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Transport accessibility and social inequities: a tool for identification of mobility needs and evaluation of transport investments

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ABSTRACT

Although the concept of social equity seems to be ubiquitous in most mobility plans of major Latin American cities, when evaluating transport projects for financing and prioritisation there are no specific or solid indicators to measure how they can contribute to promoting better access to opportunities, particularly for the most vulnerable segments of the population. In response, we designed a methodology that uses the concepts of accessibility and affordability as a complementary means for evaluating public transport investment, and identifying transport disadvantages and priorities for project generation. This is based on the calculation of accessibility levels to the labour market for different zones of a given city, by introducing a function of impedance composed by travel time budget and the percentage of income spent on transportation.

The characteristics of time and percentage of income spent for accessing work obtained from transportation surveys define the "real accessibility" to employment for all the zones of a city. Then, a stated preference survey was applied in order to determine the desired expenditure in both variables, and the accessibility to jobs in this new situation was subsequently calculated. We calculated a third type of accessibility, using "standard" values of travel time and expenditure budget.

This methodology is therefore used to evaluate different policies in Bogota, corresponding to changes in the fare structure of the existing public transport system, by proposing the development of cross subsidies, and carrying out an appraised on the impact of the development of a new Bus Rapid Transit line. The results show that depending on the population, its location and purchasing power, the impact of a redistributive fare with respect to accessibility to the labour market can be greater than the expansion and improvement of the public transport network.

1. Introduction

In transport policy formulation, attributes that give value to transport systems have been progressively changing. While in the past, speed and reduced travel times were the important assets of a good transportation system, currently the relevance of characteristics such as system reliability, low environmental impact, accessibility and contribution to equity are now more relevant than ever. Examples of the relevance of accessibility in the definition of mobility can be easily found in the European experience (LOTI Transport Act of France (1982) and the United Kingdom's DfT), where the necessity to strengthen mobility in terms of reasonable access, quality, and price for the individual has been clearly defined and included in the official planning documents.

Most mobility plans of major cities in Latin American, as well as other developing and industrialised countries, emulate this tendency of including social exclusion and equity as critical issues in the planning and development processes. However, the tools for the analysis and evaluation of transport projects and conditions do not measure, with either specific or solid indicators, their contribution to the accessibility levels to opportunities and their social implications, particularly for the most vulnerable segments of the population.

At the moment, in many developing countries as well as in some cities of industrialised areas, there is an obvious problem with respect to accessibility to transport, and therefore to opportunities. The capacity of individuals to travel in the poorest segment of the population of cities such as Bogota, Colombia, is reduced to less than 1.5 trips per day, while the corresponding percentage of their total income spent on transport exceeds 20%.

Accessibility concepts focus on estimating the availability of opportunities generated as a result of both transportation supply and land use characteristics. As a result, accessibility can be used as an indicator of social inclusion and the potential of economic

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development at an individual level (Scottish Executive, 2000a, 2000b).

Consequently, this research focuses on the construction and application of a series of indicators linked with the different components of accessibility in the urban transport domain, particularly those that cover the relationships between transport costs and income level. Affordability should be one of the main aspects to consider when formulating public policies in developing cities in order to provide better accessibility.

2. The problem

Among other strategies to improve public transport in developing cities of certain importance, the development of the Bus Rapid Transit systems (from now on BRT) has proven to be an efficient solution to fulfil most of the critical public transport requirements, since these systems are proficient in transporting medium to high passenger volumes.

BRT projects have focused on improving efficiency, providing transport supply and technology according to existing and expected demand. In Colombia, seven cities with over 700,000 inhabitants have implemented these initiatives, following the success of *TransMilenio* in its capital, Bogota. Nowadays, many cities in both the developing and industrialised world are planning, building or operating such systems.

The development of these projects includes the application of *ex ante* cost–benefit assessments, and financial structuring of projects involving an interesting component of public–private participation. As usual, the main benefits of the projects were considerable reductions in travel times and operating costs; while the financial structuring sought to cover transport operating costs entirely by fare revenues. The calculation of the equilibrium rate of the system should cover the payment of the operation and sustainability of the system, and these costs should be covered by the fare paid by the users, sadly, these being mainly the poorest of each city.

Unquestionably, users of the new system save time. However, increased fares can represent a strong limitation of its use. As a result, the policy of increasing mobility by improving the system through price increases, adversely affects individual accessibility, given a spatial distribution of activities that makes it even more difficult to access opportunities from the peripheral areas.

It is likely that the traditional evaluation of these projects could have ignored the negative effect of increased fare costs on transport demand. However, the problem lies beyond the lack of evaluation tools for transport projects that respond to these inequalities. In fact, an accessibility methodology for analysing transport disadvantages while considering socioeconomic conditions can provide evidence of disparities between different areas of the city and help in the formulation of adequate response strategies. In that order, a central issue in transport research is the development of an accessibility analysis tool that helps quantify and differentiate access inequalities, evaluate existing projects as well as prioritising needs and contribute to project generation.

Therefore, by introducing the concept of accessibility in the analysis of mobility conditions for specific population groups, it will be possible to consider not only an indicator that relates the transport system to land use, but the real possibility of transport use and ease of access to the city opportunities depending on individual purchasing power. This tool can be used to analyse different types of policy related to the relocation of activities and improvements in access to transport systems. It can also search for a shift in the statements of mobility plans in cities experiencing transport and access-related inequalities by providing additional value on matters such as equity and productivity allowing verification of the achievement of these objectives.

3. Accessibility as a means to analysing social inequities and transport investments

The study of transport accessibility has produced a large amount of research and working papers over the years. New studies and practical approaches are continuously emerging on this subject; however, most of them apply the existing methodologies to the contexts and data previously examined. This section presents a compilation of the most representative methodological approaches to the study of transport accessibility and an overview of relevant concepts that are directly and indirectly related to the study topic that can contribute to the study of accessibility in developing countries as a tool for evaluating transport investment.

3.1. Accessibility definitions

The concept of accessibility has been frequently used in a diversity of scientific studies focused on mobility issues, and represents a fundamental tool in the definition of public policy. Nevertheless, many methods for defining and putting into practice the notion of accessibility have been developed over the years, and the quantity of studies centring on this topic has provoked the use of the concept in several ways.

Interpretations of accessibility generated within the scientific community include the definition of accessibility as: the potential opportunities for interaction (Hansen, 1959), the ease of reaching any area of activity using a specific transport system (Dalvi and Martin, 1976), and, the overall benefits provided by a given transport system (Ben-Akiva and Lerman, 1979), among others.

From a more classical point of view, accessibility can be understood as the ease of reaching desired destinations given a number of available opportunities and intrinsic impedance to the resources used to travel from the origin to the destination. Usually, opportunities are measured in terms of employment positions, and impedance in units of distance or time (Niemeier, 1997). Many authors have augmented this view of accessibility by adding and developing existing and new components to the approach, constructing a wider theory about accessibility.

Three main clusters can be identified according to Van Wee et al. (2001) for accessibility definitions and measures: infrastructure-related, activities-related and mixed approaches. The first approach focuses on characteristics of transport supply and demand; some examples of this approach can be found in Priemus and Visser (1995), Linneker and Spence (1992), Gutiérrez (2001), Ribeiro et al. (2009), among others. The activities approach is associated with land use and location, focusing on the number of activities accessible in a given range of travel time or distance; many authors have studied accessibility from this perspective, and among the most representative we can cite Hansen (1959), Cervero (1989, 1996), Gutiérrez (2001), Van Wee et al. (2001), Halden (2002), and Ben-Akiva et al. (2006). The last approach combines the preceding two, making a more complete analysis of accessibility; some authors found in the scientific literature who have used this kind of method are Nutley (1980), Van Wee et al. (2001), Levine and Garb (2002), Wu and Hine (2003), Curtis (2007), and Straatemeier (2009). Generally, nearly all accessibility definitions and measures consider elements linked with generalised travel costs, demand characteristics such as number of households, job clusters, commercial activities, and origin–destination interaction and access.

