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# Uncovering urban circadian pulses based on an animated cartogram: the example of Bogotá

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## ABSTRACT

This paper describes a new kind of dynamic map showing the differing location of 'day' and 'night' populations and how they balance out over 24 h. To this end, we created a smoothed animated cartogram, with visual effectiveness as the main criterion. The area of study is the Bogotá metropolitan area in Colombia, where an urban mobility survey (EODH) was carried out in 2019. This paper emphasizes the method developed and the discussions which arose over the course of our work. We used R language to process the data and create the animations in order to make them reproducible, following an open-science approach. We mainly used the cartogramR and spatstat packages. The R script is appended.

## RÉSUMÉ

Cet article propose un nouveau mode de représentation cartographique dynamique donnant à voir la localisation différenciée de la « population de jour » et de la « population de nuit » et restituant les rééquilibrages sous-jacents sur 24 heures. Pour ce faire, nous avons mis au point un cartogramme animé lissé, en visant l'efficacité visuelle pour le lecteur. La zone d'étude choisie est l'aire métropolitaine de Bogotá en Colombie où une enquête de mobilité urbaine (EODH) a été mise en œuvre en 2019. Cet article met l'accent sur la méthodologie développée et les discussions qui ont jalonné la démarche. Dans une optique de reproductibilité et de science ouverte, l'ensemble des traitements a été réalisé au moyen du langage R et repose principalement sur deux packages cartogramR et spatstat. Le code est fourni en annexe.

## ARTICLE HISTORY

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## KEYWORDS

Circadian urban pulses; micro data; animated cartogram; R script; Bogotá

## MOTS-CLEFS

Pulsation urbaine circadienne; données individuelles; cartogramme animé; script R; Bogotá

## 1. Introduction

### 1.1 Commutes, urban pulses, and dynamic maps

Commuting denotes the way a city's population moves over the course of the day between the center and the suburbs. In the morning, people travel from residential areas, often located in the outskirts, to central areas, where jobs and services are pooled together. In the afternoon, trips occur the other way round. These back-and-forth movements following a daily cycle are reminiscent of a heartbeat. That is why

some authors refer to the urban rhythm as ‘urban pulses’ (Hurez, 2010; Hurez & Richer, 2014; Klein et al., 2017; Boffi et al., 2017). The adjective ‘circadian’ refers to a 24-hour period.

Some authors have developed animated maps of urban pulses. This kind of map is well-suited to showing time-dependent or space-dependent phenomena (Harrower, 2004; Cauvin et al., 2008; Cuntly & Mathian, 2017). The Web provides many opportunities for publishing animated maps, explaining their profusion today.

In 2017, a team from the French National Center for Scientific Research (CNRS) launched the *Mobiliscope* tool.<sup>1</sup> This provides a way of visualizing the social composition of a sample of French cities at the infra-metropolitan level based on available mobility surveys (Lecomte et al., 2018). For a given city, the user can choose the time, together with the selected demographic, social, and residential profile. An hour-by-hour animation is also available. The headcounts (an estimate of the number of people in the area) are displayed via proportional symbols whose size varies over time. The percentage of a given profile of people (for example, individuals aged 65 and over) among the total population of the area is rendered using solid colors that vary over time. The tool was first developed for the Paris metropolitan area and then extended to the main urban areas in France. Since 2022, the tool has also been applied to three Latin-American metropolises (Bogotá, Santiago de Chile, and São Paulo) thanks to a partnership with the French National Institute for Demographic Studies (INED).<sup>2</sup> These three cities have open-source mobility surveys available. Mention also needs to be made of the Manhattan Population Explorer, developed in 2018 by Justin Fung from the University of Columbia, which shows Manhattan’s shifting daytime and nighttime population (Genevois, 2018). The mode of representation is an oblique prismatic map. Manhattan county is covered with vertical bars whose height is proportional to the population located in the corresponding block.<sup>3</sup> The user can scroll two cursors to see how the population varies depending on time and day of the week.

## **1.2 Using animated cartograms to show changes in space and time**

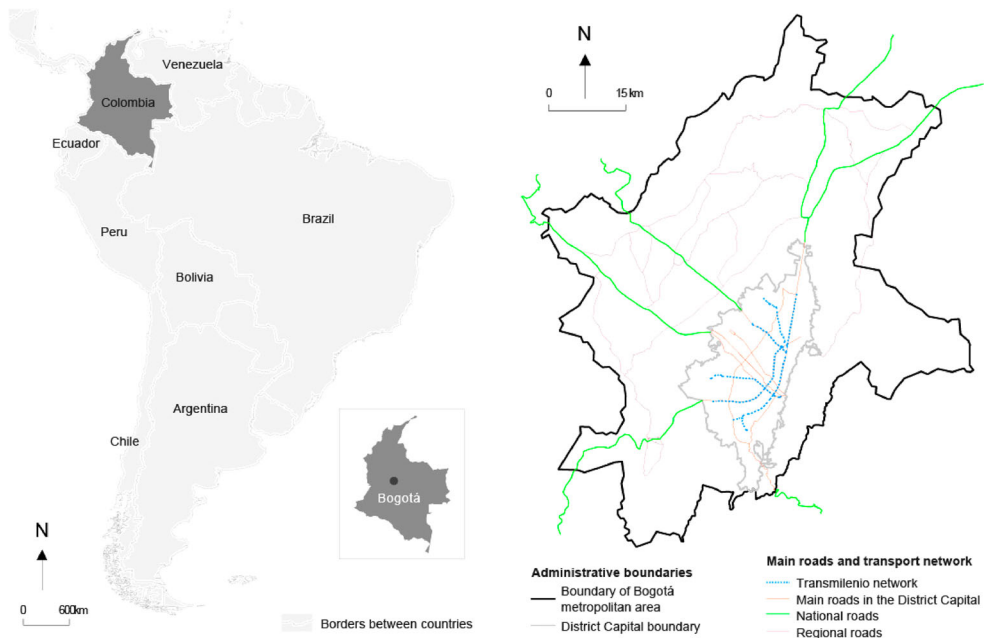
Cartograms are used to forcefully display phenomena with unequal spatial distribution (Bertin, 1967; 1983). A base map is distorted in such a way the surface of an area is proportional to a stock value, instead of the initial planimetric surface area. Lambert and Zanin (2016) point out that the earliest cartograms, devised by the French economist Emile Levasseur, pertain to the second half of the nineteenth century. However, animated cartograms are much more recent (Antoni & Klein, 2003). They are still scarce, and their effectiveness still needs to be improved (Demoraes et al., 2021). This kind of representation is nevertheless very well-suited to showing time-dependent phenomena. Demoraes et al. (2021) explore how animated cartograms may depict changes in socio-residential segregation in Bogotá (Colombia) between two censuses. These authors suggest conjointly using dynamic spatial smoothing to render a second (relative) variable. This approach is relatively new. As stated in Demoraes et al. (2021), most animated cartograms in the literature render only one variable, used to distort the base map. This same variable is also some cases used as solid colors on animated cartograms.<sup>4</sup> A smaller number of animated cartograms portray two variables, one for distortion and the other one as a solid color. However, using both mapping techniques (cartogram and solid

