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What can analysis of Space-Time of Action tell us about medium-term changes in adults' and children's access to place of activity? The example of Bogotá

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Abstract

This article draws on the space-time prism as formalized in time-geography (Hägerstrand 1970) and on spatial analysis methods to examine medium-term changes to household members' access to place of activity, against the backdrop of urban change. The analytical framework thus uses the concept of *Space-Time of Action* (Demoraes et al. 2020a), referring to the combination of all the places of work or study that individuals go to, and the time taken to reach them from home. The analysis is based on two surveys conducted in Bogotá (Colombia) in 1993 and 2009 to apprehend individuals' spatial mobilities. Two groups at different stages in their life course and co-residing in the same households are studied: schoolchildren and working adults. First, Space-Times of Action are calculated and mapped using kernel outer rings delineating the concentration of destinations for the two groups and the nine survey zones at each date. Second, the statistical significance of the discrepancies between Space-Times of Action is assessed using a bivariate colocation test. The test indicates overall stability in children's access to place of schooling, but a more contrasting situation for adults.

Keywords

Medium-term urban change, joint accessibility, daily mobility, Space-Time of Action, spatiotemporal mismatch, life course stage, diachronic analysis, bivariate colocation test, Bogotá

Résumé

S'inspirant à la fois du prisme spatio-temporel formalisé dans la time-geography (Hägerstrand 1970) et mobilisant des méthodes d'analyse spatiale, cet article a pour but d'étudier la façon dont l'accès des membres des ménages à leur lieu d'activité a évolué sur le moyen terme à l'aune des changements urbains survenus sur la même période. Pour ce faire, l'analyse repose sur le concept d'espace-temps d'action (Demoraes et al. 2020a) entendu comme l'ensemble des lieux de destination des individus pour le travail et les études, et le temps qu'ils mettent pour s'y rendre au quotidien depuis leur domicile. L'analyse s'appuie sur deux enquêtes conduites à Bogotá (Colombie) en 1993 et 2009, pour appréhender les mobilités spatiales des individus. Deux groupes à des étapes différentes du cycle de vie et qui corésident au sein des mêmes ménages sont étudiés : les écoliers et les adultes actifs. Dans un premier temps, les espaces-temps d'action sont calculés et cartographiés en gardant les limites extérieures des noyaux de concentration des lieux de destination obtenus par lissage spatial pour les deux groupes et les neuf zones d'enquête aux deux dates. Ensuite, la significativité statistique des écarts entre les espaces-temps d'action est évaluée à l'aide d'un test de colocation bivarié. Le test indique une stabilité globale dans l'accès des enfants à leur école et une situation plus contrastée pour les adultes.

Mots-clefs

Changement urbain de moyen terme, accessibilité conjointe, mobilité quotidienne, espace-temps d'action, découplage spatio-temporel, étape biographique, analyse diachronique, test de colocation bivarié, Bogotá

Resumen

Basándose en el prisma espacio-temporal formalizado en la time-geography (Hägerstrand 1970) y utilizando métodos de análisis espacial, este artículo tiene por objeto examinar cómo ha evolucionado a mediano plazo el acceso de los miembros de los hogares a su lugar de actividad en acorde con los cambios urbanos durante el mismo período. Para ello, el marco analítico utiliza el concepto de espacio-tiempo de acción (Demoraes et al. 2020a) entendido como el conjunto de lugares donde las personas van a trabajar y estudiar y el tiempo que tardan en llegar allí diariamente desde su lugar de residencia. El análisis se basa en dos encuestas realizadas en Bogotá (Colombia) en 1993 y 2009 diseñadas para aprehender las movilidades espaciales de los individuos. Se estudian dos grupos en diferentes etapas del ciclo de vida y que co-residen dentro de los mismos hogares: los escolares y los adultos que trabajan. En un primer paso, se calculan y cartografían los espacios-tiempos de acción utilizando los límites exteriores de los núcleos de concentración de los lugares de destino, obtenidos mediante el alisamiento espacial para los dos grupos y las nueve áreas de estudio en ambas fechas. A continuación, se evalúa la significatividad estadística de las diferencias entre los espacios-tiempos de acción mediante una prueba de colocación bivariada. La prueba indica una estabilidad general en el acceso de los niños a su escuela y una situación más contrastada para los adultos.

Palabras clave

Cambio urbano de mediano plazo, accesibilidad conjunta, movilidad diaria, espacio-tiempo de acción, desajuste espaciotemporal, etapa biográfica, análisis diacrónico, prueba de colocación bivariada, Bogotá

Introduction: household trips, joint mobility of parents and children, and urban change

As stated in Demoraes et al. (2020a), “many studies in environmental psychology, sociology, demography, and geography have demonstrated the relevance of studying jointly the mobility of household members. Their daily trips start from the same place of residence, whose location influences the mobility practices of each member”. In terms of daily travel distance or time, some home locations may benefit certain members to the detriment of others, given that the mode of transport and travel times of each individual tend to influence those of the others (Hägerstrand 1970, Pratt and Hanson 1991, Singell and Lillydahl 1986, Aguiléra et al. 2010). For France, mention may be made of the work by Berger and Beaucire (2002) on trade-offs regarding residential mobility and commutes within households in the Ile-de-France, and that by Jouffe et al. (2015) on the plans and tactics of poor households on the outskirts of Paris for coping with mobility inequalities. Equally, Massot and Proulhac (2010) have examined the link between working adults' lifestyle and mobility in Ile-de-France. In Latin America, Pérez López and Capron (2018) have studied arrangements and negotiations over car use in families in Mexico. Gouëset et al. (2015) have examined how spouses in Bogotá combine their commutes as a function of their income, and at the combination of their modes of transport.

Still focusing on the family unit, other scholars adopting qualitative approaches have analyzed compromises or negotiations in families' everyday mobility, and looked at the joint daily journeys of parents and children, the latter being economically dependent on the former and reliant on where their parents reside (Jensen et al. 2015, Nansen et al. 2015, Rau and Sattlegger, 2018, Waitt and Harada 2016). Depending on the age of the children studied, scholars have analyzed the spatiotemporal interdependence of trips by adults and children, or, on the contrary, the extent to which children's trips are independent of those of their parents (Depeau and Ramadier 2005), both for daily commutes (McDonald 2008, Tigar McLaren 2018, Fyhri et al. 2011) and for journeys made during free time or for leisure activities (Depeau et al. 2017). In many countries, such as in France with its system of school zoning, primary and secondary school children tend to travel a short distance from their place of residence. To apprehend these joint mobilities and resultant family trade-offs, sophisticated data collection procedures have been developed. One instance of this is the longitudinal procedure developed in France for the ANR MOBIKIDS research program (Depeau et al. 2019), relating specifically to children in transition between their final year at primary school and first year at secondary school.

The variables selected for these studies tend to be distance (either Euclidian or network-based), travel time, mode of travel, frequency of trip by purpose, income or social position, level of education, gender, and age. It may be noted that these works tend not to analyze or map the spatial location of daily itineraries by co-resident individuals, except that by Depeau et al. (2017). Furthermore, as stated in Demoraes et al. (2020a), “with only a few exceptions (Aguiléra et al. 2010, Berger and Beaucire 2002, Fyhri et al. 2011), these studies tend to examine joint mobility practices at a given point in time, thus precluding examination of how they change over the course of one or two decades. Lastly, they do not analyze how travel times or the destinations of individuals residing in the same neighborhood may evolve against the backdrop of contextual medium-term changes”. One such

change is alterations to demographic structure, such as the ageing of the population or alterations to household composition, with single-parent families and dual-income couples now being more numerous. Changes also stem from transformations linked for instance to urban sprawl, shifts in areas of employment or education, alterations to the transport system, deepening residential segregation, and so on and so forth.

Drawing on the space-time prism as formalized in time-geography (Hägerstrand, 1970) and on a spatial analysis approach, this article sets out to examine medium-term changes to adults' and children's access to place of activity in the city. We also seek to understand how the mobility conditions for these two groups at different stages in their life course have changed depending on where they reside in the city. The article works primarily with the concept of Space-Time of Action (STA) which provides a way of gauging one aspect of individuals' access to urban space. The analysis is based on data about commutes by working adults and their co-resident children gathered during two surveys at a sixteen-year interval in Bogotá (Colombia). The first survey was conducted in 1993 as part of a joint program headed by F. Dureau (ORSTOM) and C.E. Flórez (CEDE: Centro de Estudios sobre Desarrollo Económico de la Universidad de los Andes). The second was carried out in 2009 as part of the METAL research program headed by F. Dureau and funded by the French National Research Agency, under the title: "Latin American metropolises in globalization. Territorial reconfigurations, spatial mobility, public action".

The first section introduces the relevance of the concept of STA for assessing individual's access to their place of activity. Bogotá, the city for which STAs have been calculated, is presented in section 2. Section 3 details the material used, the population studied, the method for calculating and mapping STAs, and the statistical test used to check if they have evolved over time. Results are discussed in section 4. All GIS processing was performed in SavGIS, a freeware GIS (www.savgis.org).

1. The concept of Space-Time of Action: a way of assessing individuals' access to places of activity

The concept of Space-Time of Action derives from the concept of Action Space, used in the human and social sciences since the 1930s (Von Dürckheim 1932, Lewin, 1951). The concept of Action Space is found in studies about migration (Wolpert, 1965), in cognitive and behavioral studies (Höllhuber 1974, Golledge and Stimson 1997), and in those about daily or weekly mobilities (Dijst 1999, Janelle and Goodchild 1983, Noël et al. 2001). Dijst (1999) provides the following definition: "the spatial unit in which the activity spaces are located and which have been visited by a person during some period of time is called the actual action space".