As shown, accessibility has several components from which it can be analysed. Three main elements are determinant in defining accessibility in a more complete way than in previous works: Land Use, Transport and Individual characteristics. Geurs and Van Wee (2004) define each of these components, on the basis of an extensive collection of research.

3.2. Measurement techniques and indicators

Over the years, many researchers have focused on the study and development of accessibility measurement systems. Some of the most representative works on this subject range from activity-based measures (Ben-Akiva et al., 2006) and utility-based measures (Handy and Clifton, 2002) to specialised software for the calculation of accessibility levels (Bhat et al., 2000).

Among the different approaches for measuring accessibility, the most frequently used measures are based on a combination of opportunities and impedances. Hansen (1959) was the first to propose a gravity measure for accessibility in the scientific literature with the purpose of modelling land development. As described by Meyer and Miller (1984) and Dickey et al. (1983), gravity-type accessibility measures correspond to the portion of the gravity models which measure attractive power and the friction of spatial separation. New approaches and measures related to other aspects of urban mobility have been developed in recent years. Some of these classifications are described below.

- *Infrastructure-based indicators:* analyse the characteristics of the supply of infrastructure in terms of capacity and level of service, studying the quality of transport facilities using measures such as levels of congestion and average travel speed on roads. This type of indicator studies the coverage, capacity and quality of the transport infrastructure through measures of length, density, and traffic levels during periods of congestion.
- *Activities/land use-based indicators*: these measures give a perspective of accessibility at a macroscopic level. Activities-based indicators usually describe the level of access to activities distributed in space, using indicators of opportunities availability regarding their distribution in space and time. Some of the most commonly used measures of this type are potential indicators, also called gravity measures. Potential measures are generated by weighting opportunities located in a given area using an attribute of attraction (population, purchasing power, etc.), and discounting a measure of impedance (Knox, 1978; Handy, 1993; Geertman and Ritsema van Eck, 1995; Johnston et al., 2000). These accessibility indicators provide a powerful tool of analysis because they consider both measures of attractiveness and impedance to establish a reliable value of the potential of a given area.
- *People-based indicators:* these measures are based on spatial and temporal geography, and consider the restrictions of an individual reaching the activities. The accessibility measures at an individual level examine the activities that a person can perform in a given time, measured in terms of their time budgets for the mandatory activities (working, studying), flexible activities (entertainment, leisure, etc.), and the speed offered by the transport systems for moving between areas of activity.

Also known as space–time accessibility measures (Kwan, 1998; Miller, 1999; Miller and Wu, 2002; Kwan and Weber, 2003), people-based measures consider accessibility as an attribute of individuals (Kwan and Weber, 2003), and evaluate it from the daily schedule of activities and spatial and temporal constraints for an individual (Landau et al., 1982; Kwan, 1998). Using these indicators requires a considerable level of disaggregation, and involves separately evaluating accessibility for different trip purposes, modes of transport, income level, gender, age, occupational groups and types of activity (Wachs and Kumagai, 1973; Ben-Akiva and Lerman, 1979; Handy and Nieimeier, 1997; Kwan, 1998).

Utility-based indicators: these measures, based on economic studies, contemplate the benefits acquired by people when accessing activities distributed in space. This type of indicator estimates accessibility at an individual level, taking into account not only the characteristics of individuals but also those of the different transport modes (Banister and Berechman, 2000; Geurs and Ritsema van Eck, 2001).

Koenig (1980) defined the basic assumptions of these measures. First, a utility is associated with each alternative in order to compare them, and then select the most useful. Then a utility function is defined, composed of the sum of a deterministic and a random component, incorporating the variables representing each option, reflecting the attractiveness of the destination area, the impedance of the trip owing to the characteristics of the network and transport systems, and the characteristics and preferences of the individuals studied (Handy and Nieimeier, 1997). One of the main problems with this type of measure, besides that they are sometimes difficult to estimate, is that they require a large amount of information.

3.3. Accessibility, inequality and social exclusion

The concept of social exclusion in its different dimensions has progressively become an important element in social policy discourse, often limiting its scope to the field of economic poverty and income-disadvantages. However, social exclusion represents a complex notion that includes several dimensions, including economic, that considers spatial, political, societal, personal, and temporal disadvantages, among others, which can be exacerbated by poverty (Kenyon et al., 2002).

The social exclusion term refers to the co-existence of a set of social problems associated with the fragmentation of traditional social structures, the decline in participation in normal processes of society, as well as increasing deprivation among particular social groups (Burchardt, 1999; Witter, 2010). An individual is socially excluded when he or she resides geographically in a society but cannot be involved in its normal activities (Witter, 2010). Relationships between transport and social exclusion have been studied more recently with an important number of studies in the UK and the European community whose used survey methodologies to identify specific conditions related to the transport component of exclusion (Church et al., 2000; TRaC, 2000; Lucas et al., 2001; Social Exclusion Unit, 2003; Hurnie, 2006; Currie et al., 2007; Cebollada, 2009; Páez et al., 2009).

Mobility-related social exclusion is defined as the process by which, due to an insufficiency or inexistence of adequate means to travel, people are prevented from participating in the economic, political and social life of the community, as a result of reduced accessibility to opportunities (Kenyon et al., 2002). In the case of people experiencing conditions of exclusion, travel choice is removed as a result of an urban environment built around the notion of high mobility in order to access goods, services and participate in society. These conditions are often reinforced by poverty and a low quality of public transport services in neighbourhoods with low car ownership. However, it is worth noting that not all people that experience mobility-related exclusion live in poor neighbourhoods, nor that all people experiencing income poverty are excluded (Grieco, 2006).

According to Lucas (2004), the rationale for adopting a social exclusion approach to transport disadvantage resides in its capacity to help policy makers recognise three main aspects of the problem: its multi-dimensional, relational and dynamic nature. In the same way, the notion of social exclusion is also useful in terms of policy definition and evaluation because it forces one to concentrate not only on the disadvantages of being excluded as a result of transport-related inequalities, but on the economic and social outcomes that result from them. In fact, when studying the effects of the unavailability or insufficiency of transport from the social exclusion approach it is fundamental to analyse the consequences in terms of lack of accessibility to vital activities such as health, education, employment, etc., for identifying particular deficiencies of transport policies that can lead to more equal and people-focused initiatives.

The main focus of the methodology that will be described in the following sections is the quantification of accessibility levels of different groups of the population with different spatial and economic constrains for travelling. It is intended to apply the social exclusion rationale to the methodology through the identification of the effort made by people for accessing mandatory activities from different areas of an urban space designed in terms of high mobility, as well as evidencing the inequalities resulting from the necessity to gain access to an income source. Implicitly, the possibility of overcoming at least some of economic constrains that could lead to exclusion are considered. The main objective is to obtain an indicator of the effort required for not being excluded, particularly in areas of low income and deficient access to transport alternatives, considering the elements of spatial, economic and transport facilities involved in the accessibility function.

