000	155.870	-.134

The independent variable is Travel Time.

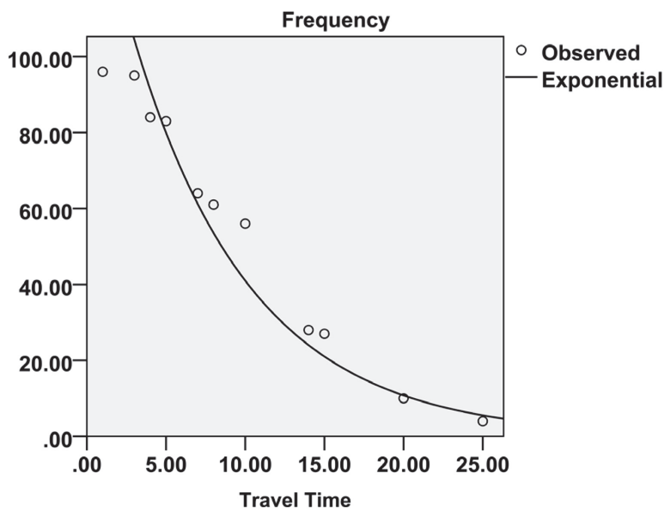


Figure D.9: Estimated decay function for walking mode per SES 5 & 6