Action space is thus based on a set of places that an individual or group of individuals visit, primarily described using spatial metrics (mean position, dispersal, size, or distance from home). But as pointed out in Demoraes et al. (2020a), "working solely with spatial metrics is far from satisfactory if we are to apprehend individuals' access to their place of activity. Indeed, spatial metrics conceal many aspects of mobility conditions, particularly travel times. It is especially important to include the time of travel, for travel time may vary greatly for a given distance

depending on the mode of transport, any connections needed (with it often easier to travel from center to periphery than from periphery to periphery), as well as the availability of a mass transit system near the place of residence”.

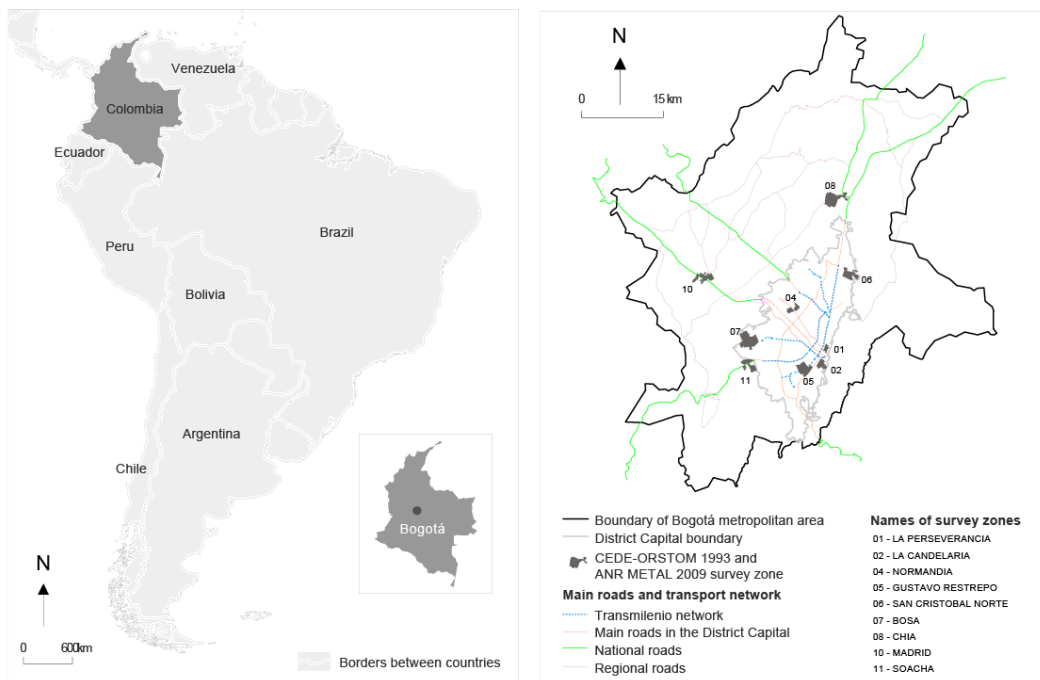
For this reason, Demoraes et al. (2020a) suggest the concept of Space-Time of Action, referring to “all the destinations visited by individuals for work or study, together with the time they take to reach them from their home on a daily basis”. The concept of STA has the advantage of broadly re-transcribing several dimensions of how individuals or groups of individuals access urban space. Indeed, following the definition put forward in Bavoux and Chapelon (2014), “four main components of accessibility may be identified: (1) the performance of the transport networks used and services delivered, expressed in terms of time, expenditure, and/or effort, determining how easy or difficult the trip is; (2) the nature and spatial distribution of the resource to reach; (3) time constraints relating to social functioning (working hours, the time at which the school day starts and finishes, when shops open and shut, etc.); (4) the characteristics of the individuals prone to travel (age, physical aptitude, income, education, etc.)”. The concept of STA includes the first component, for travel times account not only for distance from the destination but also for the performance of the mode of transport used, and indirectly for difficulty in travelling. It also includes the second component, for it resumes the nature of the places to reach (work or study) and their spatial distribution. Travel times are also indicators of hours of work or study (the third component) in so far as, all other things being equal (the same mode of transport from the same point of departure to the same destination), the time spent travelling varies depending on whether it is rush hour or not. In the case of commutes, most take place at rush hour. Lastly, STA can also be calculated for groups sharing the same characteristics (the fourth component), and so be compared.

In Latin America, travel times are especially linked to individuals' sociodemographic characteristics, being longest for the most disadvantaged (Antico 2003, Cosacov 2015, Demoraes et al. 2010, Jirón 2009, Jirón et al. 2010, Jouffe 2011), even though place-specific effects may alter this general tendency (Demoraes et al. 2012). Indeed, individuals from disadvantaged households residing in central spaces may have relatively shorter travel times. This is, however, only infrequently the case.

2. Bogotá, a city undergoing transformation

Bogotá is the capital of Columbia (map 1). It is a city undergoing extensive transformation due to the vigorous urban and demographic dynamics at work there (Dureau, Lulle et al. 2014), and to its having followed since the early 1990s globalized urban models, such as that of Barcelona (Montoya 2014). The metropolitan area of Bogotá is composed of a very extensive city center, the District Capital (DC), subdivided into 20 *localidades* or localities, together with 19 suburban municipalities (map 2). The city center is heavily populated, with 4.9 and 6.7 million inhabitants respectively at the time of the two censuses (1993 and 2005) closest to the two surveys used in this article, amounting respectively to 90% and 88% of the total metropolitan population. Nevertheless, demographic growth in the central localities of the DC has since slowed (map 2), with the highest growth rates now being in the outer localities, and especially in the municipalities outside the DC (Le Roux 2015).

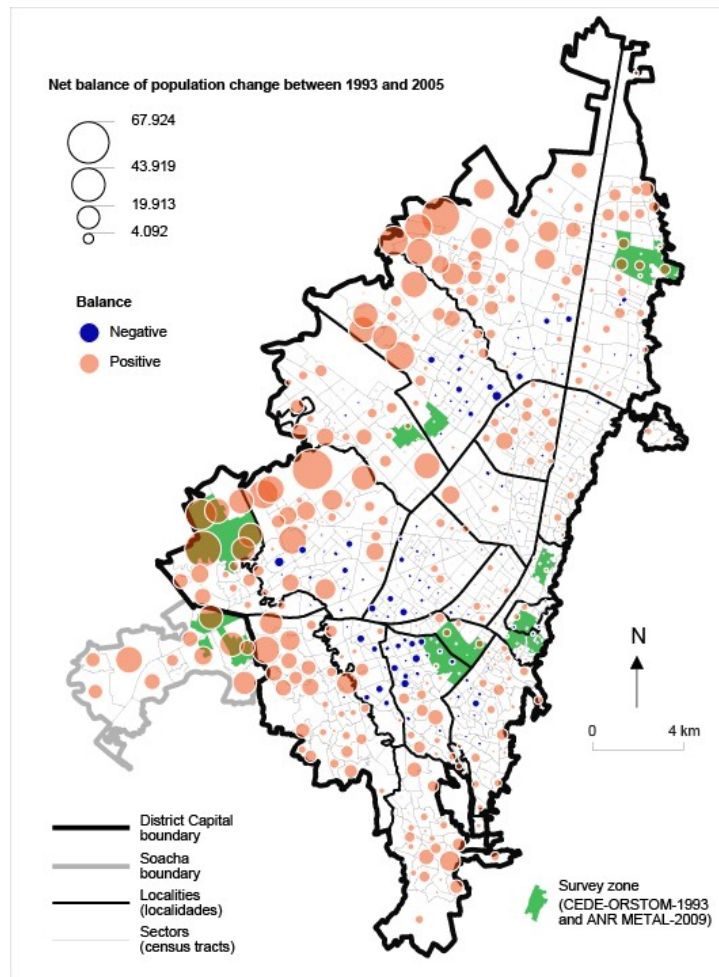
Map 1: The location of Bogotá, main roads, transport network, and location of the nine survey zones at both dates (1993 and 2009) in the metropolitan area



Left insert: author: F. Demoraes. Source: GADM maps and data (https://gadm.org/download_country_v3.html)

Right insert: author: G. Le Roux (2015: 129). Source: ANR METAL GIS database.

