



Calculation of Average Global Accessibility Conditions for Bicycles Considering the Longitudinal Road Slope: Case Study Ibagué – Colombia

CASE STUDIES

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ABSTRACT

Territorial accessibility conditions are a relevant concept for the continuous development of cities; hence, it is necessary to accurately determine their characteristics and how population or physical factors influence them when interacting with transportation. In the present study, a mathematical model is developed using transport supply models to evaluate the average global accessibility of bicycle infrastructure, considering factors such as the longitudinal slope of the road and the socioeconomic stratum. The methodology focuses on six main stages: starting with the collection of population census data and GPX traces of trips made in the mode; second, analyzing the relationship between slope and speed using linear regressions for different categories of roads with data from the previous stage; third, conditioning geographic information layers with and without slope; fourth, evaluating geographic accessibility using Dijkstra's shortest path algorithm; fifth, calculating the average global accessibility and generating isochronous curve maps using the ordinary Kriging geostatistical algorithm; sixth, estimating the relationship between travel times considering the slope of the road and a base scenario without slope. The results indicate that steeper slopes significantly reduce the average speed of cyclists, which in turn increases travel times and negatively affects accessibility conditions. Additionally, it shows how topographical features, and the city sector influence the mobility of the cycling community. These findings reveal the importance of considering road slope in urban planning to generate strategies that develop efficient road infrastructure and promote the use of bicycles as a means of transport, fostering sustainable mobility.

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INTRODUCTION

It is relevant to develop a study that quantifies the quality of active transportation, such as cycling, considering factors such as the topography of the road, specifically the longitudinal slope, which influences city mobility. Higher slopes require greater physical effort, reducing the average travel speed. For this reason, understanding that accessibility condition models typically use the average speed calculation over the arcs representing the road infrastructure network, can bias the results of average travel times (TV). Therefore, it is proposed to consider a mathematical model that calculates speed based on this factor.

The city of Ibagué, the capital of the Tolima department in Colombia, was considered for this study. It has an average altitude of 1283 meters above sea level and a surface area of 1439 km². The municipality is classified as an intermediate city with a population of 542,046 inhabitants and a population density of 361.22 inhabitants/km² (Ibagué Como Vamos 2023). Additionally, the city has approximately 542 km within the road network infrastructure (Ministerio de Transporte 2019). The city's morphology limits growth in the north-south direction, leading to expansion in the east-west direction, with the main roads running from west to east and, to a lesser extent, from north to south. The current state of the road network shows significant deterioration, with up to 60% of pavements having structural failures (Guarnizo 2018). Likewise, vehicular growth has changed drastically, reflecting an increase in travel times and presenting traffic jams, which in turn stimulate travel time problems for the population. Among other things, the city's historic center is located in the west and is one of the main points of travel attraction. Additionally, the city's geographic location makes Ibagué a strategic hub in the country's commerce, connecting small, medium, and major cities (Ministerio de Transporte 2019), leading to a large flow of heavy vehicles in different parts of the city.

The vehicle fleet has seen significant growth in recent years, from 160,122 vehicles in 2015 to 208,640 vehicles in 2019 (SMTT 2020), which is a significant increase, making it important to conduct mobility studies to understand the behavior of transport systems. As mentioned earlier, one of the main factors in the study is road slopes. In Ibagué, the steepest slopes are found in the western, southwestern, and northern areas, resulting in different travel times (TV) behavior in those areas compared to the rest of the city. Another influential factor in the study is the socioeconomic level of people. In Colombia, this is called socioeconomic strata are an official classification used by the government to group the population according to their socioeconomic level. This classification is mainly used to determine the cost of certain public services (such as water, electricity, and

gas), taxes, and subsidies, with the aim of promoting an equitable distribution of resources and services across the country (DANE, N.D.).

The stratum does not directly depend on the income of the people living there but rather on the physical characteristics and urban or rural context of the area. Municipal governments conduct studies and assign the level for each area and household, which also means that a property's stratum can change if there are improvements or deteriorations in the sector where it is located. This is a social index that ranges from 1 to 6, with 1 being the lowest and therefore the population with the least resources, and 6 being the people with the highest incomes (Figure 1). The demographic distribution shows that the majority of the population is in strata 1, 2 and 3, totaling 90% of the population (Figure 2), which indicates that the city is made up mainly of low-income residents. This variable is essential to consider within the accessibility condition model, allowing to differentiate the distribution of opportunities for people who can access private transportation.

In this research, considering socioeconomic strata is essential, as in Colombia, the lower strata often reside in areas with less infrastructure and connectivity, which could limit their options for the safe and efficient use of bicycles as a means of transport. Including this variable makes it possible to identify areas that need more investment in cycling infrastructure to reduce inequalities. Furthermore, people in lower socioeconomic strata tend to have less access to private vehicles, making bicycles an economical and sustainable transportation alternative; however, without adequate infrastructure, this option may not be viable.

Given the high demand for transportation in the city, one of the most favorable alternatives is the bicycle. Jakovcevic et al. (2016) propose long-term benefits through the use of these means, such as reducing congestion, enhancing urban environments, addressing climate change, and decreasing the use of fossil fuels. Additionally, there are more personal benefits, such as improvements in health, entertainment, travel times, and satisfaction. However, one of the most significant advantages of using bicycles is the low cost since they do not require fuel, costly maintenance, or expensive parts.

The bicycle, as a recurrent means of transportation, represents a sustainable solution for urban mobility with a significant positive impact on the environment. It drastically reduces greenhouse gas emissions and air pollution compared to motorized vehicles. As Andrade-Castañeda et al. (2017) state, Ibagué emits about 368 Gg CO₂e/year due to fossil fuel sales, mainly gasoline and diesel. To mitigate these emissions, it is recommended to reduce the consumption of these fuels, making the bicycle a great alternative. Additionally, its use helps reduce traffic congestion, resulting in improved air quality and noise reduction in cities. This means of