color) in a single animation produces a flicker effect, making it harder to apprehend how the phenomenon evolves. This effect occurs when two adjacent spatial units with close values are, in turns, in the same bin and in a different bin in following time slots. This effect is particularly pronounced if there are a high number of spatial units and many colors, necessarily implying more frequent visual changes. This observation ties in more broadly with the relatively complex characteristics of animation as described in Cauvin et al. (2008). These authors indicate that on an animated map: ‘the cartographic object may change spatially, systematically, and temporally’. This explains why it is essential to use a mapping technique that makes it possible to simplify the information referring, in our case, to the second variable, so as to reconstitute it effectively. This also explains why it is recommended to allow the user to pause on an image to have time to assimilate information about any given moment.

In this paper, we take our inspiration from the cartographic innovation introduced in Demoraes et al. (2021) and describe a method to systematize the generation of smoothed animated cartograms. For our area of study (part 2), we chose the Bogotá metropolitan area (Colombia) where a recent mobility survey is openly available Encuesta Origen Destino de Hogares 2019,<sup>5</sup> enabling us to map urban pulses over a 24-hour period. In an open science and reproducibility approach, our process (part 3) is fully based on R language. We mostly used two packages: cartogramR<sup>6</sup> (Cornillon & Demoraes, [submitted](#)) and spatstat.<sup>7</sup> In part 3, we also detail our cartographic choices. In part 4, we discuss the limits of our study and future lines of research. This work has been carried out as part of Modural<sup>8</sup> ANR-funded research program, and in interaction with the Mobiliscope project (CNRS).

## 2. Area of study

Bogotá is the capital city of Colombia; its metropolitan area ([Figure 1](#)) is home to 9 million inhabitants (Alcaldía Mayor de Bogotá, 2021). Like other Latin American metropolises (Lima, Santiago de Chile, Buenos Aires), Bogotá experienced urban transition during the twentieth century, causing the population to increase and urban boundaries to expand ([Figure 3](#)). Planned social housing and the informal construction of dwellings led to the development of densely populated suburbs ([Figure 2](#)), while formal jobs remained in the central area. The strong socio-spatial segregation acts as a ‘social centrifuge’, and the poor households have no choice but to live in the outskirts (Demoraes et al., 2021; Gouëset et al., 2021). This spatial mismatch (Gobillon et al., 2007) between housing and jobs gives rise to many commutes between the city center and the outer rings over the course of the day ([Figure 4](#)). Trips are lengthy and exhausting. The average duration of a one-way trip is 50 min (Demoraes et al., 2020). Bogotá benefited from ambitious urban transport reforms with the Transmilenio Bus Rapid Transit system which began operating in 2000 ([Figure 1](#)).<sup>9</sup> The commissioning of the BRT was followed in the 2010s by the implementation of the Integrated Public Transport System.<sup>10</sup> These reforms, together with public policies introduced in the mid-2000s to encourage urban cycling (Lucas et al., 2023), seek to establish Bogotá as a pioneering city for sustainable mobility policies in Latin America. However, these reforms face a series of hindrances hampering their impact despite initial trip improvements. Furthermore, transport and housing planning as set out in the master plans (POT) is only weakly joined up. The objective of decreasing



**Figure 1.** The location of the metropolitan area of Bogotá, main roads, and BRT network. Left insert: produced by authors. Source: GADM maps and data / Right insert: adapted from G. Le Roux (2015, p. 129).

distances has thus remained illusory (Thomas, 2022). The lengthy commutes made visible in this paper are thus a deeply entrenched feature of Bogotá.