4. Methodology

The conventional Hansen equation, one of the most used formulas in scientific literature for estimating the level of accessibility of a given area is defined as:

$$A_i = \sum_j a_j f(d_{ij}) \tag{1}$$

where A_i = accessibility of the zone i (origin zone), a_j = attractiveness of zone j (destiny zone) and $f(d_{ij})$ = function of the distance (cost) between zones i and j.

In Eq. (1), the cost function is traditionally defined in terms of travel time or distance inherent to move from one area to another, and takes the standard form of utility functions. Although this may represent a first approach in accessibility measurement in developing countries, in order to consider a component of exceptional relevance given the characteristics of the population residing in the study area it is necessary to incorporate an affordability component in the function, which can be expressed in terms of the percentage of individual income spent on transportation, obtaining:

$$f(d_{ij}) = e^{-\beta C_{i,j}} = e^{-\beta_1 Ct + \beta_2 Cc} \tag{2}$$

where C_{ij} = generalised travel cost (impedance) between zones i and j, C_t = travel time cost between i and j and C_c = percentage of the individual income spent on travelling.

The first component of generalised travel cost, the cost expressed in terms of time, is directly related to individual variables such as occupation, age, income level, among others, and land use variables such as activities distribution, which determines the travel and activity time budgets.

Similarly, it is related to supply variables that define the speed of travel and availability of transport modes that can increase or reduce waiting and walking times as the availability of alternatives varies.

On the other hand, the monetary cost component of $f(d_{ij})$ is directly connected to the income level of individuals and supply of transport. The affordability component of this function is closely associated with the travel money budget that is related to a percentage of the income of individuals which, according to Zahavi, tends to remain constant in time. As a result, the monetary cost of each mode determines whether or not individuals are able to use every alternative available to mobilise themselves, given their budget restriction and purchasing power.

Likewise, it is recognised that there are both temporal and financial restrictions that limit the ability of individuals to mobilise. These constraints represent conditions for the relationship between internal and external issues that directly affect the level of accessibility for an individual in a defined study area.

In general, accessibility to the labour market has been calculated from transportation surveys. Given the location of houses and of jobs, and the characteristics of transport modes used, it is possible to calculate the number of jobs that can be reached considering a “rational” time budget. A more complex definition of impedance allows us to introduce affordability as being relevant in the calculation. Labour market was selected as the core of the accessibility methodology, mainly due to data availability and relevance in travel needs in cities of developing contexts (more than 70% of all travel in the case of Bogota). The methodology is designed for its use in any context in which transport-related disadvantages are identified. However, its main incentive is to help developing cities to analyse mobility and social inequalities and contribute to project analysis and evaluation with limited information availability. After analysing aspects of the information convenience and relevance of the labour market in travel analysis in different socioeconomic groups of the urban population of Colombia, it was decided to focus the methodology exclusively on mandatory trips, with the anticipation of expanding it in future research.

4.1. The three types of accessibility

4.1.1. Real accessibility

Since a relationship between the costs/budgets of time and money for travel, transport supply, socioeconomic characteristics of individuals, and accessibility levels can be inferred as stated above, these variables can be used to define the parameters of Eq. (2) as:

$$C_t = f(\text{Mode}, \text{Spatial location}, \text{Socieconomic strata}) \tag{3}$$

$$C_c = f(c/i) \tag{4}$$

where Mode = transport mode(s) used to travel from origin to destination, Spatial location = travel origin, Socioeconomic strata = local classification for purchasing power and household income that starts from 1 for the poorest segment of the population to 6 for the richest and c/i = Travel cost vs. Origin zone average individual income ratio.

A primary result of this research is setting the values of the coefficients of each variable defined above for all the selected areas of Bogota, as well as their most likely value corresponding to the characteristics that determine the level of access to jobs in each zone. This first value will be termed *Real Accessibility*.

Real Accessibility is given by the number of jobs that inhabitants in different zones of the city are actually reaching. We assume this to be the number of trips made to work. Accessibility *per capita* for each zone is obtained by dividing the total number of trips to work by the population of labour force in the zone. Thus, real accessibility is known, and is given by O-D surveys.

From this kind of survey, it is also possible to determine the way in whichjobs are reached. It is possible to calculate for each OD pair, the average time and percentage of income spent. Therefore, it is possible to calibrate the $f(d_{ij})$ function for several study areas with this data.

In order to calculate the coefficients for both of the variables that are considered in the impedance function, the values of daily working commutes are estimated from a 2005 survey, and compared with the total job positions offered in each zone, obtaining an approximate value of $f(d_{ij})$. In addition, averages of time and percentage of income employed on travelling between each i and j pair are known from given databases, permitting regression analysis to be performed, providing the values of β_1 and β_2 for each of the selected zones.

The resulting equation allows researchers and transport planners to evaluate the effects of different policies on accessibility to jobs in each zone by transforming time and cost savings into a measurable number of additional opportunities obtained from each alternative. These analyses can lead to new forms of the evaluation of transport projects, based on benefits in terms of access and inclusion, particularly for the most vulnerable population groups.

4.1.2. Accessibility given standard parameters

Zahavi (1974)hypothesised that the average individual travel time budget is around an hour a day, however, when looking at the most vulnerable population of Bogota it is noted that the amount of time spent on travelling is very close to, and in many cases exceeds, 60 min per trip. In addition, the same author suggests that most people have a travel money budget closely related to their income level. Zahavi argues that depending on certain individual characteristics, the travel money budget remains fairly stable, ranging from 7% to 9% of the individual's income. Yet, evidence has shown that in Bogota the poorest people spend more than 20% of their income on transport.

Therefore, if the international standards of travel money and travel time budgeting are applied as a restriction to the variables used to determine accessibility to jobs, the reduction in the number of reachable job positions may decrease to a critical level depending on the characteristics and the ease of using transport systems that provide an acceptable service even under these conditions.

Accessibility levels under these restrictions are estimated in order to determine possible inequalities in terms of accessibility in areas with different purchasing power, access to transport systems, and specific spatial location relative to job clusters in the city, under the same maximum budget of money and time for accessing mandatory activities such as work.

4.1.3. Available accessibility under desired preferences

The study of the effects of homogeneous budget restrictions applied to population groups with different characteristics of transport demand and supply can be useful for the preliminary analysis of the effects of travel budgets on accessibility. However, if the actual budget of time and money that people in each area of study are willing to spend on travelling to work is determined, researchers could have better resources to estimate their effect on accessibility, and be allowed to draw relevant conclusions about the disposition of individuals to sacrifice resources (such as time or money) given the disparities of opportunities. This exercise could be the first step in the study of access inequity generated from an unequal distribution of activities or an insufficient supply of transport systems in some neighbourhoods.

Therefore, the application of the model obtained from the first type of accessibility to the information gathered from the declared preference surveys conducted in each of the areas of study, seeks to establish the access level subject to the budgets of time and money as defined by the inhabitants of each zone, which is classed as *Available Accessibility* under desired preferences. This type of accessibility helps better identify the level of effort that people make in order to improve their levels of accessibility to mandatory activities, and the resulting access if these preferences were adopted.