Map 2: Changes to population distribution between 1993 and 2009 in the District Capital of Bogotá and Soacha

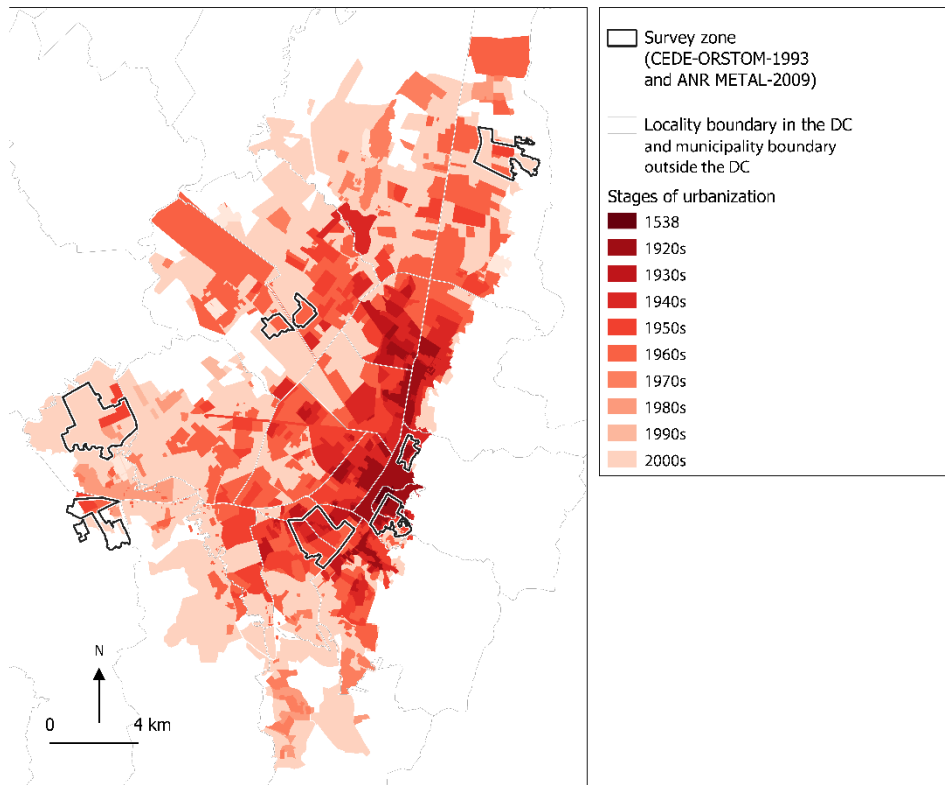


Authors: F. Demoraes. Sources: DANE 1993, 2005. Data processing: A. Salas, ANR METAL

The process of urban sprawl in Bogotá (map 3) has been well documented by various researchers (Garavito and De Urbina 2019, Montoya 2012, Salazar et al. 2014). Between 1990 and 2010, the area of the District Capital increased from 241km² to 327km². Over these two decades, urban sprawl filled in the interstitial gaps between built-up areas in the first outer-ring, and also reached the outskirts.

This urban sprawl was accompanied by changes in socio-residential segregation. Socio-residential segregation is a classic process in Latin America (Carman et al. 2013, Capron and González Arellano 2006, Demoraes 2015, Dureau et al. 2014c, Kilroy 2007, Schteingart 2001). In Bogotá, the wealthier classes (photo 1) have long been concentrated in the north-east of the District Capital, and the poorer classes (photo 1) have long been relegated to the southern and north-western edges of the DC and to most of the suburban municipalities (Demoraes et al., 2011; Dureau, 2000; Dureau, Contreras et al. 2014; Salas, 2008).

Map 3: Urban sprawl in the District Capital of Bogotá until 2010



Author: F. Demoraes. Adapted from Garavito and De Urbina 2019.

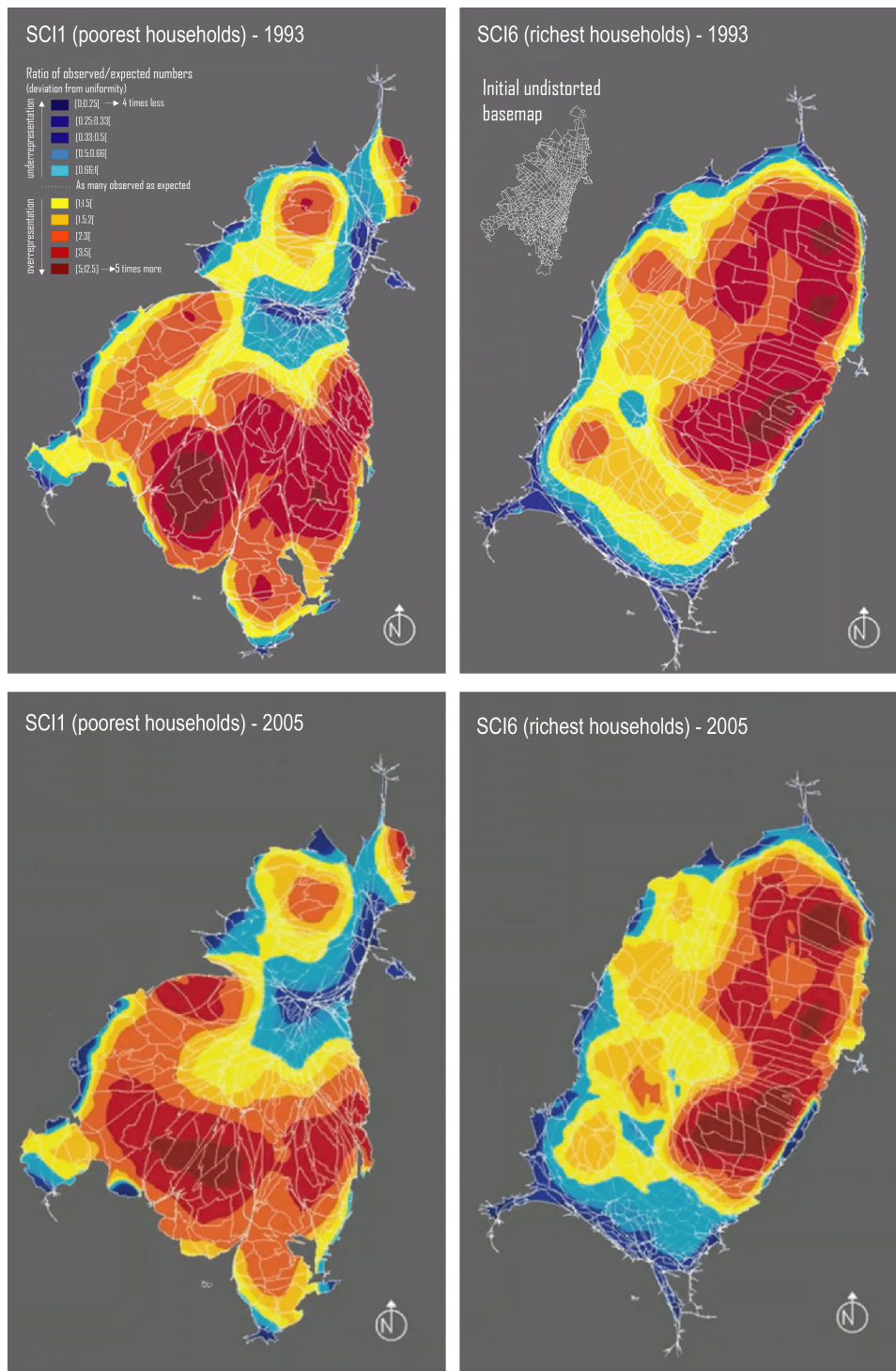
Photo 1 – Example of deprived housing in the southern outskirts versus upmarket building in the north-east of the District Capital of Bogotá



Credits: V. Gouëset, 2020 (left) and 2018 (right)

A recent analysis in Demoraes et al. (2021) based on the two censuses (1993 and 2005) closest to the two surveys used in this article brings out the continued existence of this segregated model in Bogotá, particularly at either end of the social hierarchy (map 4).

Map 4: Evolution of socio-residential segregation between 1993 and 2005 based on the household's Social Condition Index (SCI) in the District Capital of Bogotá and Soacha

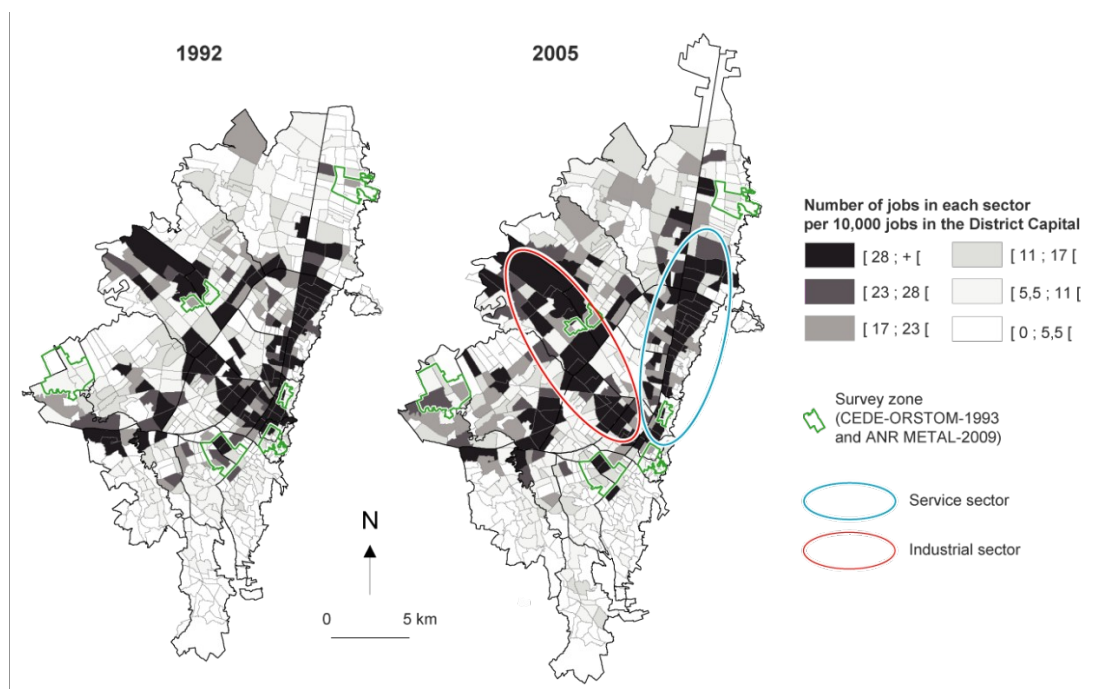


Author: F. Demoraes. Adapted from Demoraes, Bouquet, and Mericskay 2021. Sources: DANE 1993 and 2005 - Initial data processing: A. Salas, M. Piron, and F. Dureau - Base map: A. Lepetit and F. Bahoken.