### 3. Method

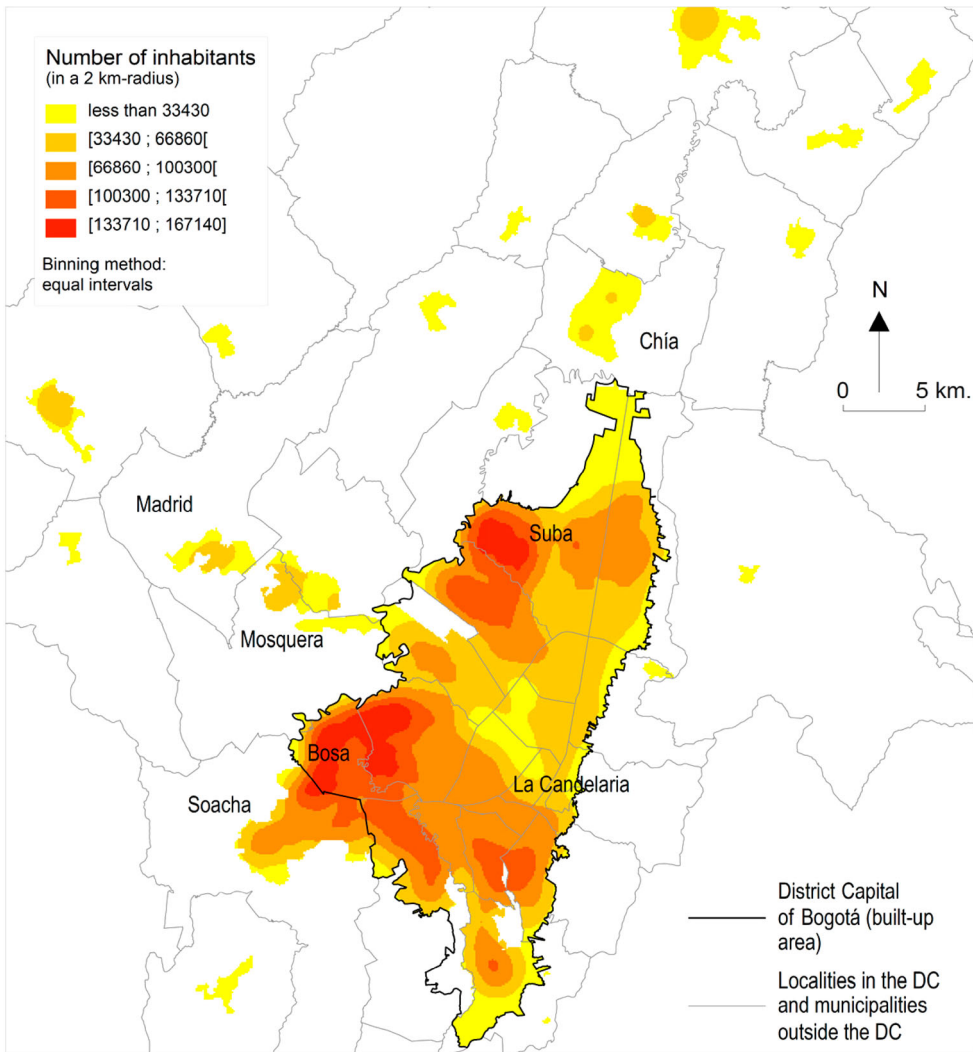
This section goes over the method and processing. It also describes the data sources and the choices made. The workflow is summarized in Figure 5.

#### 3.1 Cartographic choices, algorithm used, and timestep chosen

We had to start by making two major decisions. The first was about the type of cartogram to be used. The second was about how to render the second variable to enhance its visual effectiveness.

We chose a contiguous cartogram to better visualize the phenomena under study, namely daily commutes which are organized continuously and progressively in time and space. An animated contiguous cartogram is well suited to portraying progressive distortions, the shape of which is reminiscent of a heartbeat when the phenomenon converges on a specific area, as commutes in Bogotá do. Non-contiguous cartograms (Dorling or Carters cartograms) would not produce such an effect.

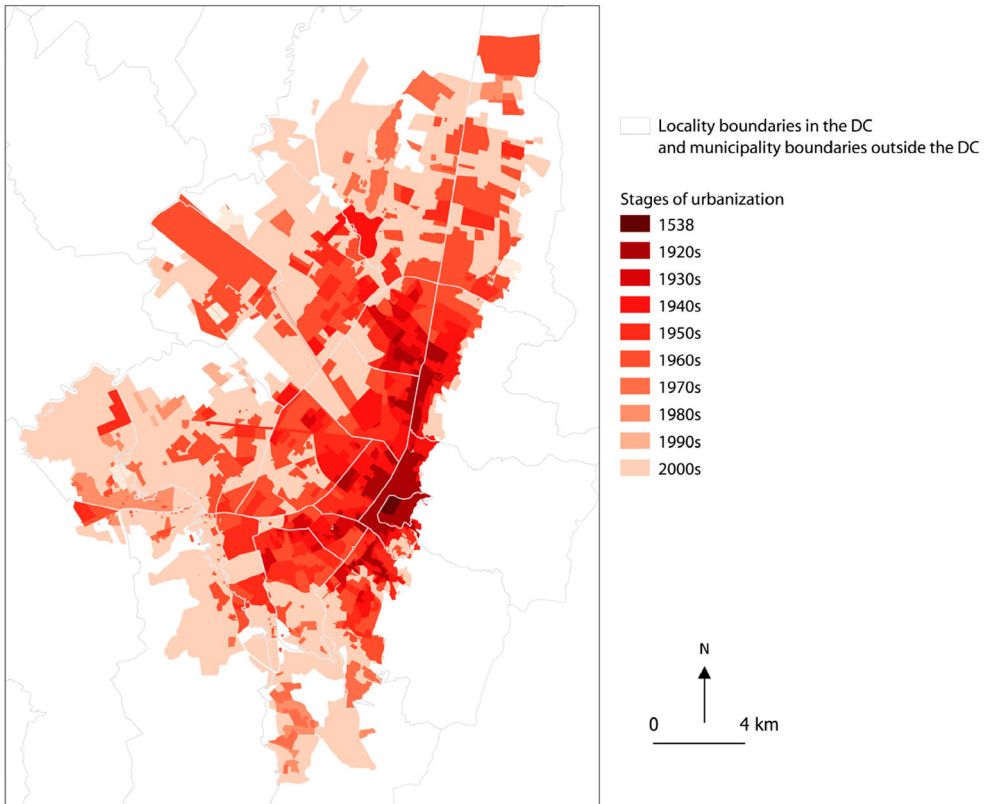
The second choice about how to effectively render the second variable is discussed in section 3.5. As we shall see, we tried three mapping techniques.



**Figure 2.** Population density in Bogotá (Robert et al. 2022).

The final animation is built from successive snapshots showing the location of Bogotá's population every 15 min over a 24-hour period. This timestep was selected as a trade-off between two opposing objectives. First, the need to produce a sufficiently smooth and fluid-feeling animation without jitters. This implied producing a large number of maps but without excessive calculation times, which was the second objective. Using the cartogramR package helped reduce calculation time.<sup>11</sup> Indeed, this new easy-to-use R package (Cornillon & Demoraes, 2021) implements the latest Gastner et al. (2018) high-performance algorithm.<sup>12</sup> This generates contiguous cartograms and is an optimization of the Gastner et al. (2004) algorithm.<sup>13</sup> As stated in Nusrat et al. 2016, the Gastner et al. (2004) algorithm provides the best results, that is, the greatest accuracy for size, shape, and topology.