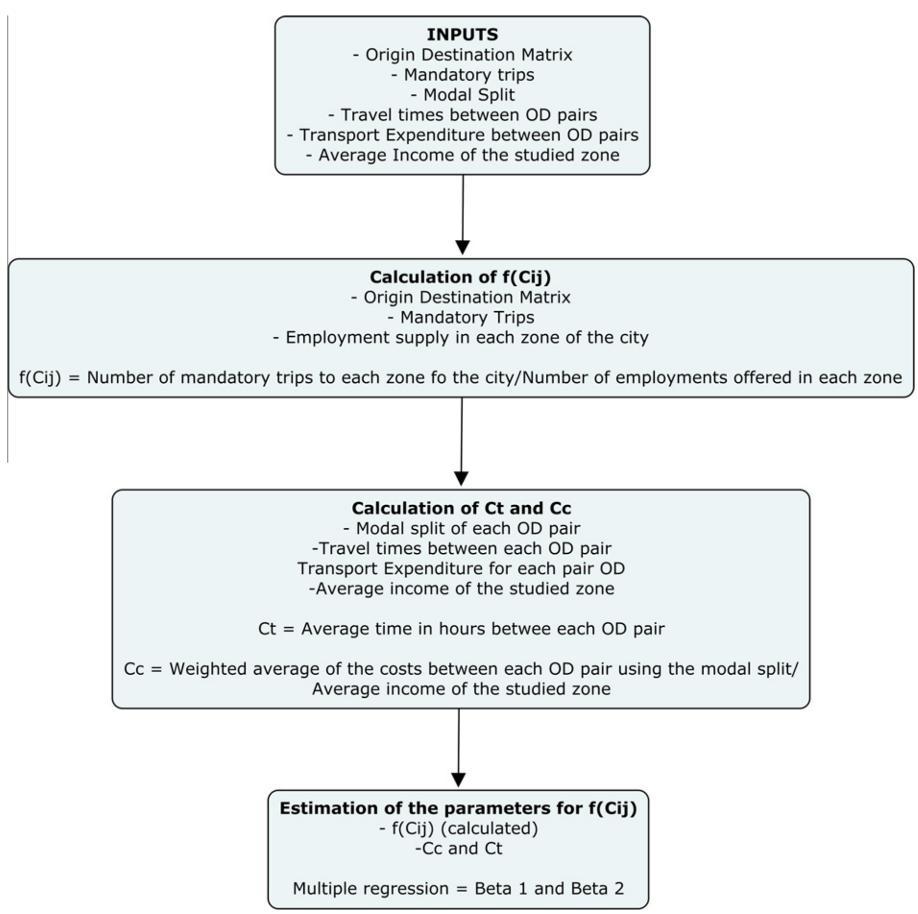

Fig. 1. Methodology.

4.2. Evaluation of transport policies

Our laboratory is the Bogota transport system. In the year 2000, Transmilenio BRT system started operation, a second phase was implemented in 2006, while a third phase should begin operation by the end of 2011. In 10 years, the Transmilenio system will be carrying almost 30% of the public transport demand, almost 2 million trips per day.

Transmilenio's impact in terms of travel time savings has been important. Nevertheless, cost may have increased for some users.

Considering the accessibility approach, it is possible to estimate the improvement that Transmilenio has brought to the population, with respect to different incomes, location and access to the system. This will be done for some of the zones served by the third phase of Transmilenio.

As the fare may be a critical issue for a large part of the population served by Transmilenio, we also calculate the variation in accessibility brought by a subsidy policy.

Fig. 1 provides a brief summary of the main steps of the developed methodology.

5. Results

In order to test our methodology we decided to analyse the different types of accessibility in different zones of Bogota.

5.1. Available information

Information on travel patterns can be accessed from the 2005 OD Travel Survey of Bogota (Universidad Nacional, 2005), which considers 846 homogeneous zones in terms of socio-economic characteristics. These zones are grouped into 117 planning zones, called UPZ.

Information on the number of jobs and locations is provided by the Planning Department of the District (Secretaría Distrital de Planeación de Bogota, 2005). For a better understanding of the distribution of activities in the city of Bogota, as well as the characteristics of each of the selected areas, the job distribution of the city and a summary of the attributes of each of the ten selected areas are summarized in Fig. 2 and Table 1.

Fig. 2 allows us to identify a large CBD, which also concentrates on education, health and cultural activities.

Information on the level of income has been provided by the Planning Department (Secretaría Distrital de Planeación de Bogota, 2005). A scale that goes from 1 to 6 depending on the average income level of households is used in socioeconomic studies and statistics. Fig. 2 shows the geographic distribution of the poor and rich areas in Bogota.

It is possible to note that the high income population tends to settle close to the CBD (according to Fig. 2), while the poorest live at the city's boundaries. Socio economic segregation is quite dramatic.

5.2. Choice of study zones

In order to evaluate the three types of accessibility defined previously, we have analysed UPZs that have different characteristics, related to the level of income, quality of transport system and location in relation to main work areas, as shown in Table 1.

This table briefly summarises the characteristics of each of the areas chosen for the study and reflects the differences between each of them, demonstrating that there are areas such as Lucero and Bosa Central which are not only located in a unfavourable

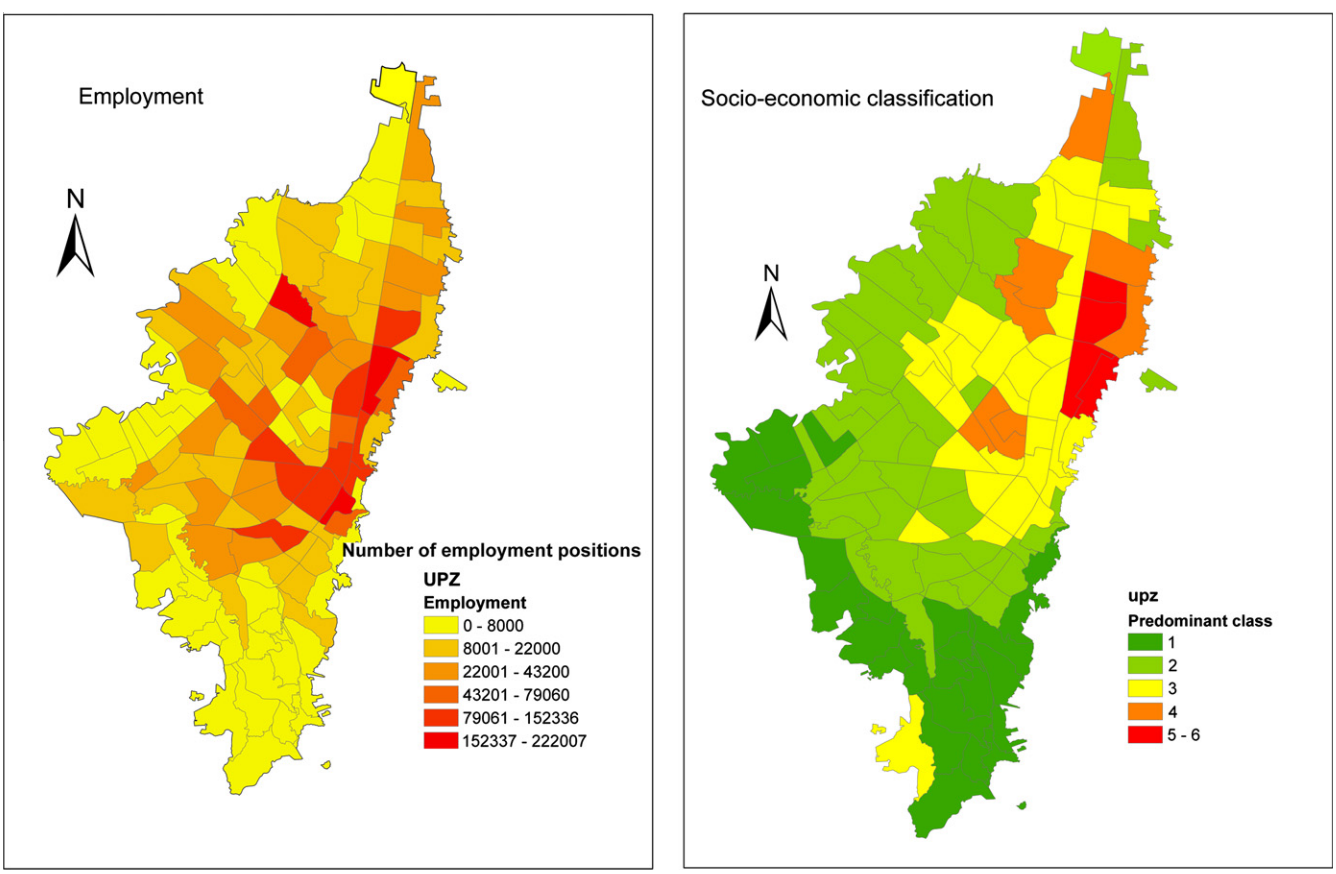

Fig. 2. Employment and income distribution of Bogota.