On the cartogram, the size of the spatial units is distorted as a function of the number of households classed using the Social Condition Index (SCI). The SCI is a commonly used index in Latin America (Barbary et al., 1999; Dureau et al., 2007; Salas, 2008; Le Roux, 2015; Demoraes et al. 2020c). It is obtained from individual census data. The index is calculated as follows: the educational climate (average years of education of people aged 15 and over in the household) is divided by the promiscuity index (number of people in the household divided by the number of rooms in the dwelling). We here retain solely classes 1 (SCI1) and 6 (SCI6), corresponding respectively to the poorest and richest 10%. The smoothed surface conveys the ratio of *observed numbers* to *expected numbers* were the distribution of households spatially uniform, a distribution which would thus correspond to that of a non-segregated city. This ratio shows what could be called the *deviation from uniformity* for each SCI. When the ratio is above 1, this means that there is an overrepresentation, and vice versa.

These processes of urban sprawl and segregation, together with the fragmented (Alfonso 2012) or polycentric pattern of Bogotá (Beuf 2011, Le Roux 2015), mean that resources are unequally distributed across the metropolitan areas. Work opportunities are spatially concentrated (map 5), with job density tending to disadvantage the poorer localities and municipalities. This urban model, which is very common in Latin America, places major constraints on people's daily mobility. Commutes are much longer, take more time, and are much more expensive for households living far away from the inner city of Bogotá. The level of public transport service is much lower and more informal in the outskirts. Moreover, in 2009 suburban municipalities still did not have an integrated transport system with the DC (Moreno 2016).

Map 5: Changes to the distribution of jobs in the District Capital of Bogotá between 1992 and 2005



Author: F. Demoraes, taken from G. Le Roux (2015: 129). Sources: for 1992, taken from F. Dureau (2000: 249); for 2005, taken from DANE 2005. Data processing: G. Le Roux

Concerning education, a broad distinction may be made between two different rationales, one pertaining to primary and secondary schools, the other to higher education. In the first case, public schools are uniformly distributed in space, while the best reputed private schools are concentrated in the upmarket districts or suburban municipalities (particularly in Chía, see map 1). The universities are mainly concentrated in the city center and on the northern outskirts of Bogotá, with certain specific improvements between the two dates: while mid-quality technological and higher education courses became available in the poorer outskirts, more upmarket university courses developed in the wealthy localities of the capital and in the municipality of Chía.

Lastly, transport service provision is another important variable in changes to daily mobility in Bogotá. This is characterized by recent growth in household car ownership rates. According to the 2005 and the 2011 origin-destination surveys conducted in the Bogotá Metropolitan area (SDM, 2005 and SDM, 2011), these rates rose from 30% to 41% between the two dates. Another key process over this period was the modernization of public transport with the commissioning of a Bus Rapid Transit (BRT) system as of 2001, known as the *Transmilenio* (map 1). Broadly speaking, and as shown in Gouëset et al. (2014), cars still tend to be the preserve of the wealthy, while poor people walk, travel by bus, bike, or motorbike. The only mode of transport used by all social classes in Bogotá in 2009 was the *Transmilenio*.

3. Material and method of analysis

3.1. Material used: two surveys for apprehending changes to spatial mobility in Bogotá between 1993 and 2009

Our analysis is based on two surveys conducted in Bogotá, devised in the wake of work by the GRAB research initiative (steered by INED—the French National Institute for Demographic Studies) to apprehend individuals' spatial mobilities from a biographical perspective. The first of these was the 1993 CEDE-ORSTOM survey headed by Dureau and Flórez, in which 922 households and 3,973 individuals were questioned; the second was the 2009 ANR-METAL survey, headed by Dureau, in which 881 households and 3,256 individuals were questioned. Their respective purposes and methodologies are detailed in Dureau et al. (1994) and Dureau et al. (2011 et 2015). In these surveys, spatial mobility was studied in a global approach including all mobilities irrespective of distance (intra-urban travel or to the rest of the national territory or abroad) and travel time (ranging from daily trips to migrations). Nine survey zones were common to the two dates (map 1).

These zones constitute an illustrative mosaic of the range of socio-economic profiles, housing conditions, and urbanization stages (map 3) in the Bogotá metropolitan area. This diversity derives directly from the sampling method implemented in the 1993 and 2009 projects (Dureau et al., 1994; Dureau et al., 2011), whose objective was to confirm the influence of these parameters on households' mobility. These zones thus bring out the wide variety of daily mobility strategies households use, and also show highly contrasting levels of access to activity places as analyzed in Demoraes et al. (2020a; 2020b), Dureau et al. (2013) and Dureau, Gouëset et al. (2014). It

should be noted that the households surveyed at the two dates were statistically representative of their zone of residence. It should also be noted that it was not a longitudinal survey, for the households surveyed in 1993 were not the same as those surveyed in 2009.

This article uses only one component of these two surveys, namely commutes from home to place of activity (place of work and place of study), collected in similar fashion at both dates. Given the purpose of the surveys (an overall understanding of all forms of mobility throughout the life cycle), and the quantity of information which may be gathered in a reasonable length of time using a questionnaire, sequences within daily journeys were not recorded. We therefore do not have details about the routes through the city, only about one destination per day per individual recorded at the level of sectors, which is a fairly fine-grained spatial level (there being 630 sectors in all in the Bogotá metropolitan area, map 2). In addition to destination, we also have data for both dates concerning mode of transport and travel time.

The fact that there is only one destination per day and per person (the place of work or study) implies that the accessibility we characterize is only one facet in individuals' overall accessibility to the city's resources. In Bogotá, this overall accessibility is in fact not so different from that measured based solely on places of work and study. Indeed, the last three major origin-destination surveys in 2005, 2011, and 2019 respectively show that in Bogotá, 59%, 57%, and 55% of trips were made to work or study (excluding the return home). Most trips are therefore essential, non-delegable, and non-deferrable (except in the context of a pandemic), and clearly mark the pulse of the city. Furthermore, polygonal mobility in Bogotá is rare, i.e., on days when a person is working or studying, they make very few trips on the same day for other purposes. This is due both to the high cost of transport in relation to household income and to the length of the journeys, which involve leaving home very early in the morning and returning very late at night with no time for other activities. In addition, the working week is 48 hours, also leaving little time for other activities.

As already pointed out in Demoraes et al. (2020a), "both CEDE-ORSTOM and ANR-METAL surveys are precious sources of data without equivalent for Bogotá for the period under consideration. One of the limits to detailed study of daily mobility in Colombia, as in many Latin American countries, relates to the paucity of secondary sources, mainly origin-destination surveys and, to a lesser extent, population censuses". Origin-destination surveys provide overall knowledge about daily trips (their frequency and intensity) depending on age, gender, mode of transport, purpose, and income. They also provide information about household car ownership rates. These surveys have the advantage of being representative of the entire city and being conducted regularly, following a largely standardized methodology enabling diachronic analysis. However, in the case of Bogotá, the first major standardized OD survey dates from 2005. An earlier survey exists for 1996, financed by Japan, but it was devised using a specific methodology and sectorization, precluding comparison with the 2005 survey. Furthermore, it is not possible to access individual data for the 1996 survey. The only available results are aggregated by sector, making it impossible to study jointly the mobilities of various household members. The CEDE-ORSTOM and METAL surveys are thus the only sources for analyzing the changing conditions in which

commutes were conducted by Bogotá households during the 1990s and 2000s, a pivotal period characterized, as seen earlier, by the mass expansion in the number of private cars and the commissioning of the *Transmilenio*.

3.2. Selection of the study population

To meet our objective of understanding medium-term changes in how co-residing children and adults access their activity places, we selected households with at least one working individual (with a main or secondary paid activity, including at home) and at least one child in primary or secondary education (table 1). We thus retained 49% of households surveyed in 1993, and 44% of those surveyed in 2009. We excluded students from our study, because there were too few of them among the households surveyed, especially in 1993, and so analyzing them would have led to insignificant results.

Table 1: Distribution of households in Bogotá with at least one working adult and one child in education, by survey zone in 1993 and 2009 and by category of individual (working adults, schoolchildren)

Survey zone (Id)	Number of households		Number of individuals		Number of schoolchildren		Number of working adults	
	1993	2009	1993	2009	1993	2009	1993	2009
Bosa (07)	50	57	165	190	86	90	79	100
Chía (08)	29	27	101	81	44	32	57	49
Gustavo Restrepo (05)	51	52	185	156	89	65	96	91
La Candelaria (02)	53	47	181	146	98	69	83	77
Madrid (10)	49	47	182	162	96	88	86	74
Normandía (04)	46	26	158	70	61	19	97	51
Perseverancia (01)	44	19	144	58	73	26	71	32
San Cristobal Norte (06)	66	35	233	108	126	50	107	58
Soacha (11)	46	50	155	165	75	69	80	96
Overall total	434	360	1504	1136	748	508	756	628

Sources: CEDE-ORSTOM 1993 and ANR METAL 2009 surveys, Bogotá. Data processing: F. Demoraes. Reference population: individuals co-residing in households where at least one adult is in paid work (either at home or outside place of residence) and where at least one child is in education (primary or secondary school). NB: the numbers are of individuals with a known destination in the Bogotá metropolitan area.