In-depth discussion with the Mobiliscope team enabled us to hone the process and final layout.<sup>14</sup> Choices were needed regarding the trips used for the analysis, the



**Figure 3.** Urban sprawl in the Bogotá Capital District since the sixteenth century (adapted by the authors from Garavito and De Urbino, 2019).

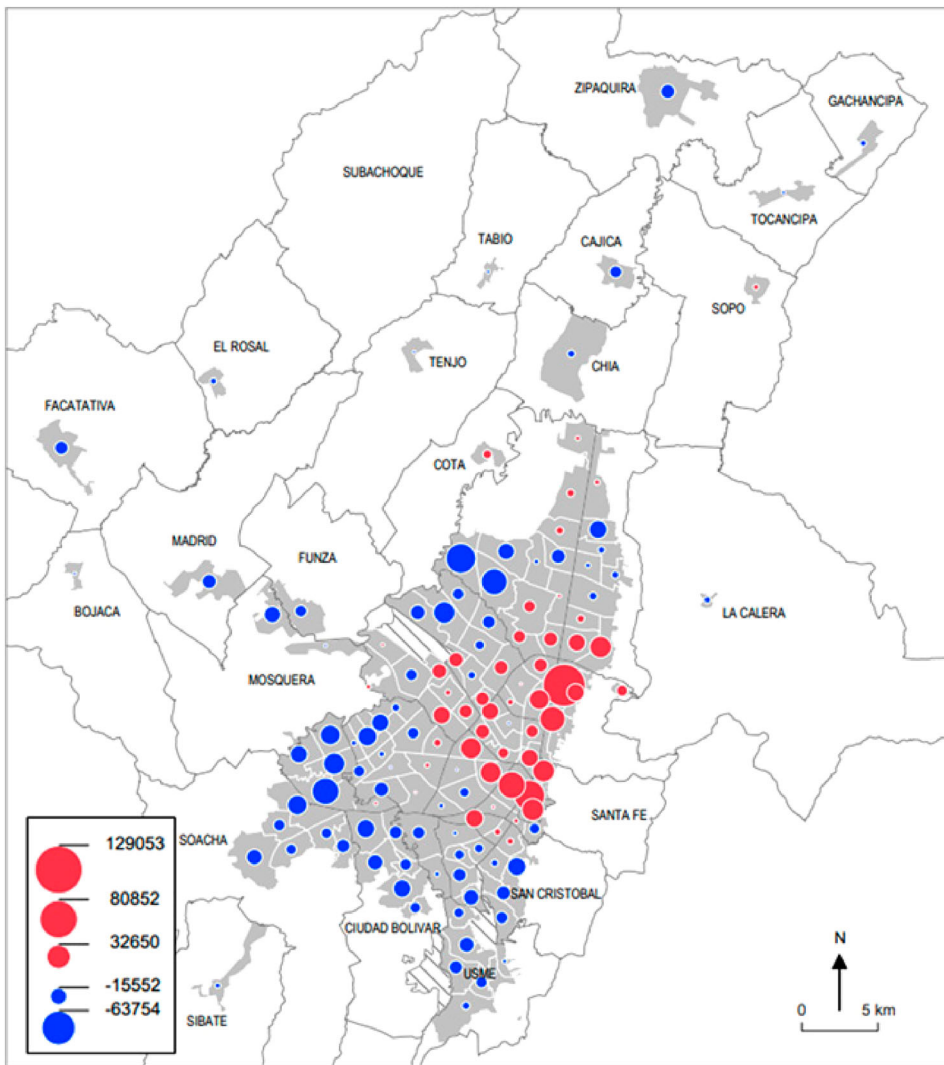
binning method, and the number of classes for the second variable. The animation and R script are available on GitHub.<sup>15</sup> We generated animations in two formats, *gif* and *mp4*. The advantage of the latter is that the reader can adjust the viewing speed and use the cursor to stop the animation.

### **3.2 Dataset: source, preparation, and geographic level of analysis**

We used data from two sources. First, we used the trips dataset from the 2019 Bogotá EODH funded by the Bogotá *Secretaría Distrital de Movilidad*. This file is a table pooling 134,497 trips made by 66,688 people, that is, 0.9% of the population of the District of Bogotá. For each trip, we retained the following variables: departure time, arrival time, place of origin, and place of destination. ‘Place’ here refers to the 132 Mobility Analysis Territory Units (UTAM)<sup>16</sup> in the built-up area of the study zone. Second, we used the 2018 census,<sup>17</sup> from which we calculated the night (or dwelling) population in each UTAM.

We filtered the trips dataset to select only those which are part of a daily circular chain in a ‘typical workday’. In other words, we only retained journeys made by people who returned to their start point at the end of the day (for example home → work → shopping → home, see Figure 6). We made this choice for graphical purposes, that is, to produce a





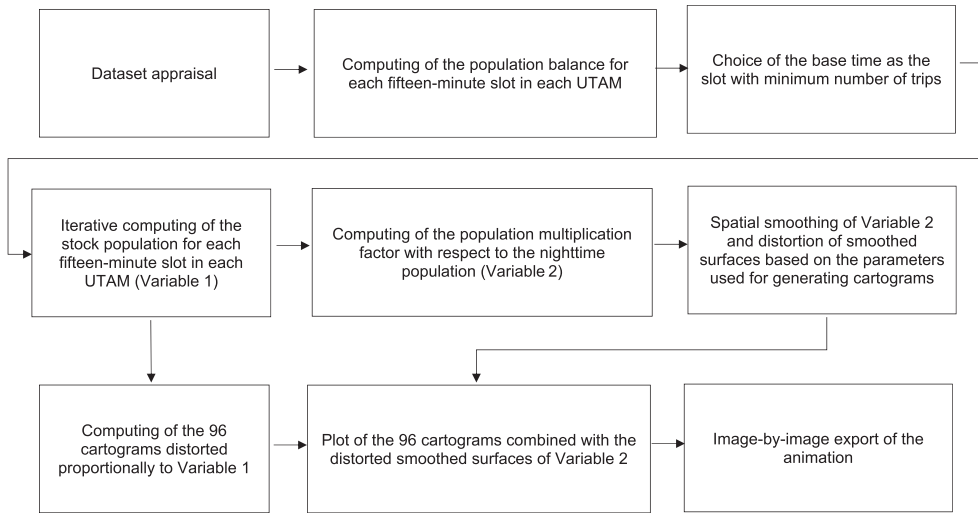
**Figure 4.** Difference between incoming and outgoing trips in each UTAM (Mobility Analysis Territory Units) between 4.00 and 9.59 am (Demoraes et al., 2020).