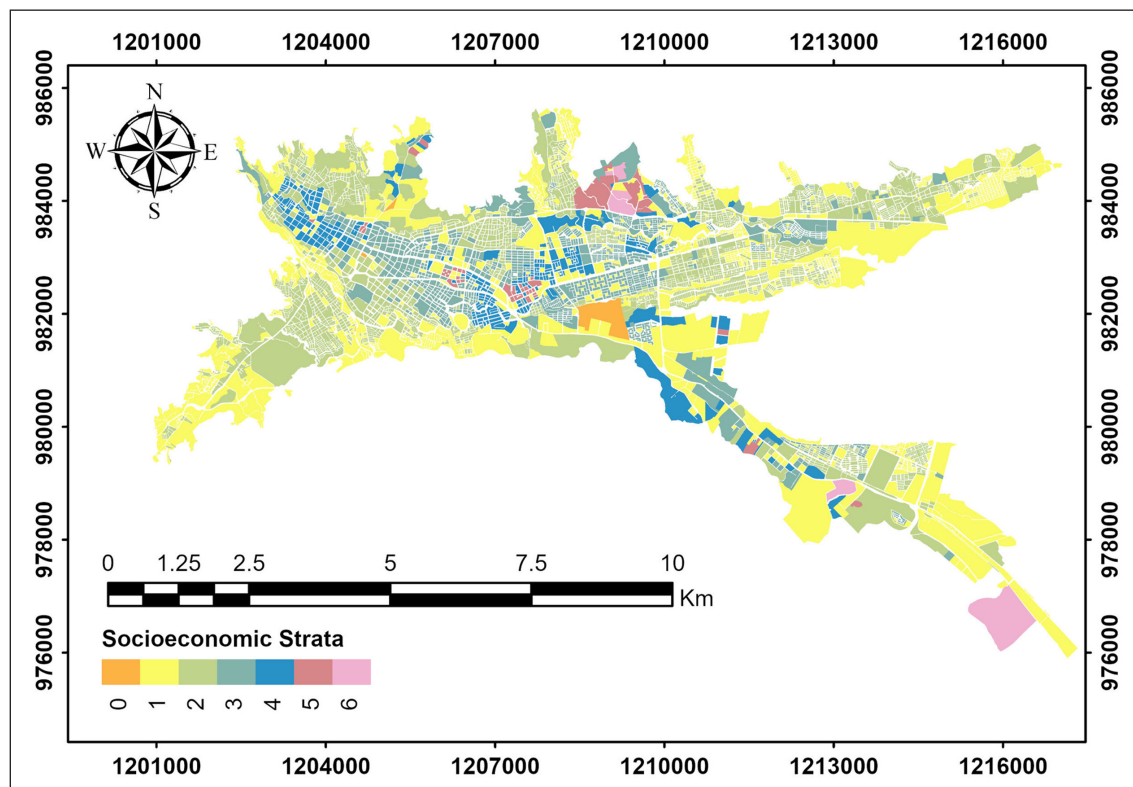


Figure 1 Geographic distribution of socioeconomic stratification for Ibagué. Own elaboration.

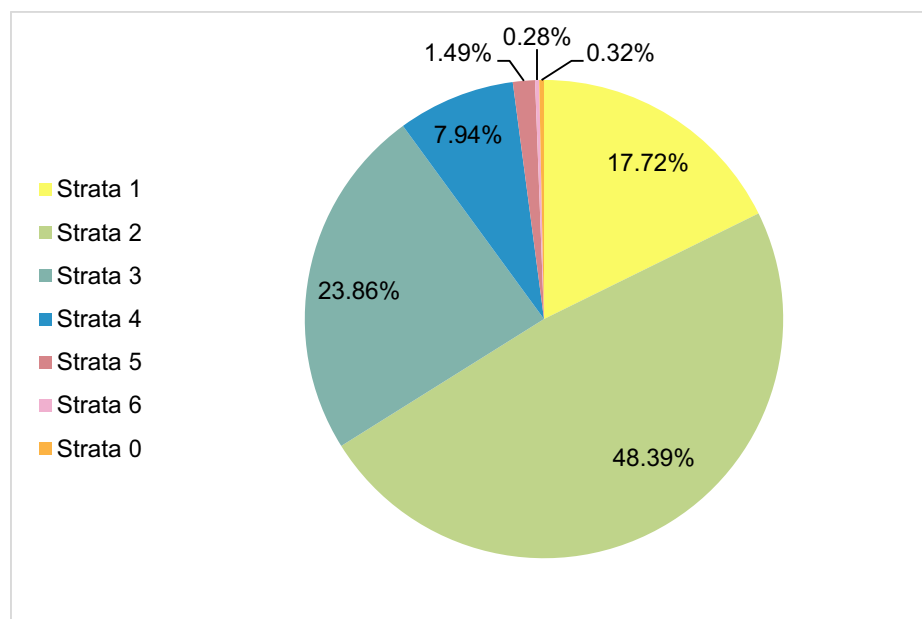


Figure 2 Percentage distribution of socioeconomic stratification for Ibagué. Own elaboration.

transportation also promotes an active and healthy lifestyle, thereby enhancing the physical and mental well-being of its users while becoming a fundamental ally in the fight against climate change and the preservation of the environment for future generations. Moreover, the use of this transportation method contributes to the development of the city.

In the present study, the average global accessibility is calculated, allowing an analysis of how the road infrastructure and city topography influence the time

and manner of traveling by bicycle. Thus, the supply of this active transportation mode can be evaluated, determining how the presence of the road's longitudinal slope affects accessibility. First, to perform this calculation, linear regressions indicating the relationship between slope and speed are found to provide information for each arc. Subsequently, specialized modeling and calculation software such as TransCAD, which implemented Dijkstra's shortest path algorithm, and ArcGIS, which used the ordinary Kriging geostatistical algorithm, are used. The

results include isochronous curve maps, a relationship between travel time and geographic location distributed across the study area, calculated for two scenarios: one without considering the linear speed prediction models according to the slope and another with these models, and coverage ogives, which are graphs relating travel time to the accumulated percentage of covered population. With this data, a better understanding of the road network in the city and the interaction of transportation with people can be achieved.

LITERATURE REVIEW

The increase in inhabitants coexisting in the territory causes expansion to the city peripheries and a greater number of destinations that are more dispersed and inaccessible from home (Obregón et al. 2018), resulting in longer distances and average travel times (González et al. 2018). Considering that the bicycle is currently chosen by users for its various positive aspects such as comfort, confidence, and safety (Jakovcevic et al. 2016), an accessibility study is decided, which is a fundamental tool for planning and evaluating the transport offer. This leads to appropriate decision-making by identifying deficiencies in access to goods and services or the impact generated by new infrastructure works (Cardona et al. 2018).