3.3. Principle and method of calculating Space-Time of Action for groups of individuals

The principle for calculating Space-Time of Action we adopted in this article is inspired by that detailed in Demoraes et al. (2020a, 2020b). STAs were calculated at an aggregated level, that is, by category of individual (working adults, schoolchildren) and for each survey zone for the two dates (1993 and 2009) so as to detect changes in how these categories access their activity place on a daily basis. Each category for each survey zone and for each date is hereafter referred to as a group.

To calculate the STAs, we used location of place of residence (at the city block scale), location of place of activity (at the sector scale), and travel time. These three variables were processed using a series of GIS operations. This comprised three main stages. The first two stages are individual-based, and the same as those in Demoraes et al. (2020b). We refer the reader to this work for further explanation about these first two stages. The third stage is group-based and derived from that in Demoraes et al. (2020a). The three stages are the following: 1. Calculating distances and speeds 2. A series of translations 3. A series of calculations of smoothed surfaces and kernel outer rings.

3.3.1. First stage: calculating distances and speeds (individual level)

In the surveys we used, different travel times may be assigned to a single destination, either because individuals go there from different places, or because individuals departing from the same place of residence do not use the same mode of transport. It was thus a matter of retaining the times of individual trips for each destination to bring out any variations in how individuals access their activity place. In this first stage, calculations were therefore made at an individual level.

The first step consisted in calculating the Euclidean distance for each origin-destination pair in 1993 and in 2009, and in calculating average speed of travel for each pair.¹ The second step consisted in calculating overall average speed of travel for all the origin-destination pairs in 1993 and 2009. Since the objective was to define a synthetic measure of access to place of activity, we did not break this down into speed by mode of transport. It should be noted that for our reference population, overall average speed did not change between 1993 and 2009 (10.8km/h). In the third step, this average overall speed was used to calculate a Distance-Time, corresponding to the distance an individual would have travelled in the length of time recorded for their actual journey had they been travelling at the overall average speed. This distance-time was calculated using the following formula:

$$\text{Distance Time} = \frac{\text{OD Euclidean distance m} * \text{Overall average speed m/min}}{\text{Speed m/min}}$$

¹ Expressed in meters per minute (m/min).

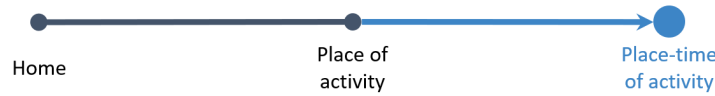
3.3.2. Second stage: translation operations (individual level)

In this second stage, calculations were once again made at an individual level. Distance-Time was used to calculate the location of what we called Place-Times of Activity (PTAs). These lay at different distances aligned with the initial origin-destination segment (maps 5). PTAs are shifted as follows:

= nearer to home when the individual reaches the place more quickly, i.e. at greater speed than overall average speed,

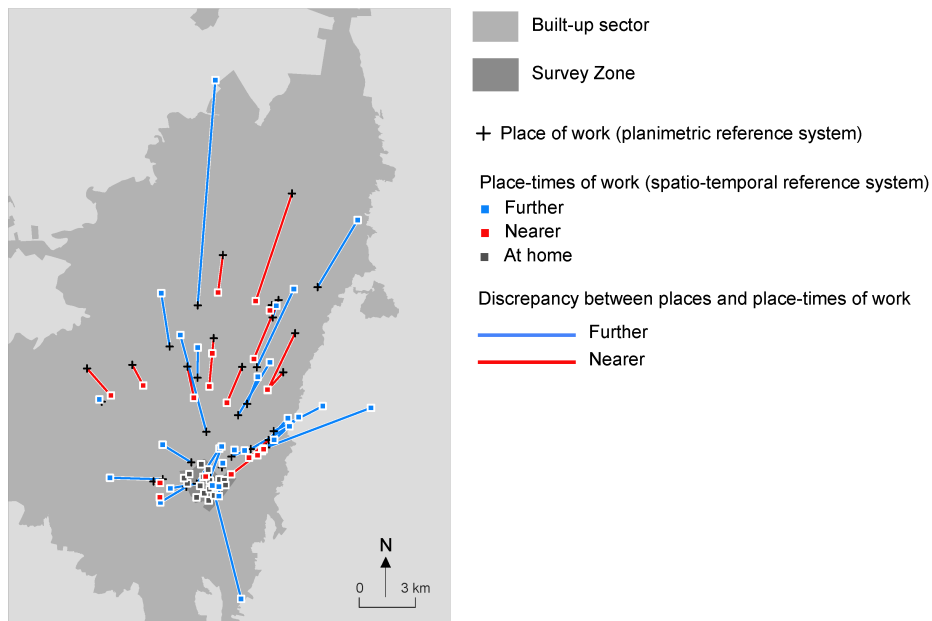


= further from home when the individual reaches the place less quickly, i.e. at less than overall average speed.



The PTA coordinates were calculated by applying trigonometric principles (more detail in Demoraes et al. 2020a). The location of PTAs is not solely geographic, since they include a time dimension (derived from travel time). PTAs were thus positioned in a new, spatiotemporal reference system. Map 6 shows the results of the operation for the group of working adults residing in the *Gustavo Restrepo* survey zone in 1993.

Map 6: Comparison for working adults residing in 1993 in Gustavo Restrepo (Bogotá) of Activity Places (in blue) and Place-Times of Activity (in red), positioned respectively in planimetric and spatiotemporal reference systems



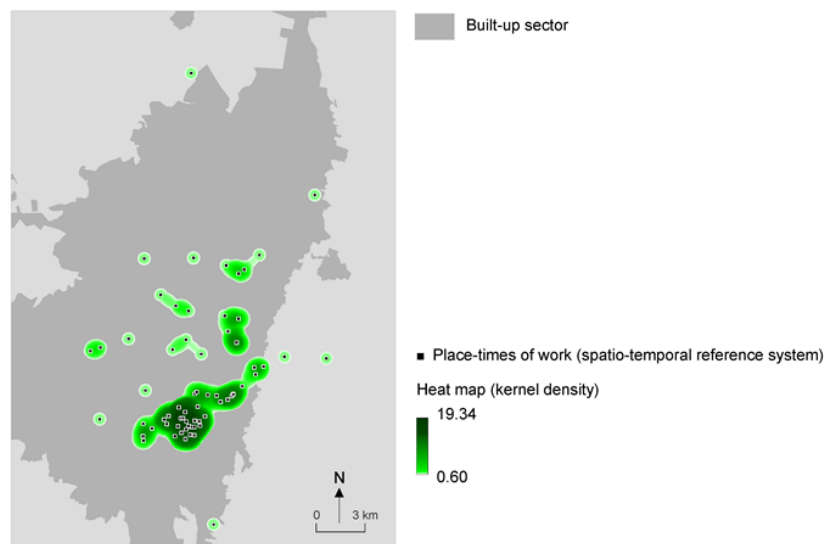
Author: F. Demoraes. Source: 1993-CEDE-ORSTOM survey.

3.3.3. Third stage: smoothed surfaces and kernel outer rings (aggregate level, group-based)

The locations of PTAs form a simple point pattern that can be summarized to shape a STA for each category of individual (working adults, schoolchildren) and for each survey zone for the two dates (1993 and 2009). Several methods (standard deviational ellipses, travel probability fields, kernel density estimations, convex-hull polygons, Cassini ovals, bean curves, etc.) exist for summarizing and visualizing point patterns. For an extensive review of these mapping techniques, see Schönfelder and Axhausen (2003), Rai et al. (2007), Lord et al. 2009, Patterson and Farber (2015), and Vich et al. (2017).

We experimented with three of these methods, namely standard deviational ellipses, convex-hull polygons, and kernel density estimations, which seemed well suited to our data and for mapping STAs at an aggregated level, by group of individuals in our case. In the end, we opted for kernel density estimations, also called smoothed surfaces or heat maps (map 7). We used these surfaces mainly because they schematize very accurately the spatial distribution of the point patterns, unlike standard deviational ellipses which are far too sketchy. We also discarded convex-hull polygons which connect the furthest removed points without taking the distribution of the other points into account, thus tending to exaggerate the extent of STAs. More specifically, after several trials, we used the following parameters to compute the smoothed surfaces: a 1000-meter-bandwidth,² a triangular smoothing function,³ and a sum function to calculate local concentrations.

Map 7: Kernel density estimation (heat map) symbolizing the Space-Time of Action of working adults residing in Gustavo Restrepo in 1993 (Bogotá)



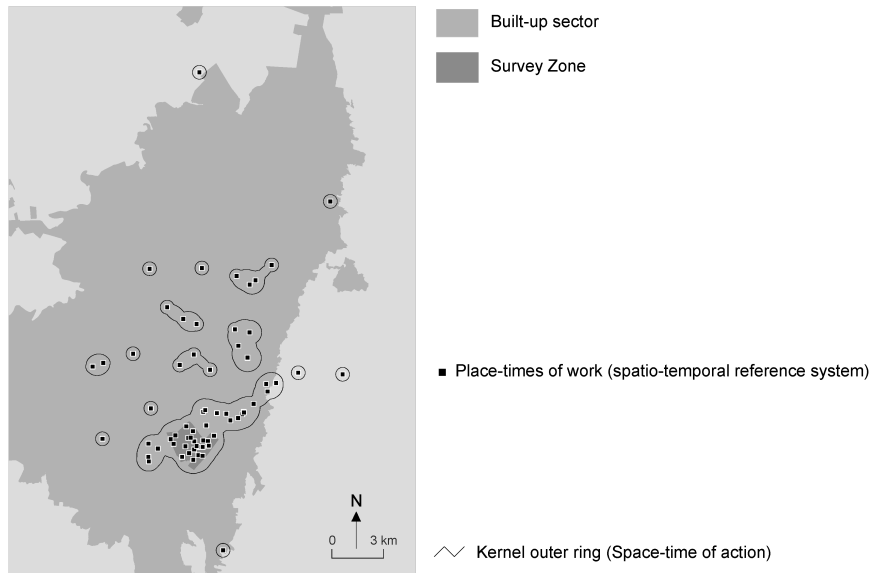
Author: F. Demoraes. Source: 1993-CEDE-ORSTOM survey.