loop animation without any ‘jitter’ caused by different nighttime populations on day D and day D + 1.

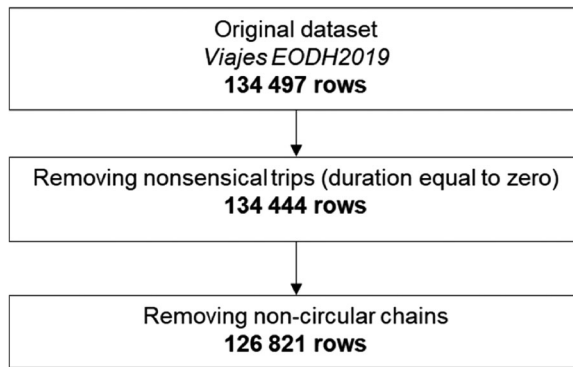
These first steps led to a 6% loss of the initial information. It is also important to point out that local trips (within an UTAM) do not trigger a change in a UTAM population. At our geographic level of analysis, such local trips are equivalent to no trip. Conversely, 68% of the trips are ‘inter-UTAM’ and so contribute to a variation in population.

### **3.3 Computing the hourly population balance and stock**

We first computed a table of the net variation in population (balance) per UTAM. We pooled trips by 15-minute slots, rounding times down. For example, individuals who



**Figure 5.** Workflow (by authors).



**Figure 6.** Filters applied to the original dataset.

leave at 8.23 am and reach their destination at 9.07 am are assigned 8.15 am as a departure time, and 9.00 am as an arrival time.

It is worth noting that it is not possible to pinpoint the exact location of people during their journey and therefore to assign them to a transit zone. To estimate that location using average speed would have led to excessive approximation. So the question was where to locate people during their trips. The very first cartograms we produced rendered instantaneous trips, or ‘catapulting’: people were subtracted from the UTAM they left and added to the UTAM where they arrived at the same time. The result was not satisfying. The suburb deflated too early and the central zones inflated too early in comparison to what is observed in the morning. The same problem occurred in the afternoon, the opposite way.

To address this issue, individuals were subtracted from the population of the UTAM they leave at the departure time slot, and they were added to the UTAM where they arrive at the destination time slot.

We then computed the stocks, that is, the population present slot by slot, following three steps:

- (1) We first chose the base time slot when we may consider that everybody is at home. To this end, we computed the overall number of departures for each time slot and chose the slot with minimum departures. This was the 2.45 am – 3.00 am slot.<sup>18</sup>
- (2) We assigned the nighttime population from the 2018 census as the stock value for each UTAM to the previous base time slot.
- (3) We computed the population for each UTAM and time slot  $t$ , by means of the following iterative sum:

$$\text{population}(t_i + 1) = \text{population}(t_i) + \text{net variation}(t_i + 1) \quad (1)$$

We made sure that the computed population looped, that is, that after 96 iterations we got back to the initial value of the population for the slot starting at 2.45 am:

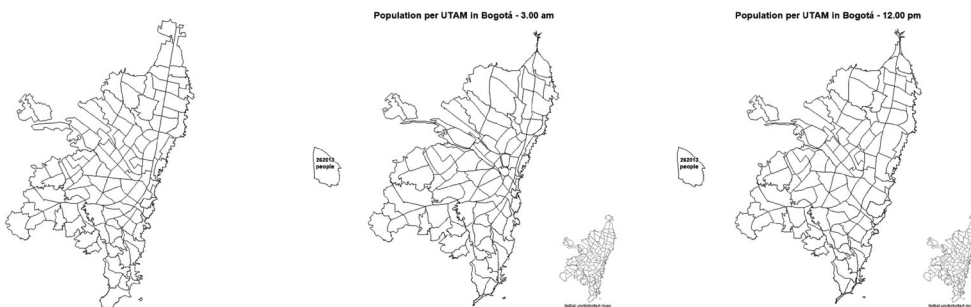
$$\text{Population}(2.45 \text{ am}) = \text{population}(2.30 \text{ am}) + \text{net variation}(2.45 \text{ am}) \quad (2)$$

This produced the stock table that we used to compute the cartograms.

### 3.4 Plotting the first cartograms, distorted according to population, for each 15-minute slot

We plotted a first set of 96 cartograms.<sup>19</sup> The result for two time slots is shown below in Figure 7. The surface area of each spatial unit on the distorted map is proportional to the population located there in the time slot. Were the population uniformly spread, the map would not be distorted. This technique gives more weight to spatial units with large headcounts.

The total surface is the same on the three maps. In comparison to the undistorted map (on the left), the cartogram distorted for nighttime population (in the center) shows that there are more people residing in the suburbs than in central areas, a fact already evidenced on the density map (Figure 1). On the map for the daytime population, on the



**Figure 7.** Undistorted map (left), cartogram distorted as a function of the nighttime population (center), and of the 12.00 pm population (right). See animation in GIF format: <https://bit.ly/3QFGLuM> and in MP4 format (pausing possible): <https://bit.ly/3NfNWX8>

right, we may see the inflated central areas (along the *Carrera Séptima* following a north–south axis) where formal jobs are concentrated.