Currently, one of the major problems facing the world is environmental issues. In this regard, Tello et al. (2016) highlight that the use of bicycles does not represent an environmental threat as they do not pollute, reduce the consumption of non-renewable fossil resources, and contribute to physical activity, health, and well-being. Various studies have proven the positive impact of bicycle use on the environment, such as Ávila et al. (2019), which measures the level of awareness regarding the positive consequences of using this means of transport, including reducing environmental pollution, cost savings, reducing vehicular traffic, and health benefits. This aligns with Casafranca et al. (2023), which states that bicycle use generates significant learning of the environmental cross-cutting approach, making it essential to consider the bicycle as a sustainable and health-beneficial mode of transport, both physically and emotionally.

There are various definitions for what is known as accessibility. According to Obregón et al. (2018), accessibility is the ease with which a destination can be reached from different points of origin, synthesizing opportunities for interaction and contact. Morris et al. (1978) explain that accessibility is the ease or difficulty of connecting inhabitants in different modes of transport due to physical and operational barriers. Similarly, Geurs and Van Wee (2004) argue that accessibility is a key concept for mobility planning, and its evaluation can help

identify and improve the efficiency and sustainability of transport systems. An example to consider is the study by Tansley et al. (2017), which evaluates access capacity to trauma centers in Nova Scotia, Canada, improving accessibility to these places by providing better services and safeguarding integrity.

There are different types of accessibility: relative, integral, and global. Relative accessibility refers to the existing travel ease between two points. Integral average accessibility is calculated depending on the location of one or more nodes of interest (such as schools, universities, banks, shopping centers, among others). Lastly, global average accessibility calculates the factor between all network nodes, determining this factor from all points to all points (Escobar et al. 2022).

Various studies have related accessibility and bicycles. Pritchard et al. (2019) focus on a specific case of conditions, using spatial analysis to examine the combined use of bicycles and public transport in the labor field and spatial equity in Sao Paulo, Brazil, based on surveys and geospatial analysis. Additionally, Lovelace et al. (2018), Carstensen et al. (2015), and Zheng et al. (2019) relate bicycle accessibility, considering the impact of cycling infrastructure. These studies were carried out in London and Lyon, Denmark, and Australia, respectively. One of the most representative works in the study city was conducted by Zuluaga et al. (2022), estimating accessibility conditions according to the time slot for different types of transport, including bicycles.

This research aims to determine the accessibility conditions for bicycle use around the city of Ibagué. These conditions result from measuring average travel times between different points in the city (Cardona et al. 2018). It proposes starting with Dijkstra's shortest path algorithm (Dijkstra 1959) and continuing with the ordinary Kriging geostatistical model (Lindner et al., 2016) to calculate global average accessibility and coverage ogives. Finally, the savings gradient model with its respective isochronous curves and general and stratified savings graphs is constructed.

METHODOLOGY

The present study develops a six-stage methodology (Figure 3) designed to examine the global average accessibility for bicycles in the city of Ibagué, considering two fundamental factors: the longitudinal slope of the roads and the socioeconomic stratum of the population.

Stage 1. Data Collection: Population census data divided by blocks in the city of Ibagué are obtained, considering their stratification. These data are acquired from the databases of the National Administrative Department of Statistics (DANE) (DANE 2018). Additionally, a road network is constructed containing

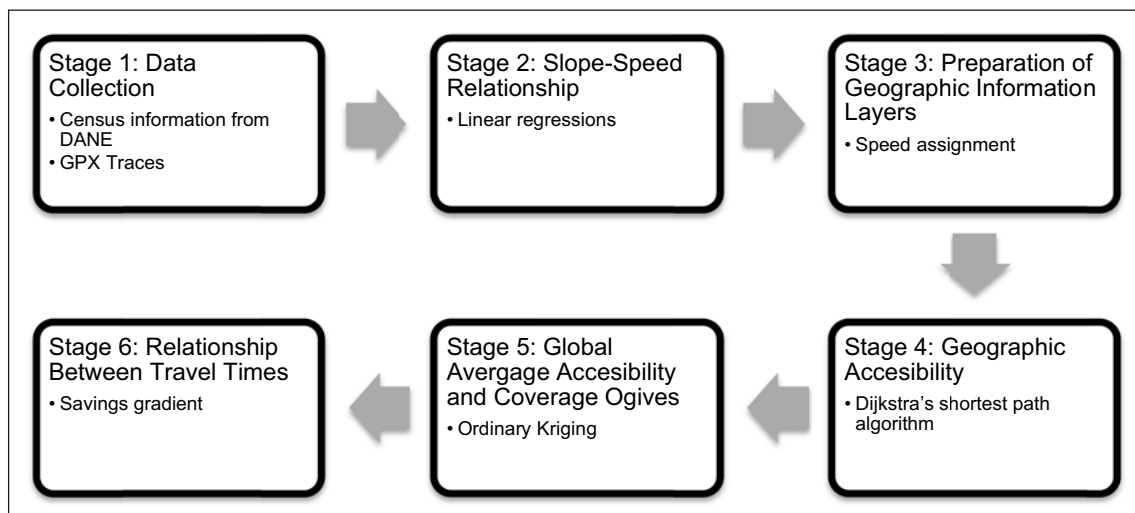


Figure 3 Methodology Process Map. Own elaboration.

the city's traversable roads, with their respective types of roads. GPX traces are collected, which contain information corresponding to geographic location, travel time, distance, and average speed for the vehicle under study, in this case, a bicycle. These traces were collected through the OsmAnd application by people making their daily bicycle trips over two months, in addition to public information provided by the cycling community of Ibagué.

Stage 2. Slope-Speed Relationship: Subsequently, with the data obtained from the georeferenced speeds of each trace and the information from digital elevation models, which contain the heights of the initial and final points, the longitudinal slope of the road is calculated, relating the road infrastructure, called arc, and the calculated average speed. Then, scatter plots of speed versus slope are made and reviewed according to the coefficient of determination to identify the model that best approximates reality. This allows analyzing these two variables through an equation that helps obtain the speed in arcs without GPX trace information. The procedure is carried out on the different types of roads in the city, considering an initial proposal that the behavior is different in each one, and therefore, they will have different slope-speed relationships. Thus, depending on the type of road and the degree of slope, an estimated speed value is assigned to the arc.