Table 1
Main attributes of selected study zones.

No	Zone	Income			BRT service		Car ownership			Distance to main job clusters			Population density			Job density			Road density		
		H	M	L	Yes	No	H	M	L	H	M	L	H	M	L	H	M	L	H	M	L
1	Bosa Central			X	X				X	X			X					X			X
2	Lucero			X		X			X	X			X					X			X
3	San Blás			X		X			X	X			X					X			X
4	Zona Franca		X			X			X			X		X		X				X	
5	El Rincón		X		X			X		X			X					X		X	
6	Bolivia		X		X			X			X		X				X		X		
7	La Esmeralda	X			X		X					X		X				X	X		
8	Ciudad Salitre	X				X	X					X	X				X		X		
9	Country Club	X			X		X				X			X				X		X	
10	Chicó Lago	X				X	X					X		X			X		X		

H = high, M = medium, L = low.

Table 2
Real accessibility results.

Zone	Socioeconomic class	Accessibility (number of employment positions)	Accessibility per inhabitant[a]	Average travel time (min)	Average percentage of income (%)
Bosa Central	1–2	93,713	0.53	60	24
Lucero	1–2	42,286	0.22	63.1	26
San Blás	1–2	43,279	0.62	59.4	27
Zona Franca	2–3	35,704	0.87	54	21
El Rincón	2–3	148,238	0.86	68	15
Bolivia	3	76,336	0.83	44.9	13
La esmeralda	4	24,249	0.85	39	5
Ciudad Salitre	4–5	23,997	1.1	38.5	6
Country Club	5	27,860	1	50	4
Chi co lago	5–6	28,363	0.99	36.9	3

[a] This indicator is calculated based on the potential of the population that could work in the zone of analysis. In this case, population in terms of working age was used, resulting in accessibility per member of the potential labour force of a specific area.

places relative to the position of employment centres, but that also have a fairly low income level. In addition, some of the selected zones, despite their high income level, may also be affected in terms of accessibility because they are far away from the city centre. Similarly, middle income areas such as Bolivia, are considerably closer to the main sources of employment and have a public transport service of good quality. In contrast, Ciudad Salitre not only is an area of high income but is also very close to the major work centres of Bogota.

5.3. Accessibility estimation

Table 2 shows the main information obtained for each zone in terms of accessibility in number of work trips (Aj) *per capita*, average travel time and percentage of income used in transportation. The following are some initial facts that may be determined from this analysis:

First, *per capita* real accessibility does not depend entirely on level of income. Even though the lowest income areas tend to have lower real accessibility, some interesting exceptions can be identified. Accessibility in areas such as 09 and 08, the latter being on average of a lower income, shows that location regarding employment and public transport availability can be determinant. With less time spent commuting, Ciudad Salitre (08) has the same accessibility level as Country Club (09). In contrast, some areas with high travel time, like 05, have a higher access to employment than other zones with a similar income level.

Second, according to the results obtained, the potential access for the observed conditions of supply and demand reveals a dilemma of inequality with respect to access to opportunities of work. Although the difference in time spent by the lower strata is greater than 48% compared to the upper classes, the most critical differences correspond to the percentage of income intended for travel that is 400% higher. In addition, some of these zones show some kind of resignation in terms of the amount of some attributes which indicate that, in the case of mandatory travel, they are inclined to spend a lot more than what is expected because of the need to earn a basic income. In some cases, sacrifice "pays off" as more time spent allows better accessibility, as in the case of El Rincon (05) where in spite of the disadvantageous conditions and higher travel times their inhabitants have more access to work than middle income zones.

Third, from the real accessibility results it can be inferred that, due to the geographic location of some areas and the unequal distribution of activities in the city of Bogota, the trips generated for mandatory activities require a higher travel time, resulting in a lower number of jobs accessible within a similar range of distance. Furthermore, the low purchasing power combined with inadequate transport and unfavourable locations make cases such as Lucero critical examples of access inequity to opportunities in the city. Due to a centralised distribution of activities and an imbalance in the opportunities, there is a willingness from certain individuals to sacrifice certain aspects, like more time for other activities or money for other purposes, to access employment.

Fourth, even though individuals with high income have access to a car in a greater proportion than individuals on middle incomes, there is not a vast difference in terms of time and money spent, and in terms of accessibility. Car use does not have a big impact on accessibility for the people of Bogota; a dense and congested city may in part explain this fact.

As explained in previous sections, one of the main results of this research is the estimation of the parameters for the impedance function in each of the selected study areas. In this regard, the equations obtained according to the characteristics of transport supply and demand in each area studied are summarized below,

$$f(d_{El\ Rincoón\ j}) = e^{-(1.95*Ct+2.39*Cc)} \quad (5)$$

$$f(d_{Bosa\ central\ j}) = e^{-(1088*Ct+3.53*Cc)} \quad (6)$$

$$f(d_{Country\ Cub\ j}) = e^{-(5.77*Ct+0.037*Cc)} \quad (7)$$

$$f(d_{Zona\ Franca\ j}) = e^{-(3.81*Ct+4.06*Cc)} \quad (8)$$

$$f(d_{Bolivia\ j}) = e^{-(4*Ct+4.54*Cc)} \quad (9)$$

$$f(d_{Lucero\ j}) = e^{-(0.66*Ct+11.7*Cc)} \quad (10)$$

$$f(d_{Chicó\ Lago\ j}) = e^{-(9.8*Ct+0.41*Cc)} \quad (11)$$

$$f(d_{La\ Esmeralda\ j}) = e^{-(9.24*Ct+2.4*Cc)} \quad (12)$$

$$f(d_{San\ Blás\ j}) = e^{-(2*Ct+9.66*Cc)} \quad (13)$$

$$f(d_{Ciudad\ Salitre\ j}) = e^{-(9.55*Ct+2.06*Cc)} \quad (14)$$

As shown in the equations above, the coefficients vary sharply from one area to another depending on their income level, location and supply of transport. In the case of high income areas, a potential increase in the monetary costs of transport has no relevant effect, while in the low income areas the opposite is true since individuals are willing to spend more time travelling as long as this represents monetary savings. Likewise, we see that in middle income areas, which are also well located, the coefficients are similar as a result of the additional value given to the proximity to the centres of labour supply. At this point it is worth noting that in the case of the regressions used to calculate the accessibility parameters, statistically significant results were obtained for each case study, as shown in Supplementary Annex. 1.