### 3.5 Choice of the second variable and how to render it

In cartography, adding a second variable which conveys information correlated to the first variable strengthens a map’s visual effectiveness (Bertin, 1967; Béguin & Pumain, 2017; Cauvin et al., 2013). We call ‘effectiveness’ a map’s capacity to render its information as clearly as possible so that it may be quickly and easily assimilated by the reader (Bertin, 1967 after Zipf, 1935). Jégou (2016) points out that a map’s effectiveness refers to its capacity to clearly and legibly communicate its information to a given audience.

For our second variable we chose a multiplication factor, that is, the increase or decrease of the population in each UTAM in comparison to the nighttime population. We computed the factor for each time slot by dividing the present population by the base time slot nighttime population. This factor is expressed as a percentage.

We tried three mapping techniques to portray this second variable. First, we computed an animated cartogram on which spatial units are filled with solid binned colors, what we call later on the choropleth animated cartogram. Second, we computed a smoothed and distorted surface displayed with binned colors, what we call later on the smoothed binned-colored animated cartogram. Third, we computed a smoothed and distorted surface displayed with continuous colors, what we call later on the smoothed continuous-colored animated cartogram.

#### 3.5.1 The choropleth animated cartogram

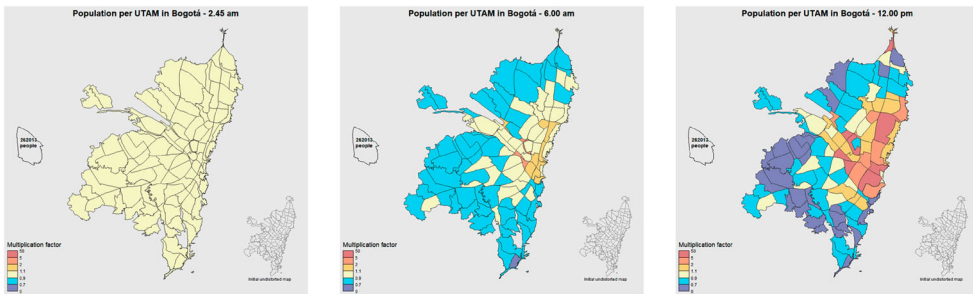
We here binned the values into 6 classes. We chose breaks which are easy to interpret (Figure 8) and we used a diverging color range from blue (factor < 1) to red (factor > 1), using yellow for a factor equal to 1 (Figure 9).

This rendering highlights the pronounced changes in population numbers over the course of the day. Suburban districts lose much of their population, while central areas see theirs multiply, as shown in Figure 10, depicting population change by time of day in a central UTAM (*Chapinero*) and a suburban UTAM (*El Lucero*).

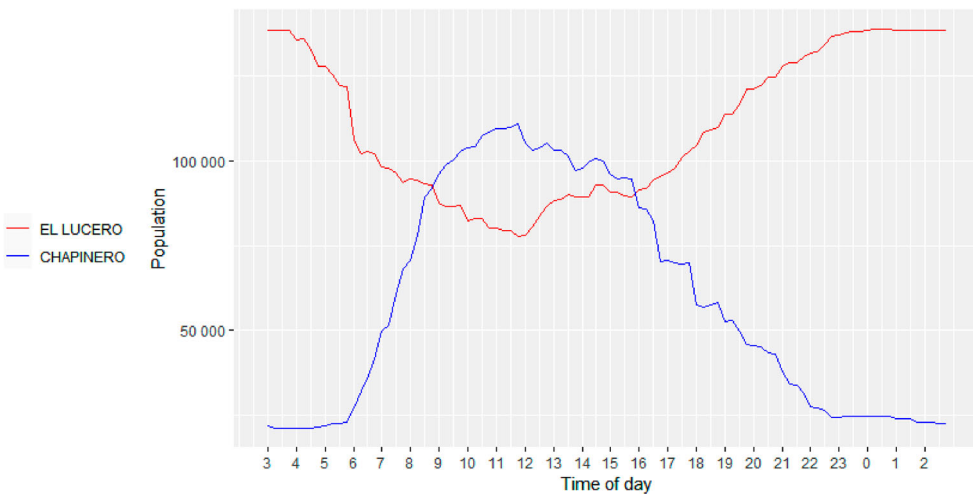
However, using solid colors in an animation usually generates a local flicker effect, as already mentioned, and this is precisely what happens in this first animation, confirming

Class label	Meaning	Variation
>= 5	Daytime population is at least 5 times higher than nighttime one	Very strong diurnal increase
[ 2 ; 5 [	Daytime population is between 2 and 5 times higher than nighttime one	Strong diurnal increase
[ 1.1 ; 2 [	Daytime population is between 1.1 and 2 times higher than nighttime one	Intermediate diurnal increase
[ 0.9 ; 1.1 [	Daytime population does not alter much compared to nighttime one	Stability
[ 0.7 ; 0.9 [	Daytime population is between 10% and 30% lower than nighttime one	Intermediate diurnal decrease
< 0.7	Daytime population is at least 30% lower than nighttime one	Strong diurnal decrease

Figure 8. Intervals chosen for the choropleth animated cartogram.



**Figure 9.** Choropleth cartogram rendering the multiplication factor (second variable) as binned colors. See animation in GIF format: <https://bit.ly/3W0IVqU> and in MP4 format (pausing possible): <https://bit.ly/3ZvA4iN>

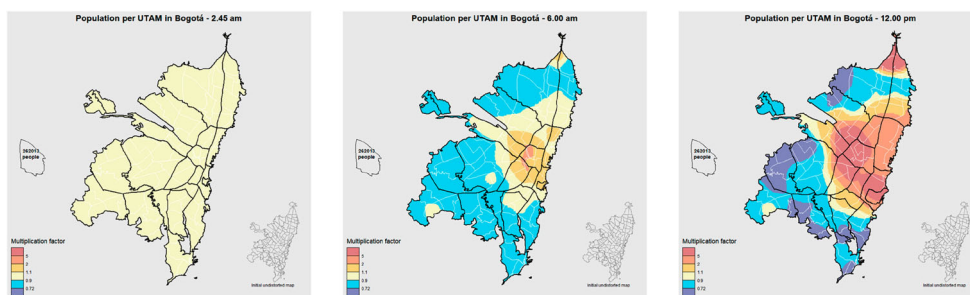


**Figure 10.** Population variation over 24 h in a central UTAM (Chapinero, blue line) and a suburban UTAM (Lucero, red line).

that this cartographic solution is not visually satisfying for effectively conveying information on an animated cartogram.