Stage 3. Preparation of Geographic Information Layers: The previously created network is conditioned; arcs and nodes are established to create intersections between different points in the network. Next, speeds are assigned between the nodes obtained previously by linear regressions in the slope condition or by averaging, considering the type of road in the no-slope condition. The network consists of a graph with 27,275 arcs representing each street in one direction (if it has two directions, it counts as 2 arcs, one on top of the other drawn in the opposite direction) and 10,940 nodes representing the connections.

Stage 4. Geographic Accessibility: In this stage, the travel time for each node (t_v) must first be obtained. This t_v is the average time it takes for each node in the city to reach the destination point. This process is carried out through a specialized graph analysis algorithm to find the shortest path, generating a matrix with these t_v , using Dijkstra's shortest path algorithm (Dijkstra 1959). Next, the vector of average travel times (TV) that each node takes to travel to the rest of the city is determined, considering a number of $n-1$, as the starting node is included. These averages are calculated (equation 1) (Escobar et al. 2022).

$$\bar{T}_{vij} = \frac{\sum_{j=1}^n t_{vij}}{(n-1)} \quad i = 1, 2, 3, \dots, n; j = 1, 2, 3, \dots, n \quad (1)$$

Stage 5. Global Average Accessibility and Coverage Ogives: Based on the geographic accessibility conditions, the isochronous curve map is constructed using the ordinary Kriging geostatistical model (equation 2), which generates an estimated curve (S_o) according to observed curves (S_i), considering the weighting parameters (λ_i) (Escobar et al. 2022).

$$\hat{X}(S_o) = \sum_{i=1}^n \lambda_i X(S_i) \quad \lambda_1, \lambda_2, \lambda_3, \dots, \lambda_n \quad (2)$$

Along with this data and the census information of inhabitants by block, coverage ogives are created according to average travel times and the accumulated population percentage. It should be noted that the same procedure from Stage 4 and Stage 5 must be developed for both cases (with and without slope).

Stage 6. Relationship Between Travel Times: Once the accessibility measures corresponding to the analysis with and without slope are obtained, the relationships between this factor are estimated through the calculation of the savings gradient (Ga), represented by equation 3 (Cardona et al. 2020), where the difference

between the base methodology without slope (T_{vij}) and the condition with slope (T_{vijf}) is calculated, thus finding the difference between the two conditions.

$$Ga\% = \frac{\overline{T_{vij}a} - \overline{T_{vijf}}}{\overline{T_{vij}a}} * 100 \quad (3)$$

RESULTS

The results obtained through the proposed methodology are presented in four sections. The first section presents 5 linear regressions corresponding to 5 types of roads present in the city, where data on speed versus slope were taken. The second section shows the analysis performed under the no-slope condition. The third section analyzes the slope factor, and finally, the gradient that relates the two conditions to perceive the change between them.

LINEAR REGRESSION MODELS

According to Stage 1, information was collected through georeferenced data, including the user's geographic position, speed, distance traveled, average time, and height above sea level. The collected data were refined considering a speed range at our discretion, for primary, secondary, and local roads from 5 km/h to 45 km/h, and for collector and zero-emission roads from 2 km/h to 30 km/h. This corroborates the aforementioned proposition of the different behavior experienced by road type. Next, the slopes in each travel section were found and related to the average speed between them.

A mathematical model representing a linear approximation for each type of road was calculated, with 95% confidence and their respective correlation coefficients. These mathematical models allowed assigning speeds to the road network arcs without GPS speed information based on the longitudinal slope of the road, making the model more representative of reality.