² This bandwidth is a compromise to ensure a minimum number of PTAs are considered for the smoothing calculation given the nearest neighbour distance among PTAs. It also avoids excessively enlarging the STA around the furthest removed points.

³ The triangular function relies on a linear decreasing function of the weight of the neighbours to be considered in the calculation. It thus gives an aesthetic result with a regular colour scaling.

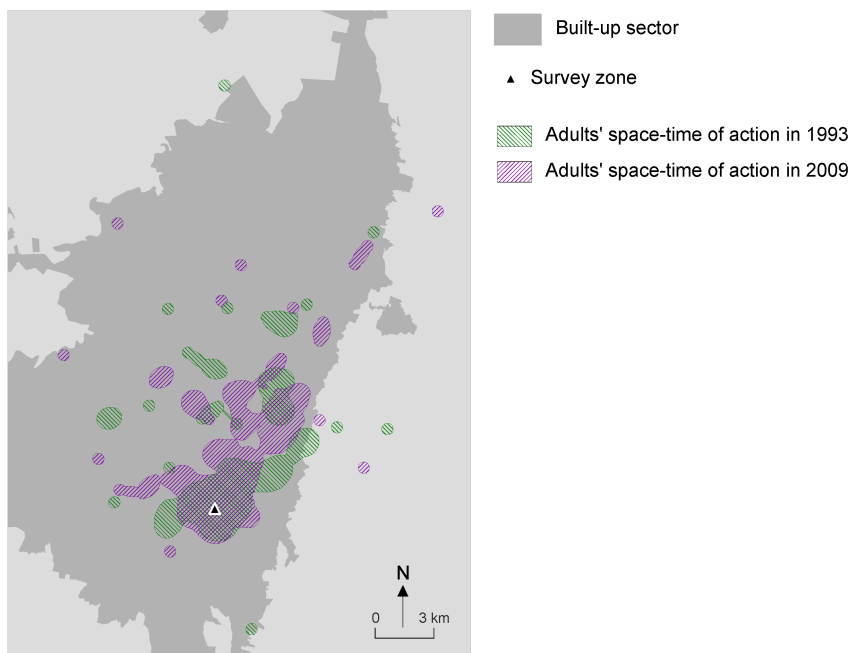
To display the STA of two groups on a single map (and so detect any changes between 1993 and 2009) and to better delineate the STAs, we vectorized the heat map (initially a raster layer). For each group, this produced a kernel density outer ring which is a polygon encompassing all the PTAs of a group (map 8 and map 9).

Map 8: Kernel density outer ring delineating the Space-Time of Action of working adults residing in Gustavo Restrepo in 1993 (Bogotá)



Author: F. Demoraes. Source: 1993-CEDE-ORSTOM survey.

Map 9: Kernel density outer rings delineating the Space-Times of Action of working adults residing in Gustavo Restrepo in 1993 and in 2009 (Bogotá)



Author: F. Demoraes. Sources: 1993-CEDE-ORSTOM and 2009-METAL surveys.

We applied the same method for the two categories of individuals (working adults, schoolchildren) in the 9 survey zones for the two dates. We therefore computed 36 STAs portrayed in 18 faceted maps (map 10). Visual examination of these maps indicates apparent discrepancies between STAs in many cases, but may we really detect changes between 1993 and 2009 in how groups of individuals access their place of activity?

Map 10: Kernel density outer rings delineating the Space-Times of Action of working adults and of schoolchildren residing in the nine survey zones in 1993 and in 2009 (Bogotá)



Sources: CEDE-ORSTOM 1993 and ANR METAL 2009 surveys - Bogotá - Author: Florent Demoraes - Software: SaviGIS

Author: F. Demoraes. Sources: 1993-CEDE-ORSTOM and 2009-METAL surveys.

4. Assessing the significance of the differences between Space-Times of Action using a bivariate colocation test

Space-Times of Action can be modeled as two-dimensional objects. We therefore used a spatial statistical test to assess the significance of the spatial differences between these objects. More specifically, we selected a bivariate colocation test primarily used in spatial epidemiology (Souris and Bichaud 2011). This test ascertains whether, overall, the points of one spatial distribution are significantly close to points of a second spatial distribution. Souris and Bichaud applied this colocation test to check if cases of two diseases were spatially congruent. We selected this test for our study because it seemed well suited to checking any discrepancies between the STAs associated with the groups described earlier. A first attempt at applying the bivariate colocation on action spaces in Santiago de Chile may be found in Demoraes, Souris et al. (2021). A formal description of this test, detailed in Souris (2019: 135-136), is summarized below.

The bivariate colocation test works on the following principles. Let S_1 represent a set of N_1 locations, S_2 a set of N_2 locations. Each location is characterized by a Boolean mark (0 or 1). P_1 is the set of positive locations in S_1 , and P_2 the set of positive locations in S_2 . In our case, P_1 represents the PTAs of the individuals belonging to group 1 (for instance, schoolchildren living in *Gustavo Restrepo* in 1993), and P_2 the PTAs of the individuals belonging to group 2 (to keep the same example, schoolchildren living in the same survey zone in 2009). First, the Euclidian distance between each PTA from group 1 and its closest PTA from group 2 is calculated. Second, the mean of these distances is computed. This mean is hereafter referred to as the index.

Two hypotheses can be stated:

- a null hypothesis H_0 : the observed index cannot be differentiated from the indices obtained by a random spatial distribution of the positive marks. If the test returns H_0 , no spatial relation between the two point patterns can be detected. In this case, it cannot be said that there was any stability or, on the contrary, any significant change in how groups of individuals access their place of activity;
- an alternative hypothesis H_A : the probability of obtaining the observed index by chance is lower than a determined α value (0.05 for instance). If the test returns H_A , a spatial relation between the two point patterns does exist. In this case, the relation can either be a significant similarity (no change) or a significant dissimilarity (significant change) as we shall see below.

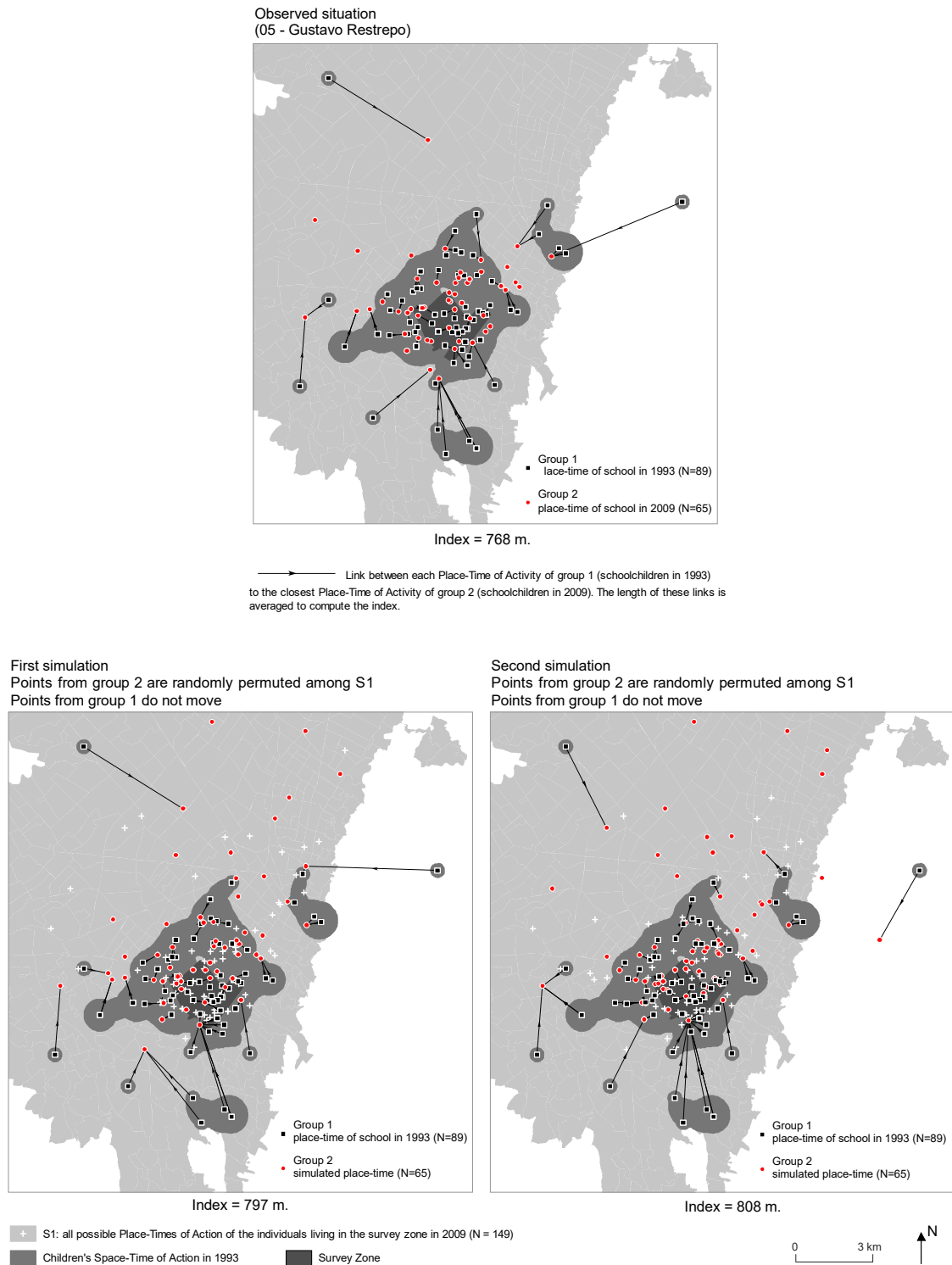
The statistical distribution of the index under the H_0 hypothesis is estimated using a Monte Carlo simulation (4,000 iterations): at each iteration and for each zone, the P_2 PTAs are randomly permuted among S_2 , which refers to all PTAs of individuals living in the zone in 2009, and the index is calculated using the P_1 PTAs. The probability of the observed index can be inferred from this estimated statistical distribution. The null hypothesis (H_0) is rejected if the probability of the observed index is lower than the α value, which equates to a risk of wrongly rejecting H_0 (Type I Risk).