### 3.5.2 The smoothed binned-colored animated cartogram

We hence applied spatial smoothing to solve this issue. Spatial smoothing (Silverman, 1986) is a mapping technique that generalizes information and highlights trends or gradients, dimming local variations or discontinuities such as those seen here. This approach hinges on the choice of a smoothing bandwidth and a weight function (the kernel). The choice of smoothing bandwidth and of kernel have a significant impact on the result (Zaninetti, 2005, Aschan-Leygonie et al., 2019). When data are aggregated in spatial units, smoothing applies to the values at the centroid of the latter. We computed the distance to the closest neighbor and spatial autocorrelation (Moran's I) for each centroid and time slot in order to choose a value for the bandwidth. We performed various trials before selecting a smoothing bandwidth of 1,000 meters. We also tested various kernels before



**Figure 11.** Cartograms rendering the multiplication factor (second variable) as a smoothed binned-colored surface. Gaussian smoothing, 1000 m bandwidth. See animation in GIF format: <https://bit.ly/3QyBrSM> and in MP4 format (pausing possible): <https://bit.ly/3X6ch7z>

choosing a Gaussian function. As stated in Genebes et al. (2018), this function offers a good compromise between the weight given to close neighbors and that given to remote ones.

On this animated cartogram (Figure 11), we displayed the smoothed surface using the same breaks and the same colors ranging from blue (factor < 1) to red (factor > 1), and we also used yellow for a factor equal to 1.

Binning a smoothed surface is often used because it simplifies the information, in our case that conveyed by the second variable. In this sense, the smoothed binned-colored animation is very good at schematizing and communicating the overall trend and how it evolves over 24 h. Here, the reader is not saturated with information and may follow the multiplication factor of the population over space and time. It is thus easier to identify the sectors characterized by a strong population increase during the day as compared to night.

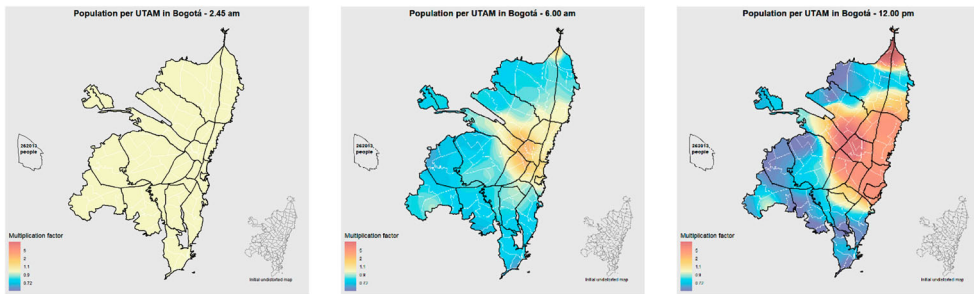
However, this rendering has the two limitations. First, binning the smoothed surface generates marked edges between contiguous colors that does not correspond to real divisions in the city. Second, binning creates slight jitters in the animation as the values of the pixels of the smoothed surface constantly fluctuate implying, in many occasions, a rapid translation of the boundaries between bins.

### 3.5.3 The smoothed continuous-colored animated cartogram

To improve the visualization, we finally used a continuous color scale for displaying the smoothed surface (See Figure 12). As previously, we retained the same breaks and the same colors ranging from blue (factor < 1) to red (factor > 1), and we also used yellow for a factor equal to 1.

As indicated in the semiology of graphics (Bertin, 1983), the eye cannot distinguish between a wide range of shades. For this reason, the visual effectiveness of such smoothed continuous-colored cartogram is theoretically not fully convincing. It could also be expected that this limitation would even be truer in animation mode which implies a permanent change between tints everywhere on the map.

However, this final rendering is very pleasant for the reader's eye. Using a continuous color scale generates fuzzy edges between contiguous colors dimming the jitter effect. It also avoids generating artificial and excessively marked boundaries. On this animated



**Figure 12.** Cartograms rendering the multiplication factor (second variable) as a smoothed continuous-colored surface. Gaussian smoothing, 1000 m bandwidth. See animation in GIF format: <https://bit.ly/3izwa7T> and in MP4 format (pausing possible): <https://bit.ly/3INQ7T4>.

cartogram both visual variables (size and colors) change simultaneously and harmoniously. This cartographic solution is visually satisfying for effectively rendering, in our case, the urban pulses.

### 3.6 Constructing the animated cartograms

For every of the four types of cartograms we generated and exported to MP4, we assembled the animation from three sequences (Figures 7, 9, 11 and 12). The advantage of the MP4 container is that the reader can adjust the viewing speed and use the cursor to stop the animation.

In the first sequence of each animated cartogram, we slowly distorted the initial map into a cartogram featuring the nighttime population (at 2.45 am). We inserted seven intermediate pictures between the initial map (image 0) and the distorted map (image 8) to achieve this transition. We created intermediate pictures computing a cartogram based on fictitious population stocks. The latter are computed, for each UTAM, as the linear interpolation between the nighttime population and a fictitious nighttime population proportional to the surface area of the zone.

Formally, for  $i$  between 0 and 8 and  $j$  in the interval  $[1; \text{number of UTAM}]$ , the population allocated to UTAM  $j$ , at step  $i$  is:

$$POP_j^i = \frac{i}{8} \cdot POP_j + \frac{8-i}{8} \cdot \frac{AREA_j}{AREA_{tot}} \cdot POP_{tot} \quad (3)$$

where  $POP_j$  is the nighttime population in UTAM  $j$ ,  $AREA_j$  is the surface area of UTAM  $j$ ,  $POP_{tot}$  is the total census population of the city, and  $AREA_{tot}$  is the total surface area of the city.