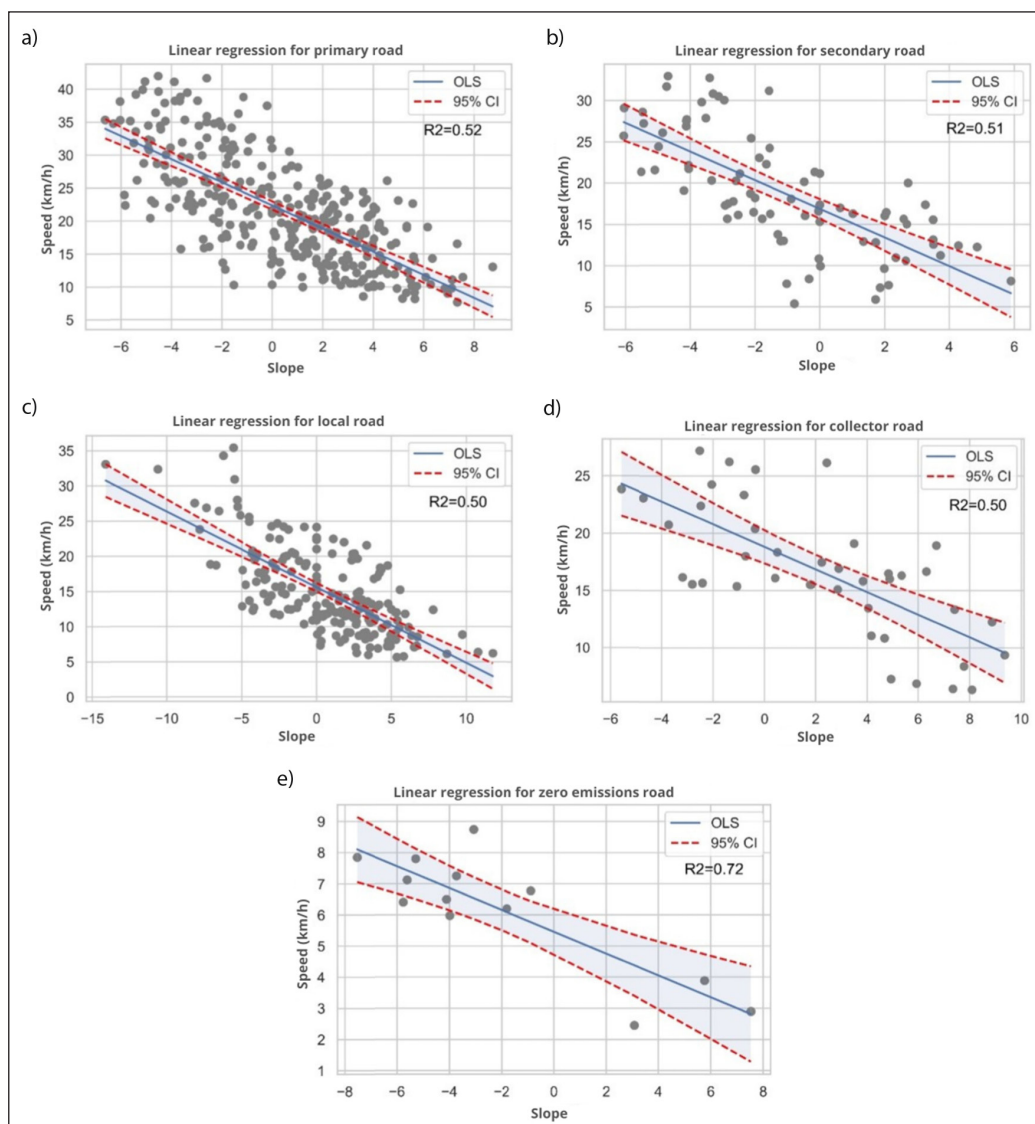


Figure 4 a. Linear regression for primary road. Own elaboration. b. Linear regression for secondary road. Own elaboration. c. Linear regression for local road. Own elaboration. d. Linear regression for collector road. Own elaboration. e. Linear regression for zero emissions road. Own elaboration.

It should be noted that people who travel by bicycle tend to ride differently in the same scenarios, depending on the cyclist's physical condition or the experience that gives them confidence in moving. This leads to different speeds for the same slope observed in the linear regression graphs. Examining Figure 4a–4e, the linear trends of the obtained data are determined, and it is verified that the correlation coefficients (R^2) are greater than 0.5, which relates a speed of 23 km/h on primary roads on flat slopes and 18 km/h on secondary roads. Additionally, high speeds can be observed on local roads (Figure 6), which may be due to the low influx of motorized vehicles in those sectors, allowing free and safe movement of bicycles.

CONDITION WITHOUT SLOPE

With the speed information obtained from the GPX traces, an average per road type is stipulated to introduce them into the arcs without an imposed value. Next, the isochronous curves (Figure 5) were calculated with the average travel times for the respective condition, indicating an area where the population will have the average TV by location in the city, considering the geographic location. With the population census information by blocks, different coverage ogives were created by socioeconomic strata (Figure 6), relating travel times with the accumulated population percentage, considering the inhabitants' stratification.

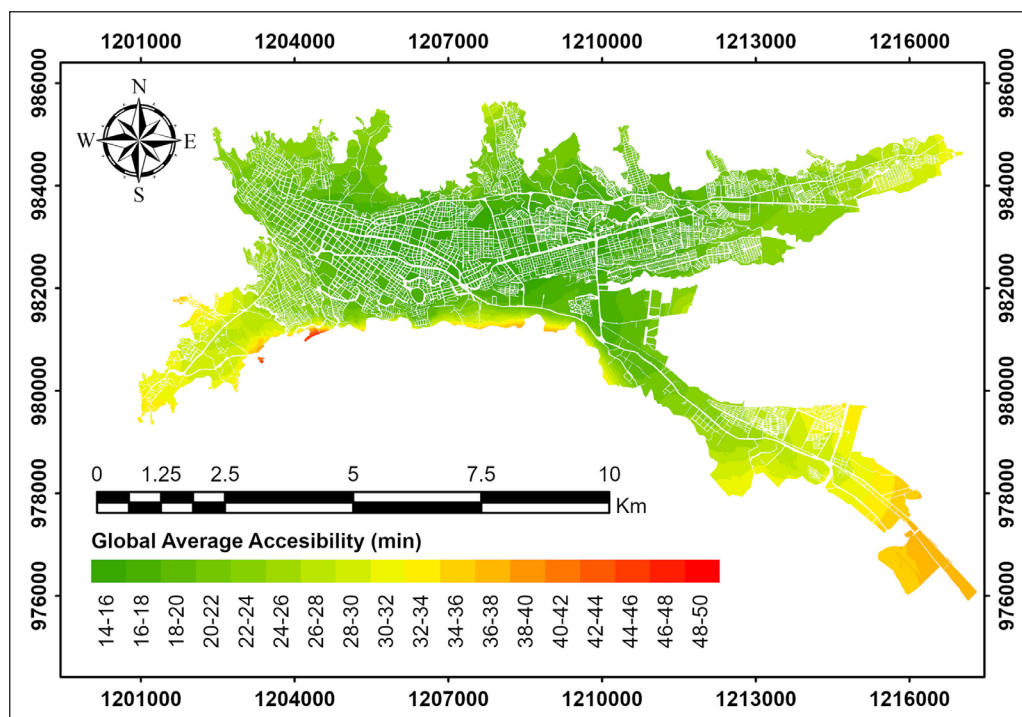


Figure 5 Isochronous curve map, global average accessibility, condition without slope. Own elaboration.

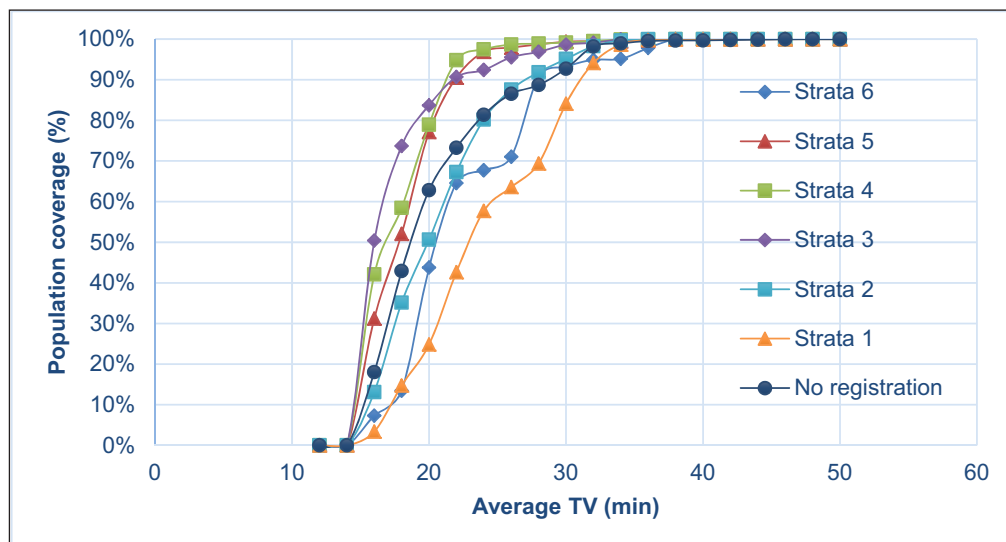


Figure 6 Coverage ogives by stratum, condition without slope. Own elaboration.