For our analysis, we used bilateral tests to search for both similarity and dissimilarity. We compared the STAs of pairwise groups for each of the survey zones. If the observed index is lower than the lowest simulated indices ($I_{obs} < I_{min-sim}$), the null hypothesis is rejected and HA_{inf} is accepted, meaning that the two point patterns are significantly characterized by global similarity. If the observed index is greater than the greatest simulated indices ($I_{obs} > I_{max-sim}$), the null hypothesis is rejected and HA_{sup} is accepted, meaning that the two point patterns are significantly characterized by global dissimilarity. All in all, 18 tests were carried out (two tests for each one of the nine zones).

Map 11 illustrates the principle of the test using the example of STAs associated with schoolchildren living in *Gustavo Restrepo* in 1993 and in 2009. The top map corresponds to the observed situation. The observed index equates to 768 meters. The other two maps below are the first 2 of the 4,000 iterations of the Monte Carlo simulation, given as examples. The first simulated index equates to 797 meters. The second equates to 808 meters.

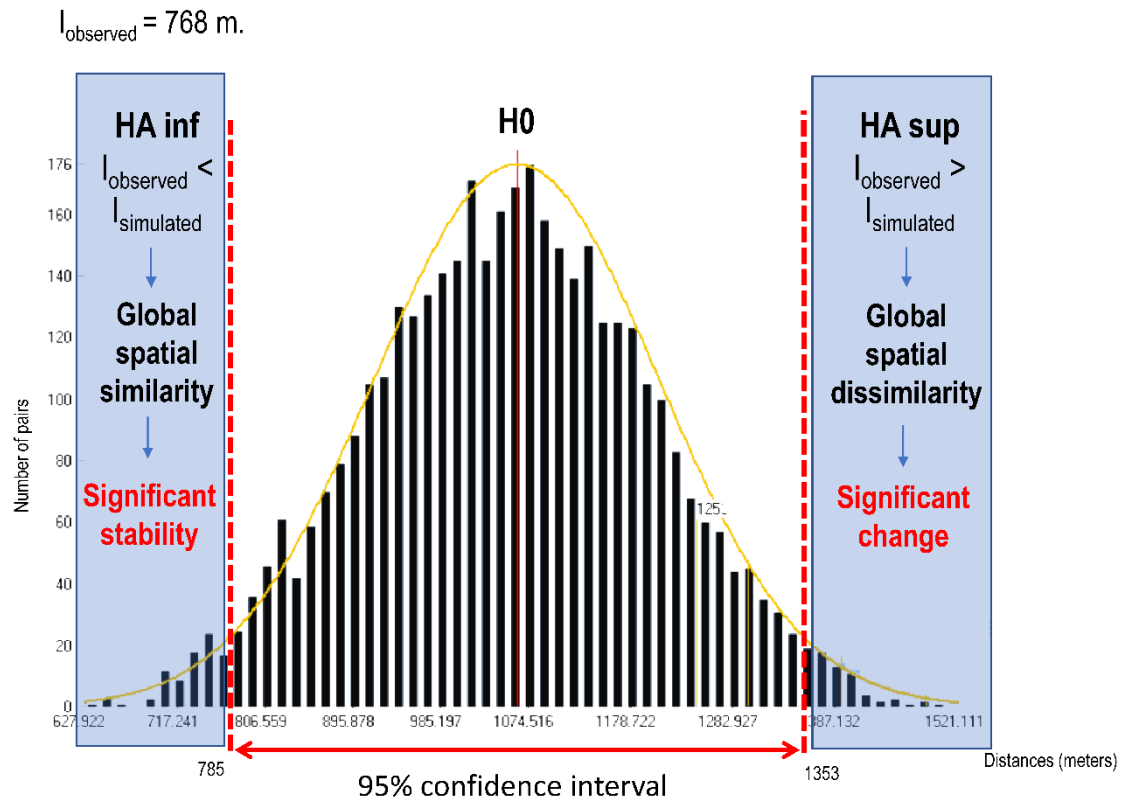
The related statistical distribution of the index under the H_0 hypothesis based on the 4,000 simulations is plotted in graph 1. The observed index (768 m) lies outside the 95% confidence interval [785 m; 1353 m] and is lower than the lowest simulated indices ($I_{obs} < I_{min-sim}$). Hence the null hypothesis is rejected and HA_{inf} is accepted, meaning that the two point patterns are significantly characterized by global similarity. In other words, the STA of schoolchildren living in *Gustavo Restrepo* in 1993 is significantly the same as the STA of schoolchildren living there in 2009. This result exhibits a significant stability in how children access their school from this survey zone between 1993 and 2009.

Map 11: The principle of the bivariate colocation test: observed situation versus simulated situations based on the example of STAs associated with schoolchildren living in Gustavo Restrepo in 1993 and in 2009 (Bogotá)



Author: F. Demoraes. Sources: 1993-CEDE-ORSTOM and 2009-METAL surveys.

Graph 1: Result of the bivariate colocation test for schoolchildren in Gustavo Restrepo



Author: F. Demoraes. Sources: 1993-CEDE-ORSTOM and 2009-METAL surveys.

5. Results and discussion

The results of the statistical colocation tests indicate an overall stability in children's access to place of schooling in 6 out of the 9 survey zones, and a more contrasting situation for adults. More specifically, the results bring out four types of change between 1993 and 2009 if we conjointly consider how schoolchildren and working adults access their place of activity (table 2).

The first type of combined change is observed in four survey zones (*Gustavo Restrepo*, *San Cristobal Norte*, *Bosa*, and *Soacha*). In these zones, there was a significant stability in children's access to place of school, but the situation for working adults changed significantly. The second type encompasses *Candelaria* and *Chía*. In these zones, children's access to place of school was also significantly stable, but there is no evidence of any significant trend concerning working adults' access to place of work. The third type corresponds to *Normandía*, where we may observe the opposite situation. The fourth type is characterized by *Perseverancia* and *Madrid*. In these zones, we may observe neither any significant stability nor any significant change for either children or adults.

Table 2: Test results of the significance of the differences between Space-Times of Action, by place of residence and by category of individual (working adults, schoolchildren) in 1993 and 2009

Type 1: Gustavo Restrepo, San Cristobal Norte, Bosa, Soacha

	Schoolchildren 1993	Adults 1993
Schoolchildren 2009	HA inf	-
Adults 2009	-	HA sup

Type 2: Candelaria, Chía

	Schoolchildren 1993	Adults 1993
Schoolchildren 2009	HA inf	-
Adults 2009	-	H0

Type 3: Normandía

	Schoolchildren 1993	Adults 1993
Schoolchildren 2009	H0	-
Adults 2009	-	HA inf

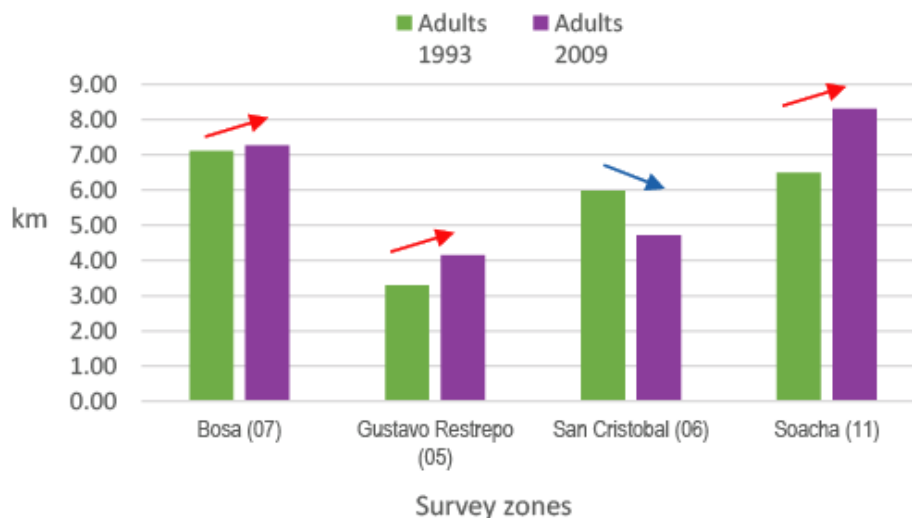
Type 4: Perseverancia, Madrid

	Schoolchildren 1993	Adults 1993
Schoolchildren 2009	H0	-
Adults 2009	-	H0

Author: F. Demoraes. Sources: 1993-CEDE-ORSTOM and 2009-METAL surveys.