Therefore, we get a very smooth transition thanks to linear interpolation.

In the second sequence, we gradually added the legend, the title of the map, the scale, and the miniature initial map. To do so, we assembled 5 intermediate pictures using cross fade showing either the black-and-white cartogram (Figure 7), the choropleth cartogram (Figure 9), the smoothed binned-colored surface (Figure 11) or the smoothed continuous-colored surface (Figure 12).

In the third sequence, the longest, we rendered the animated urban pulses as such, made from 96 cartograms above which the second variable appears as a choropleth map, a smoothed binned-colored surface or a smoothed continuous-colored surface.

Beforehand, we computed and distorted these smoothed surfaces for each time slot using the same settings as for the cartograms.

Information gradually appears before the pulses start, allowing the reader to progressively follow the evolution of the density of population in the city over the course of the day.

#### 4. Limits and future lines of research

Debates about rendering smoothed animated cartograms with the Mobiliscope team and members of the ANR Modural program – of which this work is part – brought out two limits.

The first is about the smoothed binned-colored animated cartogram. In this animation, the reader's eye is attracted by the red spots, corresponding to parks and universities, with a low nighttime population but a daytime population at least five times bigger. The spot-lighting of these very specific zones may have disconcerted specialists of Bogotá, who expected to find the main central zones along the *Carrera Séptima* depicted in red too. This issue directly derives from the choice of the second variable, which is not perfectly redundant with the first. Multiplication factor is not always correlated to headcounts in the city over the course of the day. The second limit is that using binned colors generates marked edges between contiguous colors which tends to weaken the visualization of the pulses. We tried to correct this using fewer classes and understated pastel colors. Furthermore, we only plotted UTAM boundaries and not the outlines of every color bin, but even so, pulses are much more visible on the 'naked' animated cartogram (Figure 7) and on the smoothed continuous-colored animated cartogram (Figure 12).

In addition, we made other adjustments to improve the overall legibility of the smoothed animated cartogram: (1) the choice to add place names or not. Though some labels could have been plotted to enable readers to find their bearings, the map should not be overloaded, therefore we did not add any place names. (2) the choice of the breaks, number of classes, and colors. These parameters affect the level of generalization of the information rendered, to ensure that readers can assimilate it and interpret it well. They also influence the stress placed on low population zones whose population multiplies during the day.

The workflow we devised in the R environment to create this kind of smoothed animated cartogram opens various avenues. First, this method may be applied to other cities with mobility surveys available in open data. Second, developing an online interface could enable a broader audience to automate the generation of this type of map, for instance by letting users upload their own datasets and base maps without needing any coding knowledge. Finally, this method could be adapted to depict other space- and time-dependent phenomena. It could be used to portray (i) movement – summer-time population flows over a country, or continental migration – and (ii) stock variation – such as changes in the distribution of places of residence of deprived households within a city over several decades, the number of lightning impacts by county over a period of time, changes in CO<sub>2</sub> emissions by country since the 1980s, etc.

In addition to academic purposes, smoothed animated cartograms may be used as effective communication tools to convey simple messages about a broad range of contemporary social and environmental issues. In the medium-term, we may therefore



expect to see smoothed animated cartograms becoming part of the infographics used by online newspapers and on the web more generally.

## Notes

1. Link to the Mobiliscope Project headed by Julie Vallée (UMR Géographie-cité): <https://mobiliscope.cnrs.fr/en>
2. Thanks to the involvement of a team headed by Guillaume Leroux (the “Housing, spatial inequalities, and trajectories” and “Mobility, trajectories, and territories” research units).
3. Link to the Manhattan Population Explorer: <http://manpopex.us/>
4. Although this is not suited for visualizing stock values.
5. Original mobility surveys data: <https://www.simur.gov.co/encuestas-de-movilidad>
6. <https://cran.r-project.org/web/packages/cartogramR/index.html>
7. <https://cran.r-project.org/web/packages/spatstat/index.html>
8. <https://modural.hypotheses.org/le-projet>
9. A Bus Rapid Transit (or BRT) is a public transport system based on a trunk bus network with dedicated lanes and controlled-access stations. Feeder buses connect the trunk lanes to neighboring districts.
10. In Spanish, *Sistema Integrado de Transporte Público* (SITP).
11. 90 min were needed to generate the 96 cartograms on a regular PC.
12. Another advantage is that the Gastner et al. (2018) algorithm and its implementation in the cartogramR package can easily handle 0 values. As described in Cornillon, Demoraes 2021, the default mp parameter is set to 0.2. If a spatial unit has a zero value, it will be replaced by mp times the smallest positive value in any spatial unit. It is also possible to distort spatial units using absolute error. Absolute error refers to the maximum difference between target surface areas (areas strictly proportional to values) and effective surface areas (output areas that the algorithm was able to compute). For instance, if we set a maximum 1,000,000 m<sup>2</sup> absolute error, we accept that the surface area of each spatial unit may differ to that extent from target area. To do so allows the algorithm to reach the final result more quickly. In our case, we did not have any 0 values and we did not have to change the default options of the algorithm.
13. Gastner et al. (2018) introduced a fast flow-based algorithm whose equations are easier to solve than using the Gastner et al. (2004) method.
14. Especially with G. Le Roux (Ined) and J. Vallée (CNRS).
15. See GitHub link in appendix.
16. We have retained the Spanish acronym, which stands for “Unidad Territorial de Análisis de Movilidad”. Indeed, this acronym is widely used not only for Bogotá but also for other Latin-American metropolises.
17. <https://www.dane.gov.co/index.php/estadisticas-por-tema/demografia-y-poblacion/censo-nacional-de-poblacion-y-vivenda-2018>
18. Computing the arrivals instead of the departures gives the same result.
19. 4 cartograms per hour multiplied by 24 h.

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## Declaration of interest statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix

Link to the R markdown file to render the smoothed animated cartogram shown in this paper: <https://github.com/ESO-Rennes/Animated-Cartograms>