In the respective isochronous curves (Figure 5), the color distribution on the map can be observed according to geographic locations representing different travel times divided into 2-minute sections. The areas colored green have shorter travel times, gradually increasing until reaching the red zones, indicating a higher average travel time for the population in those areas.

Lastly, the different isochronous curves were found, relating the accumulated population percentage with their corresponding travel times. Additionally, the analysis was carried out according to the socioeconomic stratum in which the population fraction corresponding to the travel time is located. Figure 6 shows the time it takes for an accumulated population percentage to

travel, with stratum 1 being the most affected, as at least 46% of the population takes 24 minutes or less to travel from one point to any other point in the city, making this the most critical group.

CONDITION WITH SLOPE

To find the accessibility conditions considering the longitudinal slope of the road, the previously performed analysis of the speed-slope relationship must be taken into account. Just as in the previous condition, they are inserted into the arcs without value to develop a more accurate analysis with realistic factors. For this condition, isochronous curves (Figure 7) and the coverage ogive with housing stratification (Figure 8) were determined, just as in the previous condition.

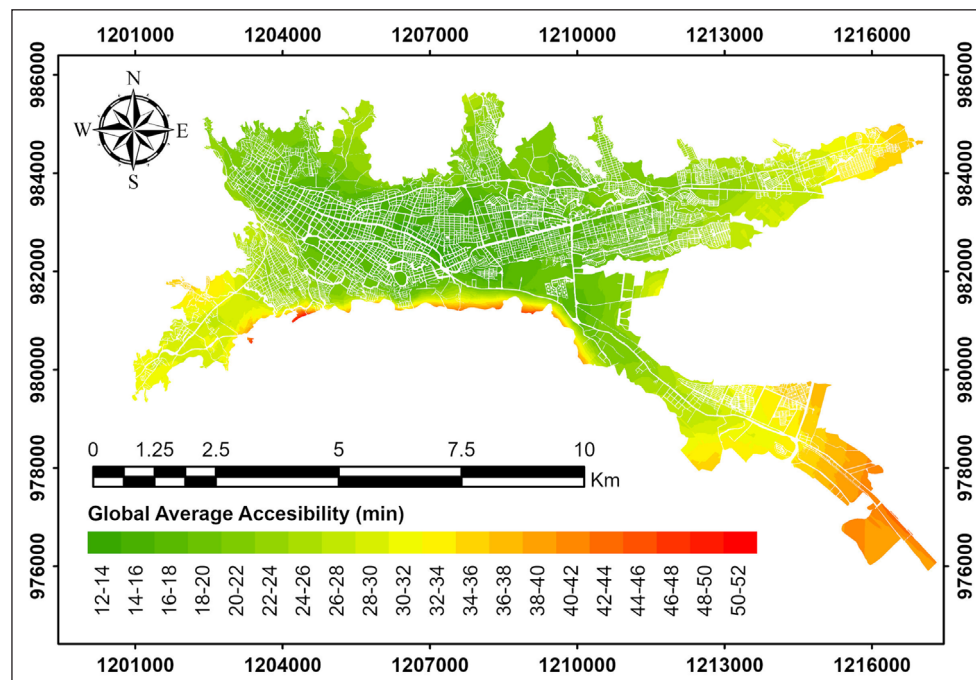


Figure 7 Isochronous curve map, global average accessibility with slope. Own elaboration.

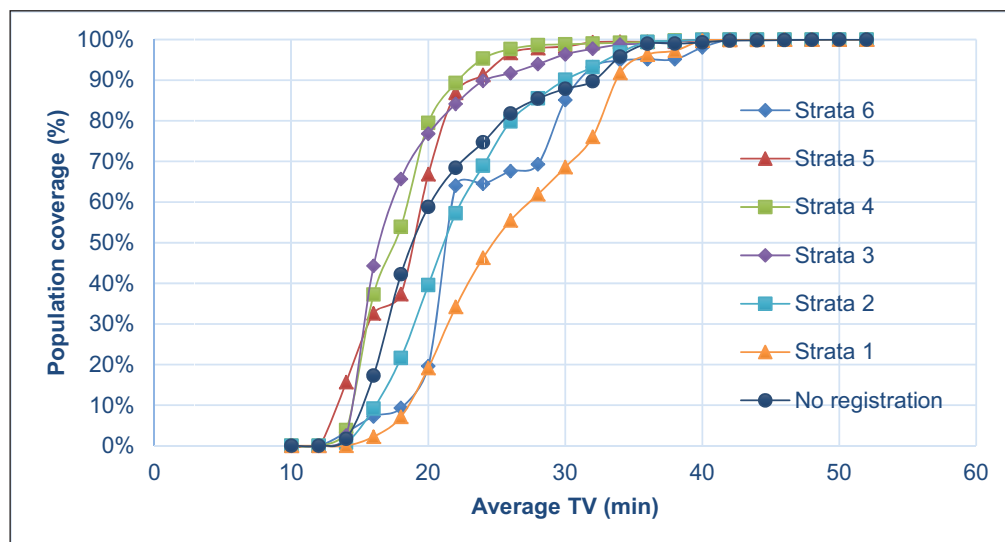


Figure 8 Coverage ogives by stratum, condition with slope. Own elaboration.

The isochronous curves in Figure 7 have the same color distribution as in the previous condition, but they are not the same. It can be observed that the range of average travel times increased, changing from a minimum of 14 to 12 minutes and a maximum of 50 to 52 minutes, indicating a considerable change due to the slope factor. Additionally, the geographic location of the curves changed compared to the condition without slope.

Lastly, in this section, the coverage ogives (Figure 8) were calculated under the same conditions but with the slope factor, as in the previous ones. Although it is still observed that the most critical group is stratum 1, with 42% of the population taking 24 minutes or less to travel from one point to any other point, there is a noticeable difference between the two conditions. This indicates

that the longitudinal slope factor does have significant relevance in the population's displacement, raising the question: How different is the analysis in the various conditions?

SAVINGS GRADIENT

To conduct a proper analysis, the differences between the two proposed models must be considered. For this, the savings gradient was determined. First, the general coverage ogives for the two conditions were constructed to have a graphical model (Figure 9) that allows for visual comparison. Additionally, an isochronous curves map (Figure 10), a general savings gradient impact graph (Figure 11), and an impact graph of the different savings gradients by strata (Figure 12) were also constructed.