As shown in Table 3, regarding the desired expenditure in terms of time and income, the results show that:

First, the time individuals would like to spend travelling to work is similar for all income levels and locations, it is close to 40 min with a few exceptions that are closer to 35 min. These atypical cases can be explained in terms of spatial location relative to employment centres, because these zones are located in favourable places, have a higher income and have better access to transport systems than other zones. Regarding percentage of income they wish to spend, it is on average 13% with marked variations depending on the purchasing power of each zone. Unusual budgets are identified following a similar explanation of the previous case.

Second, the difference between the desired condition and the real condition for individuals in Bogota is quite dramatic. The low income individuals spend 40% more time and 38% more money that they wish to. In comparison, middle income individuals spend 39% and wish to spend 5% more, for higher income these percentages are 8% and 43% less. This is certainly a means to measure transport quality and its impact on the quality of life in cities.

Table 3
Desired travel time and monetary budgets for each zone.

Zone	Travel budgets for work commutes	
	Time (min)	Money (% of income)
Bosa Central	43	18.00
Lucero	42	15.60
San Blás	40	11.30
Zona Franca	44	26.00
El Rincón	40	17.00
Bolivia	41	9.60
La esmeralda	36	7.70
Ciudad Salitre	38	5.60
Country Club	43	12.00
Chi co lago	35	6.50

Third, considering the actual transport supply and cost, as well as the locations of activity in Bogota, spending a "desired" time travelling and expenditure would create a significant decrease in accessibility, mainly in lower income classes. In the case of low income areas, we identified a higher willingness to sacrifice time in order to gain access to opportunities to increase their income. Geographic location has a significant impact that makes the inhabitants less willing to spend more time travelling, despite having a medium–low income level, which also affects the level of access under these restrictions.

Fig. 3 shows the significant decrease in accessibility if "international standards" of time and money expenditure were adopted by individuals. In the low income areas, the accessible jobs are close to zero, while in the rich income areas the reduction in accessibility per capita is close to 15%.

Results obtained for applying standard restrictions of time and percentage of income used to commute show a drastic reduction in the percentage of accessible jobs in the city from each UPZ studied for the working age population. There is a smaller reduction as a consequence of the temporal restriction in the study areas, where geographic their location or access to transport systems allows shorter trips, excluding only the most remote UPZ. In cases of peripheral areas, geographical conditions are counterproductive, which is even more serious if the access costs to inefficient transport systems are taken into account. With respect to monetary restrictions, given the modal split observed in each zone along with its income level, it is expected that in areas with a good income level and relative closeness to the CBD the restriction effect is negligible. However, for medium–low and low socioeconomic levels, the result is the exclusion of the more remote areas, which usually require more transfers and therefore higher travel costs, dramatically reducing the access of the population that is able to work.

6. Evaluation of transport policies

One of the main objectives of this research is for the developed methodology to become a useful tool for planners and researchers in developing countries, which can be applied for public policy planning and evaluation. In this regard, two types of transport initiatives, targeted at the variables considered in the accessibility model proposed, were evaluated in order to test the effectiveness of the methodology in terms of social impact and equity assessment.

6.1. Cross subsidy fare system

Since the estimation model developed for calculating accessibility takes into account the modal split of trips conducted in each zone, it is possible to slightly change the attributes of each mode to determine the effects of such variations on accessibility.

Consequently, we carried out a study on the effects of a differentiated fare system, developed according to socioeconomic classification and purchasing power, in areas currently served by the transport system that differ in their socio-economic characteristics and proximity to workplaces.

The main characteristics of these areas are summarized below, as well as their estimated level of accessibility according to the model. We selected two areas of upper and two of lower class in order to compare the costs and benefits for the inhabitants of each, considering that low socioeconomic areas are in unfavourable locations with respect to access to work opportunities.

The fare system adopted corresponds to an estimation made in 2008 that sought to define a value according to the income of each

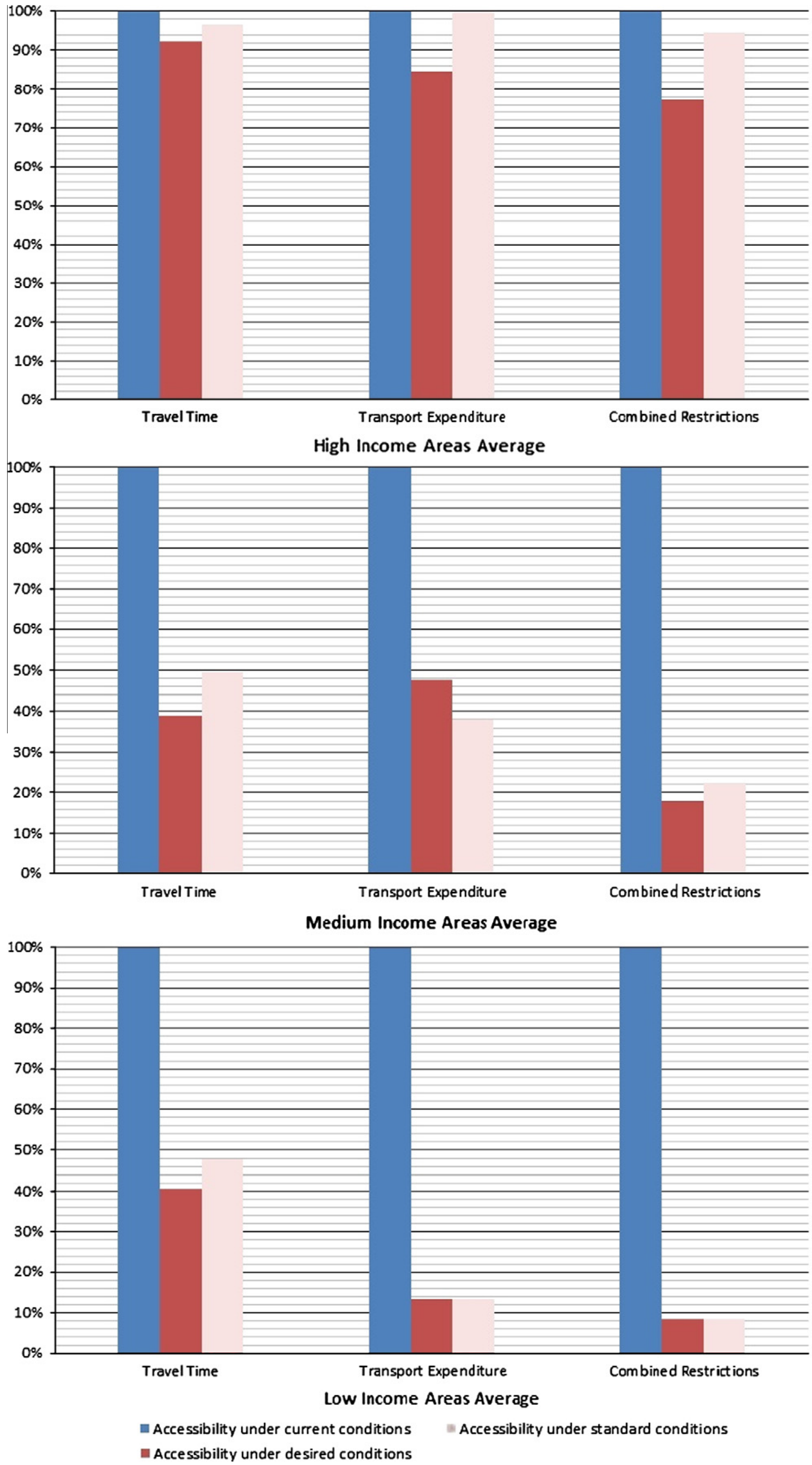

Fig. 3. Accessibility results considering desired and standard expenditure in relation to *Real Accessibility* results.

population layer without threatening the financial sustainability of the system (Scorcia and Bocarejo, 2008). According to this research, a reduction of 23% is proposed for socioeconomic levels 1 and 2, the fare for the middle income class (3) is not changed, and there is an increase for the higher income population (4–6) of 14%.