HA_{sup} observed in type 1 is thus associated with a significant change. But what exactly does a significant change mean? Does it imply an improvement or, on the contrary, a worsening in access to place of activity between the two dates? To answer this question, we took as our indicator the mean of the Distance-Time between home and PTA. In three cases (*Bosa*, *Gustavo Restrepo* and *Soacha*), Distance-Times have increased, implying longer distances and/or travel times for working adults in 2009 as compared to 1993 (graph 2). All differences are significant based on the Kolmogorov-Smirnov non-parametric statistical test.

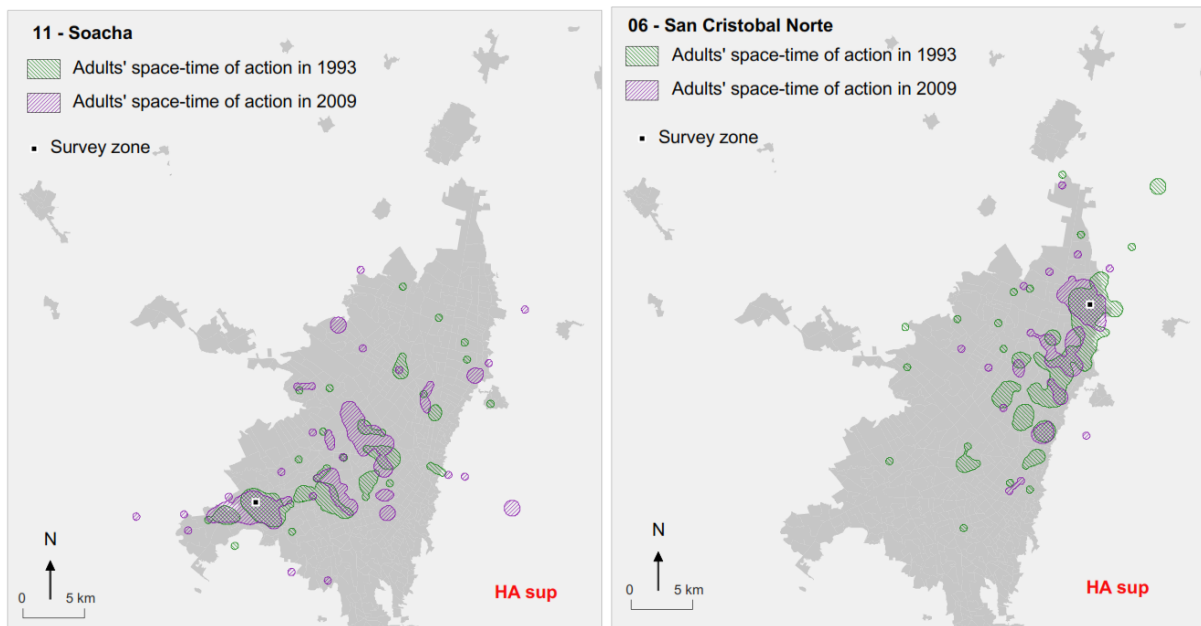
Graph 2: Mean of Distance-Times between home and Place-Time of Activity for working adults living in the four zones of type 1 where a significant change in STAs between 1993 and 2009 was detected



Author: F. Demoraes. Sources: 1993-CEDE-ORSTOM and 2009-METAL surveys.

If we take the example of *Soacha*, a disadvantaged suburb with a high proportion of SCI1-households (map 4), the Distance-Times for working adults increased from 6.49km to 8.3km. This result is consistent with what may be inferred from visual examination of the STAs at both dates on the map (map 12). The 2009 STA is much larger (44.1km²) than the 1993 STA (34.4km²), and is more offset from the survey zone.

Map 12: Space-Times of Action of working adults residing in 1993 and in 2009 in the survey zone located in *Soacha* (left) and in *San Cristobal Norte* (right)



Author: F. Demoraes. Sources: 1993-CEDE-ORSTOM and 2009-METAL surveys.

The enlargement of STAs for working adults in *Soacha* between 1993 and 2009 may be explained by three factors. First, the decrease in working at home, which dropped from 30% to 20% of the total number of working adults surveyed in this zone at the two dates. More adults left home for work each day in 2009 than in 1993, implying more travel time overall. Second, the modal share of public transport rose from 58.8% to 64.8%. Third, the increase in travel time on public transport, which rose from 58 to 64 minutes over the same period. *Soacha's* dependence on Bogotá for work was still very strong in 2009, as stated in Gouëset et al. 2016, while travel between the two municipalities remained difficult (due to road congestion) and the *Transmilenio* did not yet reach *Soacha*.

In short, in *Bosa*, *Gustavo Restrepo*, and *Soacha* (type 1), children's access to place of schooling remained stable, with a rather low spatiotemporal mismatch between home and school (the maximum Distance-Time being 3.19km), but the situation for working adults worsened between the two dates (larger STAs and longer Distance-Times). In other words, home location became less favorable for working adults than for children in these three survey zones over the period under study.

Conversely, in *San Cristobal Norte* (also type 1), a zone which urbanized mainly in the 2000s (map 3), Distance-Times for working adults decreased from 5.98km to 4.72km between 1993 and 2009, whereas children's access

to place of schooling remained stable. This improvement for working adults is also consistent with the information derived from map 12. The 2009 STA is much smaller (27.6km²) than the 1993 STA (48.3km²) and is less offset from the survey zone. This can be explained both by the increase in the use of public transport, whose modal share rose from 45.8% to 61.4%, and by the decrease in travel time in public transport, which dropped from 52 to 38 minutes over the same period. This reduction in travel time is mainly due to the commissioning of the *Transmilenio* in 2001, providing a fast service whose route passes not far from the study area.

As we saw, the case of *Normandía* (type 3) is unusual because it is the only survey zone with a significant stability in the SPAs of working adults between 1993 and 2009. Unfortunately, no significant conclusion can be drawn for schoolchildren residing there. The Distance-Time between home and work remained stable, at around 4.3km, corresponding to a comparatively low spatiotemporal mismatch in the context of metropolitan Bogotá. The drop in the proportion working at home, from 35% to 22%, which could have led to longer travel times, was compensated by the emergence of new business zones near this neighborhood, in *Ciudad Salitre*, along the *El Dorado* avenue connecting downtown to the airport, and around the airport, among other areas (map 5).

Conclusion

Using the concept of STA, this article has analyzed changes over a sixteen-year interval in how two groups of individuals—at different stages in their life course and residing in nine illustrative neighborhoods—access their place of activity in the metropolitan area of Bogotá. With the city expanding and undergoing profound transformation between 1993 and 2009, our findings bring out two main rationales: an overall stability in children's access to place of schooling wherever they reside, and a worsening situation for working adults with a growing spatiotemporal mismatch in most significant cases. Still, two exceptions emerged from this overall trend. First, the case of *Normandía*, illustrating how deteriorating access to place of activity is not inevitable in a large metropolis, thanks notably to the emergence of secondary centralities. Second, the zone of *San Cristobal Norte* which benefited fully from the BRT service introduced nearby during the study period.

STAs therefore constitute an appropriate way of gauging the medium-term impacts of commissioning new transport infrastructure and of urban transformations, whether the latter are organized (such as planning operations) or spontaneous and not fully controlled (such as urban sprawl). Nonetheless, more empirical studies are needed. First, in Bogotá, to verify if the dual trend of stability for schoolchildren and enlarging STAs for working adults has continued over the past two decades. Second, to check if such a trend also arises in other Latin American cities. Indeed, improving access to the city for all population categories is a challenge for urban stakeholders striving to develop more inclusive and sustainable metropolises. Our next step will therefore be to apply the same methodology to process data we will be collecting in 2022 as part of the ANR-funded Modural program in Bogotá (<https://modural.hypotheses.org/le-projet>). The objective is to implement a similar processing method, at least for the two survey zones analyzed in this article, namely *Bosa* and *Soacha*.

Furthermore, from a methodological point of view, calculating STAs is simple using a GIS, requiring only three input variables (origin, destination, and travel time). It may thus be applied to numerous surveys for which individual destinations is available, and to places of activity other than work and school. Above and beyond the use made of STAs and bivariate colocation tests in this article, assessing the significance of discrepancies between STAs could be applied in many other domains, either for a given date or else in a diachronic perspective. For a given date, one of the first applications which comes to mind is linked to segregation or discrimination. Following a gender-based or racial approach, or focusing on handicapped people, for instance, the test could be used to identify social groups experiencing noteworthy inequalities in access to work, education, or leisure amenities. In a diachronic perspective, STAs could be used for instance for a longitudinal study of changes in accessibility to healthcare facilities for patients with a chronic illness, with a view to reorganizing healthcare provision within a territory. The approach also seems suitable for monitoring medium-term transformations in center-periphery relations. A significant retraction in STAs between two dates would either indicate improved connectivity between the inner-city and the outskirts, or a maturing of the latter due to a growing number of local jobs, making the need to go downtown less compelling.

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