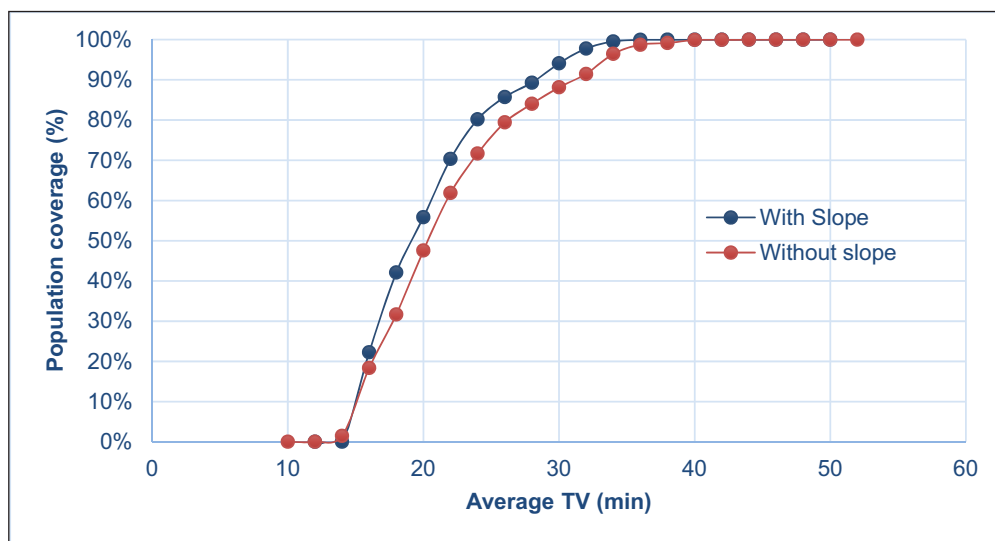


Figure 9 General coverage ogives, comparison between conditions. Own elaboration.

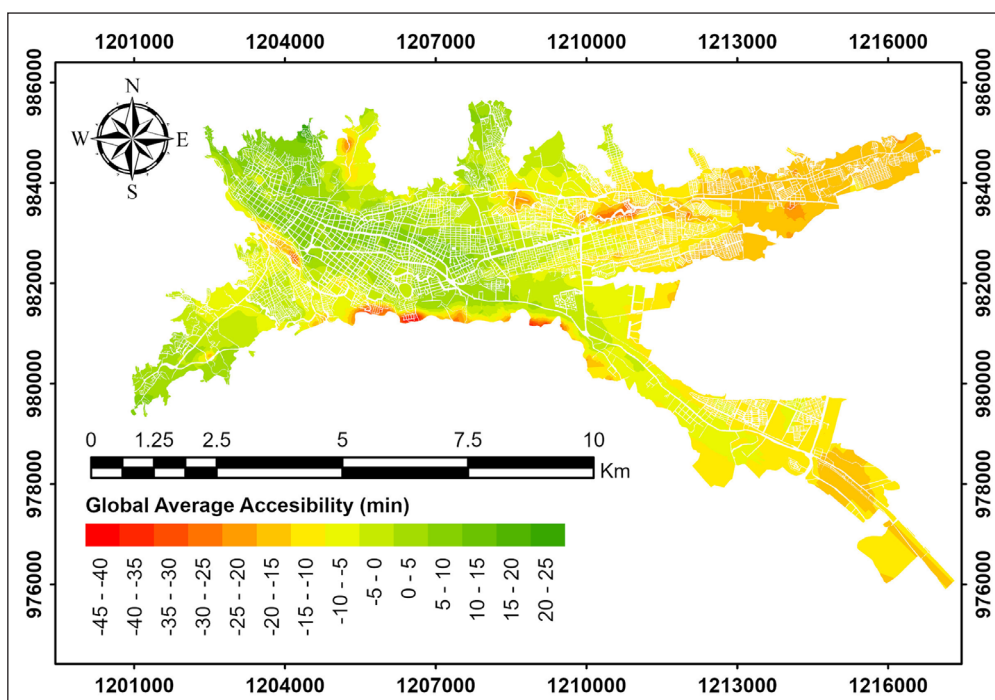


Figure 10 Isochronous curve map, savings gradient. Own elaboration.

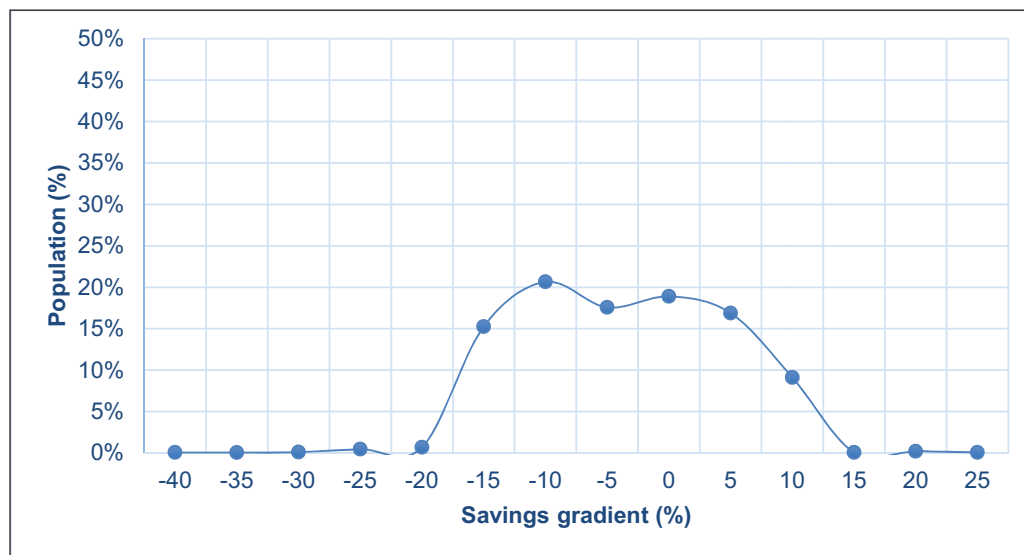


Figure 11 Impact graph, general savings gradient. Own elaboration.