Transmilenio's fare scheme is calculated in order to pay the entire operational costs from the ticket sales. The technical price for accessing the system is supposed to cover the costs of trunk lines, feeder systems, fare collection, trusteeship, and management.

Therefore, the proposed changes in the fare system take into account the purchasing power of each socioeconomic class, and the elasticity of the demand to the price for each demand layer, reducing the negative financial impact on the system. The changes in cost for the system were applied to each evaluated zone, considering their purchasing power and the existing demand for each transport mode, which should reflect any changes in demand due to the respective increase and reduction of Transmileniós costs. Yet, for the purpose of this exercise, the modal split was not changed despite fare modifications, in order to only address the immediate changes in accessibility for testing the effectiveness of the evaluation tool.

The proposed change in the price is based on a greater elasticity for the low income population, which would be benefitted significantly by reducing costs; as well as the fact that the elasticity in the upper classes with respect to changes in the cost of public transport would lower the impact on demand. Results of the implementation of the fare policy are summarized in Fig. 4.

It can be seen from the results of the accessibility for the new price system, that target areas obtained significant reductions in travel costs, achieving savings between 2% and 3% for low income

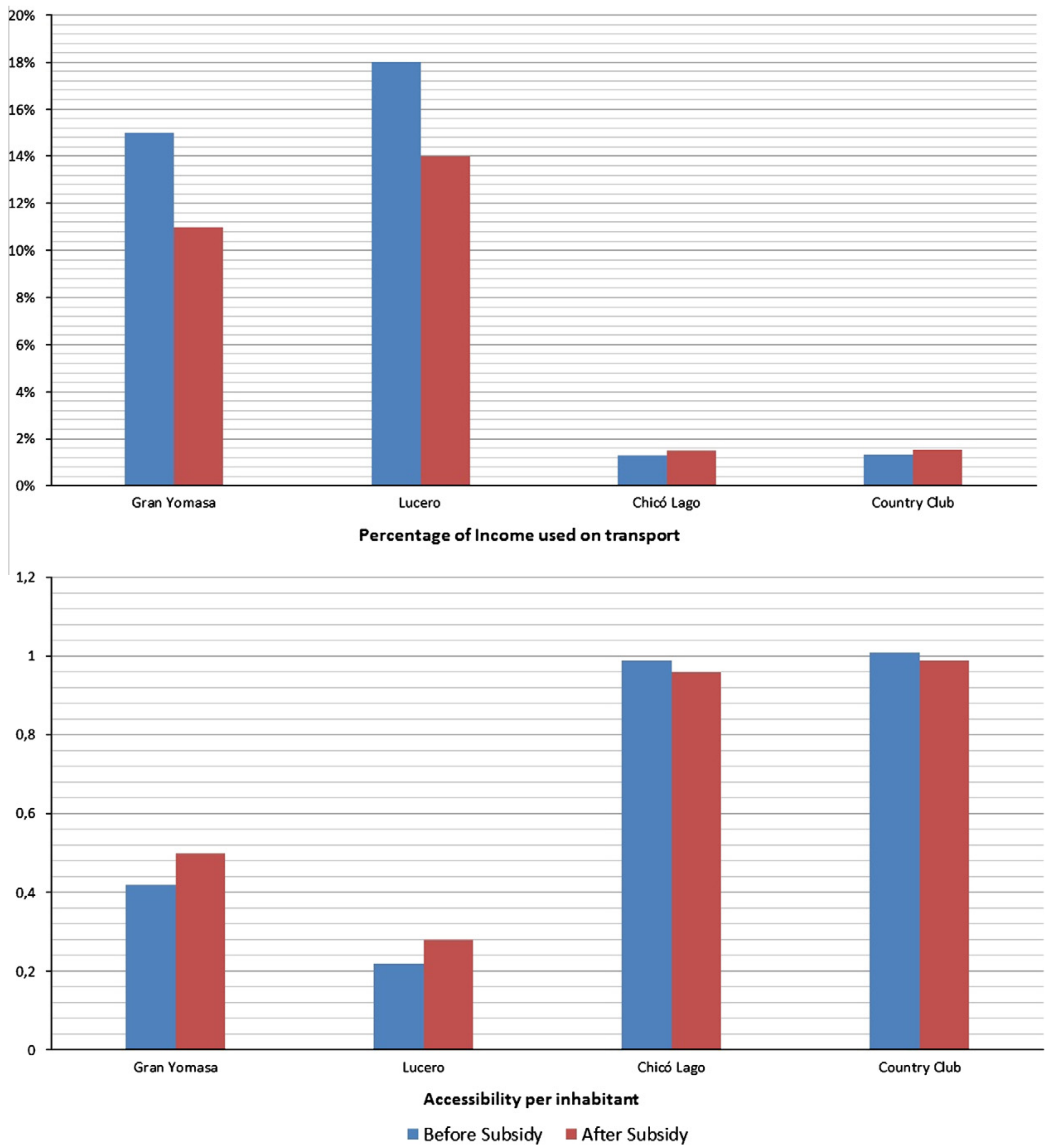

Fig. 4. Accessibility results before and after the implementation of the new fare system.

groups and an increase of only 1% for higher income areas. In addition, contrasting to these low changes in travel costs it can be seen that the benefits to individual and accessibility in areas like Gran Yomasa and Lucero are considerable, while the losses in the other zones are negligible both in absolute and relative terms.

A cross subsidy policy could generate benefits in terms of equity in cities such as Bogota, which are reflected in better accessibility to work opportunities. Nonetheless, the increasing operative costs and reduction in revenue could damage the self-financing stability of Transmilenio.

6.2. Evaluation of a new BRT line

The BRT bus system of the city of Bogota, called TransMilenio, has been expanded considerably in recent years, providing better conditions for mobility for most of the inhabitants of the city. As