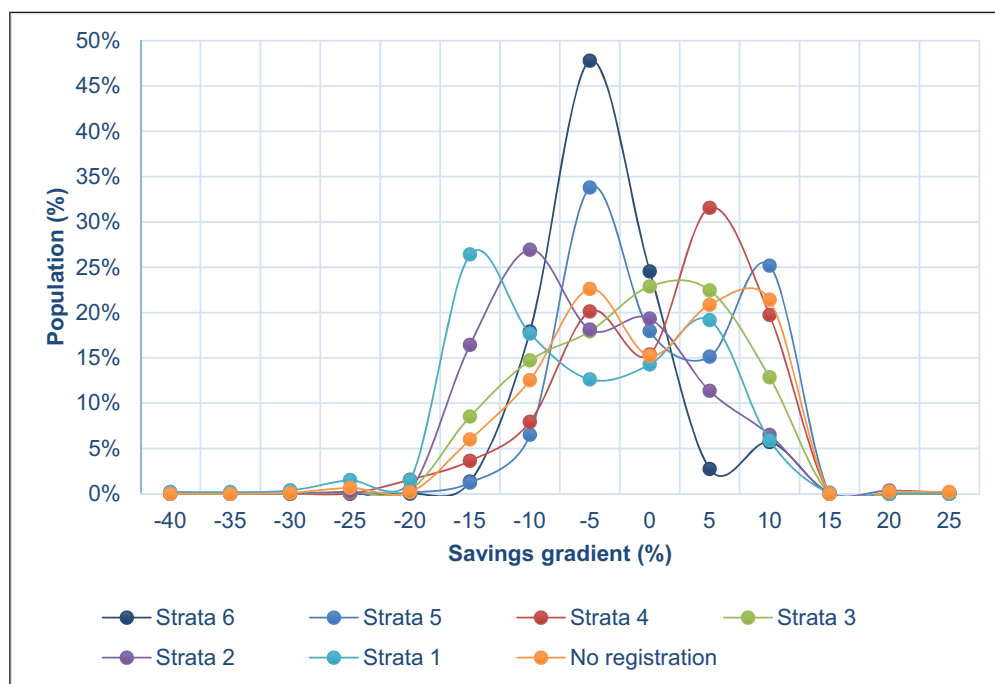


Figure 12 Impact graphs, savings gradients by stratum. Own elaboration.

In Figure 9, the comparison between the general coverage ogives conditions can be observed, showing the difference caused by the slope factor. Analyzing the two curves reveals that, in general, this variable generates longer travel times for the population and maintains the model's trend.

Considering equation 3, which determined the savings gradient indicating the difference between the general condition and the condition with the slope factor, the coverage ogive (Figure 10) was constructed. This represents the percentage of change compared to the geographic location. Examining the created map shows that the people most affected by the slope are those living in the eastern part of the city. This agrees with

the city's elevation levels, which are lower in this area, causing them to travel uphill to the rest of the city.

Next, the impact graph (Figure 11) was determined, indicating the savings gradient for the general population. This relationship links the percentage with the number of people affected by the slope in the calculation of accessibility conditions, also in percentage. It is observed that a larger portion of the population has a negative gradient, indicating that the slope's impact results in longer travel times. In contrast, those who would spend less time traveling, according to the calculation, are located in areas where the city's topography is higher, and therefore, most of their trips would be downhill.

Lastly, impact graphs were generated considering the socioeconomic stratum factor. These graphs show how the gradient varies depending on the inhabitants' stratification. It can be observed that there is a difference in how the slope affects the travel of different groups according to their economic capacity. The spatial inequity among inhabitants of different purchasing power is evident, as strata 5 and 6 do not significantly vary their savings percentages, with the gradient tending to 0. This infers that the conditions with and without slope would be practically the same for these groups.

CONCLUSIONS

The first observation when analyzing the isochronous curves (Figures 5 and 7) is the location of the most affected populations, which are those living in the southwest, southeast, and northeast areas, compared to the rest of the city. This phenomenon is due to their geographic location and the east-west elongated shape of the urban area, resulting in high average travel time values.

The behavior in the linear speed regressions for bicycles, as observed in the corresponding graphs (Figure 4a–4e), presents a negative slope. This makes sense as when slopes are negative, the vehicle moves with the force of gravity, and the physical effort required is minimal to reach high speeds, unlike positive slopes, which require a significant amount of energy to maintain good speed. This data varied in some cases, such as local roads, where the slopes are not very steep, and the consistent use of the road generates a constant speed, indicating that each type of road has different behavior depending on its characteristics. Therefore, it is essential to consider different models based on these characteristics.

Comparing the distribution of socioeconomic strata with the distribution of travel times (TV) reveals that people with longer travel times and therefore lower accessibility are in the lower socioeconomic strata. It is noteworthy that this population tends to use bicycles as a means of transport more than stratum 6, which is mostly located on the outskirts. This should be taken into account for public policy formulation, as strata 1 and 2 concentrate more than 50% of Ibagué's population. Moreover, the fact that 70% of the population in stratum 1 can spend an average of 30 minutes or less on their bicycle trips is a significant indicator for managing these strategies for this transport mode and formulating policies to improve spatial equity, leading to better city development.

Including a physical variable like the longitudinal slope allows for observing variability in the results when comparing the models. In Figure 9, these changes are detected, showing that the analysis with slope tends to have a higher accumulated population in the same

times, indicating that the slope mainly affects negatively. In Figure 10, we see geographically how the slope affects the city's inhabitants. Primarily, people located in the eastern part of the city are the most affected due to the road network slopes and specific heights of the city. In Ibagué, the highest elevations above sea level are in the west, decreasing towards the east, resulting in negative slopes in that direction, but positive slopes in the opposite direction, negatively affecting this part of the population.

Examining Figure 9 concludes that slopes affect more negatively than positively; but how much? Reviewing the general impact graph (Figure 11), we see more population on the negative side than on the positive, indicating a greater adverse impact when traveling by bicycle. This occurs because the population with fewer resources is in the lower elevation areas, resulting in positive slopes for their trips, increasing the mechanical force required, leading to lower speeds, longer travel times, and reduced accessibility. Considering the previous analyses, it is important to identify which inhabitants are most affected by this factor. Figure 12 provides this answer; those in strata 1 and 2 are the most affected, with an increase in travel times (TV) of 15% for 26% of the stratum 1 population and 16% of the stratum 2 population. This gives a better understanding of cycling behavior in the city and how to improve it.

COMPETING INTERESTS

The authors have no competing interests to declare.

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