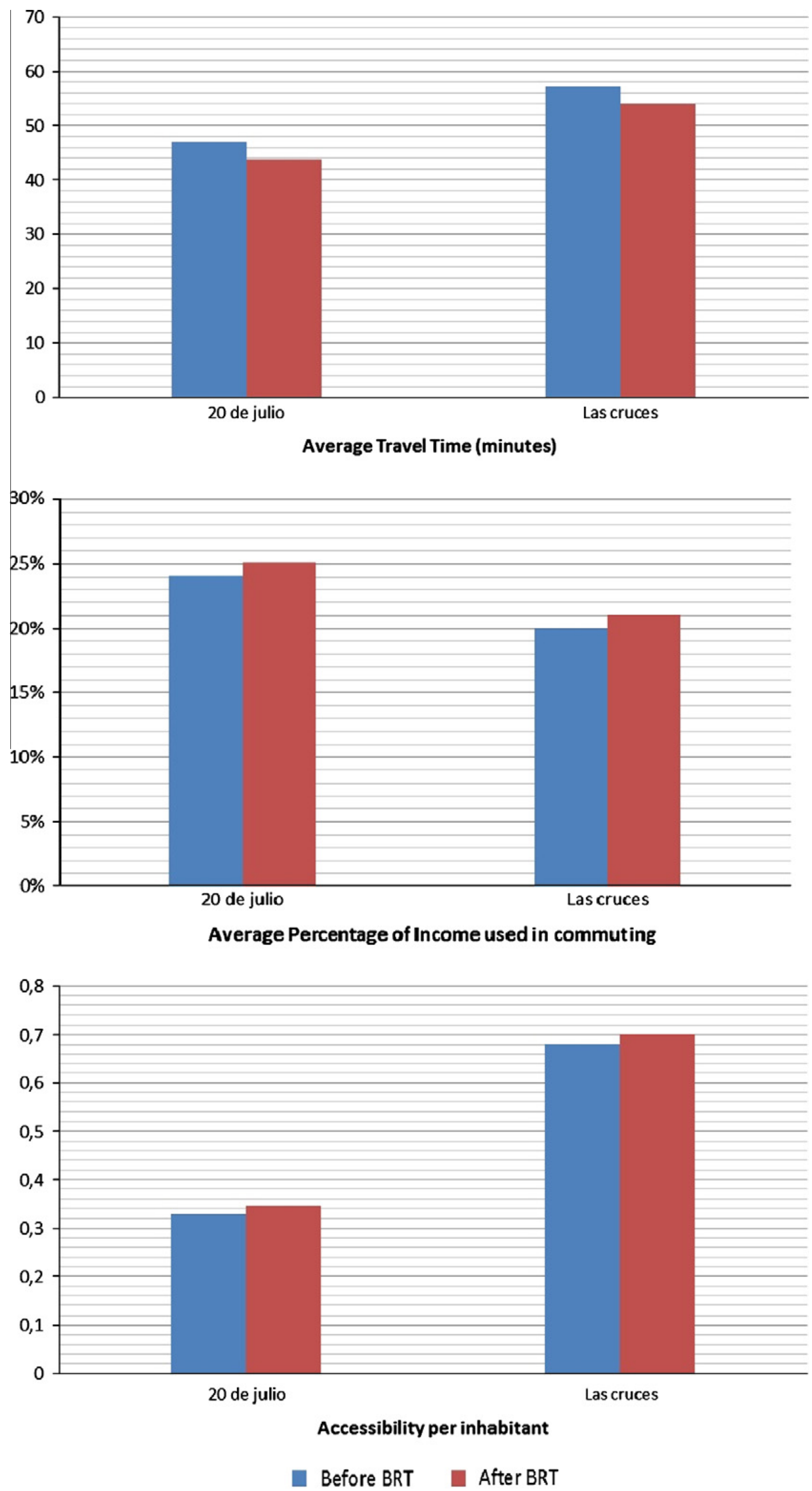

Fig. 5. Accessibility results before and after the implementation of the BRT project.

part of its expansion, Transmilenio's third phase aims to develop a new bus corridor that will connect the north and south of the city on its east side, areas of mostly low income households.

In the third phase, certain benefits of the new system compared to traditional public transport are recognised in terms of speed, that will increase from the current 15 km/h to approximately 24 km/h (9.2 km/h higher), which will reduce travel times and also generate a demand to transfer from the traditional forms of public transport. In addition, there will be a fare increase of 15%, and it is expected that half of the total demand for public transport will use the BRT service.

Two adjacent areas to the new BRT corridor have been analysed. The main objective, similarly to the previous exercise, is to estimate the combined effects of savings in travel time and fare changes over accessibility, in order to test the evaluation tool in a more complex context.

As explained in previous sections, the accessibility estimation model uses the existing modal split in every zone for work travel in order to calculate the weighted average of travel times and costs for all O-D Pairs. Therefore, the proposed changes in demand, speed and cost will be reflected in the calculated accessibility for each zone, allowing a comparative analysis of the new access levels due to the effect of the new system against the scenario without the project.

Transmilenio's new phase positively impacts on accessibility in the two zones analysed, as the increase in speed has a greater effect than the rise in fares. Nevertheless, a higher increase in tariffs or a less efficient system could produce a negative impact on accessibility. In order to explain these results, is necessary to consider the modal split of each zone; both of them characterised for having an important portion of total daily trips made on foot (approximately 23%). The increased fare costs of the BRT system prevent a greater demand for the new system due to the impossibility of paying the new fare for almost a quarter of the population. Fig. 5 presents the changes in accessibility as a result of the new BRT line.

As can be seen, there is a slight increase in the accessibility in each of the study areas, given the modal split and their locations close to employment centres, which generate the possibility of an increased number of trips on foot. In that sense, we conclude that, given the important increase in travel speed for a greater share of the existing public transport users, it is possible to obtain major benefits in terms of accessibility than the decrease in accessibility generated as result of the rise in price for those users.

It can be inferred that the estimated accessibility detriment produced by the higher cost of the new system has proved to be less likely to adversely affect the total accessibility of each area, to the extent that, under the proposed situation, time savings are more profitable than the number of additional jobs that may be lost due to the increase in costs. Transmilenio's effect on commuting efficiency in terms of speed and reduced travel times is very positive, even for zones that value transport system costs higher, as shown by the calculations made in this section. Therefore, if improvements in public transport systems, such as Transmilenio, were combined with a fare policy as evaluated in the previous section, the benefit in terms of accessibility for low income areas in cities like Bogota could be enormous.

7. Conclusions

Accessibility as a way of evaluating transport policies allows considering aspects related to urban structure, transport system quality, individual characteristics and purchasing power. The number of accessible employment opportunities related to the total number of the work force gives an idea of the impact produced by transport projects considering accessibility.

Accessibility can be related to the time and percentage of income spent on commuting. It varies upon the type of user, its location and mode used. Differences in the coefficients evidence the relevance of each variable, depending on the location, purchasing power and availability of alternative modes of transport, showing in general a higher incidence of time in richer areas and the important effect of money over accessibility in low income areas, with only some specific exceptions in well-located areas.

The proposed methodology can be used as an additional element in the decision making processes regarding where and how to respond to transport disadvantages in cities that experience transport-related inequalities, through the identification of specific needs, prioritisation and proposal of transport strategies for addressing the disadvantages caused by location or reduced purchasing power. Inclusion of affordability in the indicator immediate provides information on equity impacts related to income. This approach allows researchers and policy makers to consider the economic limitations of the population in the formulation of initiatives that aim to improve conditions of access.

In addition, the possibility of exploring travel budgets and their effect on accessibility represents a step forward in the identification of inequalities and the needs of specific population groups, and the definition of priorities-based policies aiming at reducing the effort made by people in order not to be excluded. In fact, the examples identified when comparing economic and infrastructure initiatives, evidenced the different outcomes that can be achieved by addressing these priorities.

8. Future developments

The methodology defined and tested in this paper represents a first step in the development of accessibility analysis tools for unequal mobility conditions and policy responses for their mitigation. We aim to continue improving the methodology, as well as encouraging other researchers to contribute to the development of transport analysis tools that consider social elements. The first direction for improvement is the analysis of access to other activities and services, which will require more data and aggregation, but can help better understand the level of transport-related inequalities between groups of the population with different transport and socioeconomic disadvantages. Likewise, it is recognised that there are additional elements involved in generalised travel costs that should be considered, and which can be used for the development of a more complex and precise impedance function and more in-depth analyses.

Finally, we believe that this is an indicator with great potential for the development and evaluation of transport conditions and policies, as well as the study of social impacts of mobility. Consequently, we expect to apply the accessibility indicators to the identification of mobility needs with social implications and in the development of future projects and evaluation of existing mobility strategies, not only in developing cities but in any context that exhibits transport disadvantages like those described in this work.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jtrangeo.2011.12.004.

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